Chapter 5

The Effects of Motor Imagery After a Variety of Motor Learning Times on Excitability of Spinal Motor Neurons and Accurate Motion

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Additional information is available at the end of the chapter

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Abstract

Purpose: This study aimed to examine the effects of motor imagery on the excitability of spinal motor neurons and accurate motion. Subjects and Methods: About 30 healthy volunteers were recruited. F-waves were recorded at rest, while touching a sensor and motor imagery conditions. Also, the pinch force was measured before and after motor imagery. Furthermore, the subjects mastered the 50% MVC pinch force with learning times of 10 s, 30 s, 1 min, and 2 min beforehand. **Results:** Spinal motor neuron excitability with motor imagery after motor learning for 10 s, 30 s, 1 min, and 2 min was significantly increased as compared to other conditions. Accurate motion in the pinch task after motor imagery was better maintained than in the pinch task before motor imagery with motor learning times of 30 s and 1 min. However, with learning times of 10s and 2 min, the subject's ability to sustain accurate motion in the pinch task after motor imagery was significantly decreased as compared to that of the pinch task before motor imagery. **Conclusion**: Motor imagery increases spinal motor neuron excitability. To maximally improve accurate motion using motor imagery, it is important to practice and master motor learning beforehand

Keywords: F-waves, spinal motor neuron, motor imagery, motor learning, accurate motion

1. Introduction

Motor imagery is reproduced by memory. Motor imagery especially involves the activation of cognitive processes from working memory [1]. In addition, motor imagery and the preparation for motion reportedly had mechanisms similar to those of the processes of managing motion

within the brain [2, 3]. Motor imagery might be applied to therapeutic exercise. Motor imagery may also serve as a therapeutic expedient for patients with restricted activities or in whom physical activity is contraindicated.

Effects of motor imagery on the central nervous system include the following: activations of the primary motor area, supplementary motor area, premotor area, primary somatosensory area, dorsolateral prefrontal area, cingulate cortex, and cerebellums occurred during motor imagery [4–7]. Accordingly, motor imagery increases the excitability of the central nervous system. Also, spinal motor neuron excitability was studied by using F-waves and the H-reflex. 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 in the anterior horn cells [8, 9] (**Figure 1**).

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 in the anterior horn cells.

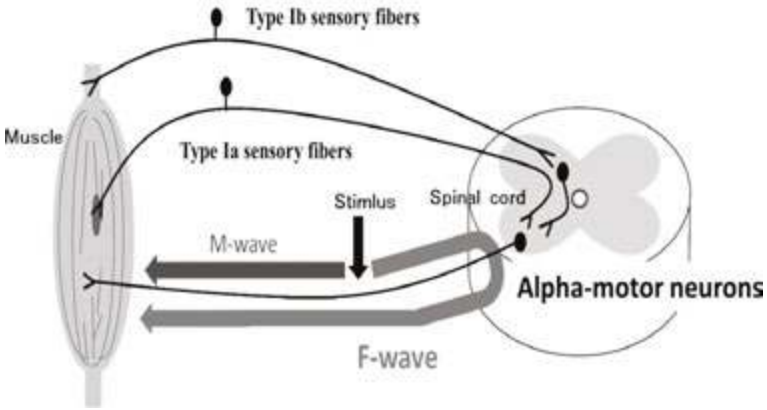

Figure 1. F-wave mechanism.

The H-reflex results from sub-maximal stimulation of type Ia sensory fibers. The potential enters the posterior horn of the spinal cord and passes through the synapses with alpha-motor neurons. Finally, a compound muscle action potential is generated and is recorded as H-waves [10]. F-waves and the H-reflex are generally used as an index of spinal motor neuron function. Suzuki et al. [11] reported that persistence and the F/M amplitude ratio during motor imagery at 50% maximum voluntary contraction (MVC) pinch action were significantly increased than those at rest. Taniguchi et al. [12] reported that persistence and the F/M amplitude ratio were significantly decreased after a sustained rest for 3 h as compared to the preresting condition. However, persistence and the F/M amplitude ratio were maintained, showing similar values, after the sustained rest as compared to the preresting condition when rest and motor imagery were combined. Kasai et al. [13] reported that no significant differences were observed in the H-reflex amplitude between the resting condition and motor imagery involving flexion-extension movements at the wrist joint.

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Additionally, Oishi et al. [14] reported that the H-reflex amplitude was significantly increased, unchanged, or decreased with motor imagery involving skating, as compared to the resting condition, in a speed skater. Thus, studies have obtained a variety of results such as increased, unchanged, or decreased spinal motor neuron excitability during motor imagery. Given this wide range of observations, the only consistent result is an increase in activation of the central nervous system, while the excitability of spinal motor neurons may not always increase during motor imagery. To optimize improvement of motor function during physical therapy using motor imagery, it is necessary to enhance the excitability of spinal motor neurons as well as to activate the cerebellar cortex.

Next, we considered the effects of motor imagery on actual motion. Yue et al. [15] reported a comparison of muscular strengths after motor imagery of the little finger MVC abduction movement for 4 weeks among motor imagery, physical training, and control groups. They found that muscular strength was reinforced at 30% in the strength training group and at 22% in the motor imagery group. Guillot et al. [16] reported flexibility of the hamstrings and ankle joint muscles to be significantly improved in the postmotor imagery condition of stretching as compared to the premotor imagery condition in swimmers. Page et al. [17] reported that upper limb motor function was improved using a combination of physical therapy and motor imagery in poststroke hemiparesis patients. Dickstein et al. [18], likewise, reported gait speed to be improved using motor imagery in hemiparesis patients with cardiovascular disease. Thus, motor imagery improves muscular strength, range of motion, and motor function. However, it is unclear whether motor imagery affects the accuracy of motion. We use a tool and an object, manipulated by the upper limb, for activities of daily living. For example, buttoning and unbuttoning, using chopsticks, picking up coins, and so forth, are important motor activities. Therefore, the acquisition of accurate motion is crucial. Herein, we studied the effects of motor imagery after various motor learning times, that is, 10 s, 30 s, 1 min, and 2 min, on the accuracy of motion and the excitability of spinal motor neurons.

2. Subjects

We included 30 healthy subjects (males, 15; females, 15; mean age, 20.3 ± 1.0) in the group with a motor learning time of 10 s. This study was approved by the Research Ethics Committee at Kansai University of Health Sciences (Approval number: 15-04).

Next, we enrolled another 30 healthy subjects (males, 15; females, 15; mean age, 21.1 ± 1.2) in the group with a motor learning time of 30 s. This study was approved by the Research Ethics Committee at Kansai University of Health Sciences (Approval number: 16-25).

Then, we included 30 healthy subjects (males, 15; females, 15; mean age, 19.7 ± 1.3 years) in the group with a motor learning time of 1 min. This study was approved by the Research Ethics Committee at Kansai University of Health Sciences (Approval number: 16-26).

Finally, we enrolled 30 healthy subjects (males, 15; females, 15; mean age, 22.3 ± 3.0 years) in the group with a motor learning time of 2 min. This study was approved by the Research Ethics Committee at Kansai University of Health Sciences (Approval number: 16-47).

All subjects provided informed consent prior to study commencement. The experiments were conducted in accordance with the Declaration of Helsinki.

3. Methods

The study process required three conditions: resting, touching a sensor, and motor imagery. We recorded F-waves during isometric contraction of the thenar muscle. We also measured the pinch force before and after motor imagery. The process is described in detail in below text.

We recorded F-waves of the left thenar muscle and used the spinal motor neurons under the resting condition as an index. Suzuki et al. [11] reported that motor imagery is not simply a matter of carrying out an action, instead actually representing a combination involving maintenance of motion position. Accordingly, we recorded F-waves while the subjects not only simply touched the pinch meter sensor [Digital indicator F340A (Unipulse Inc.)] between the thumb and index finger (touching sensor condition) but also during the combination of touching the pinch meter sensor and performing motor imagery for 1 min (motor imagery condition). In advance, we determined the magnitude of MVC in subjects holding the pinch meter sensor while exerting maximum effort for 10 s. Furthermore, the subjects were required to learn 50% MVC beforehand with isometric contraction for the pinch action with various motor learning times, that is, 10 s, 30 s, 1 min, and 2 min. At this time, the subjects were instructed to maintain the 50% MVC while viewing the pinch meter display. Subsequently, the subjects were asked to subjectively determine the 50% MVC without using visual feedback before motor imagery. In addition, we measured the pinch force for 10 s (pinch task first trial). Again, the subjects were asked to subjectively estimate the 50% MVC without using visual feedback after motor imagery, and we measured pinch force for 10 s (pinch task second trial). On a different day, the control group, while not using motor imagery in a similar process in the motor imagery phase (without motor imagery condition), underwent F-wave recording. These tasks were performed randomly in the motor imagery and control groups (**Figure 2**).

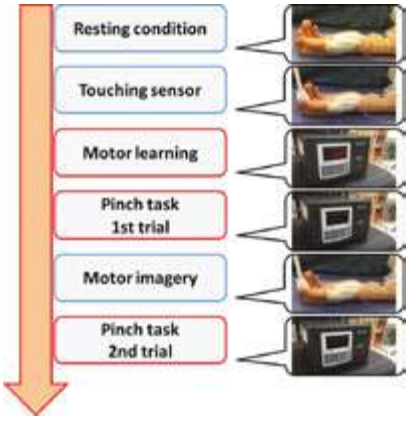

Figure 2. Study process.

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We recorded F-waves under resting, touching a sensor, and motor imagery conditions. Also, the subjects were instructed to learn the 50% MVC with visual feedback prior to motor imagery. Furthermore, the subjects were asked to subjectively estimate the 50% MVC without using visual feedback before and after motor imagery.

The testing conditions for measurement of F-waves were as follows. A Viking Quest electromyography machine (Natus Medical Inc.) was used to record F-waves. The subjects were comfortably placed in the supine position. We recorded the F-waves by stimulating the left median nerve at the wrist. Supramaximal shocks (adjusted up to the value 20% higher than the maximal stimulus) were delivered at 0.5 Hz and 0.2 ms for F-wave acquisition. We recorded F-waves of the left thenar muscles using a pair of disks attached with collodion to the skin over the eminence of the thumb and the bones of the metacarpophalangeal joint of the thumb. The stimulating electrodes were composed of a cathode placed over the left median nerve 3 cm proximal to the palmar crease of the wrist joint and an anode placed 2 cm more proximally (**Figure 3**).

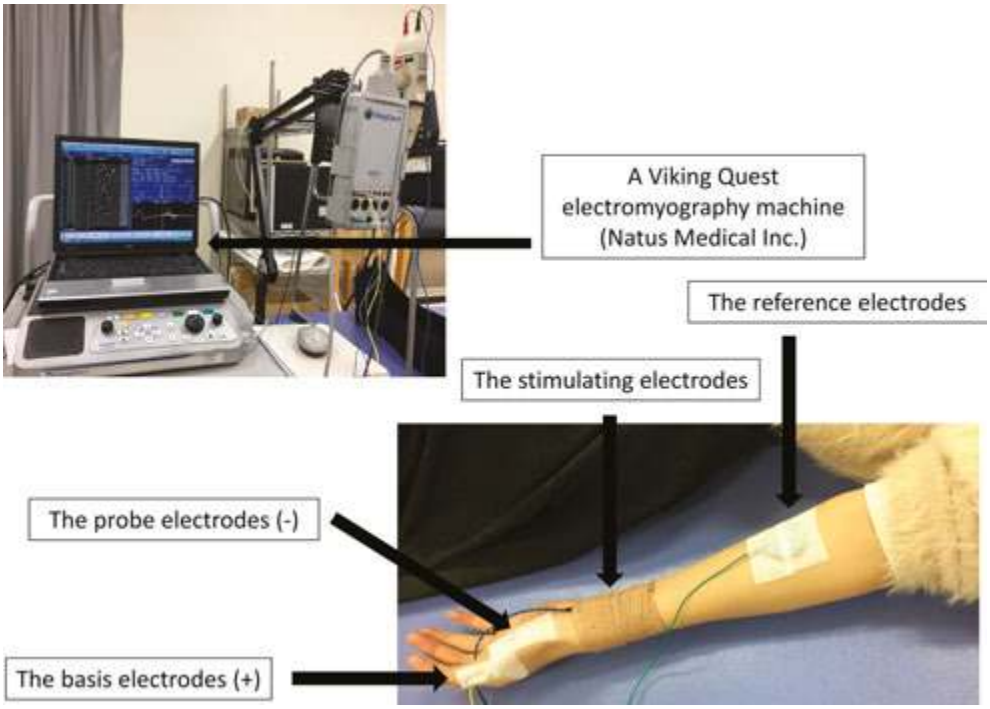

Figure 3. The F-wave testing conditions.

F-waves were analyzed with respect to persistence and the F/M amplitude ratio using 30 stimuli. Persistence was defined as the number of measurable F-wave responses divided by 30 supramaximal stimuli. Persistence reflects the number of backfiring anterior horn cells (**Figure 4**).

The F/M amplitude ratio was defined as the mean amplitude of all responses divided by the amplitude of the M-wave. The F/M amplitude ratio reflects the number of backfiring anterior horn cells and the excitability of individual anterior horn cells (**Figure 5**).

The number of measurable F-wave responses divided by 30 supramaximal stimuli. Persistence reflects the number of backfiring anterior horn cells. This case (17/30) × 100 = 56%

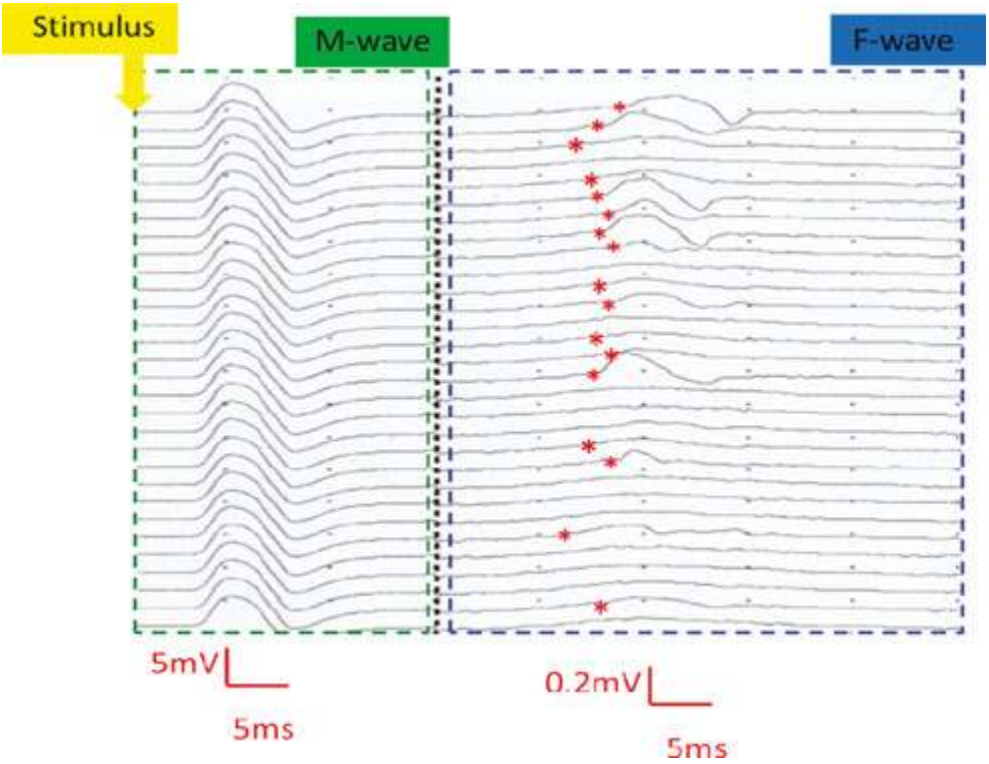

Figure 4. Excitability of spinal motor neurons examined for persistence.

The F/M amplitude ratio was defined as the mean amplitude of all responses divided by the amplitude of the M-wave. The F/M amplitude ratio reflects the number of backfiring anterior horn cells and the excitability of individual anterior horn cells.

Therefore, persistence and the F/M amplitude ratio are regarded as indices of the excitability of spinal motor neurons. In this study, provided that the excitability of spinal motor neurons in the motor imagery condition is significantly increased as compared to that in the touching a sensor condition, it may be improved by subjects performing motor imagery. Furthermore, we confirmed that no significant differences were observed in relative electromyogram integral values between the resting and touching a sensor conditions versus the motor imagery condition when using surface electromyography.

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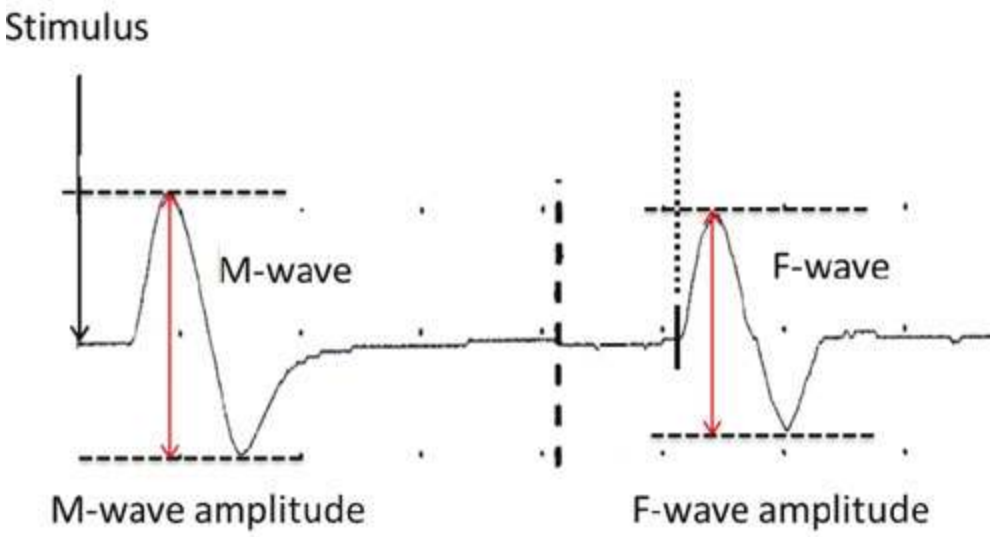

Figure 5. Excitability of spinal motor neurons examined for F/M amplitude ratio.

An index reflecting the accuracy of motion was applied, as follows. In this study, we defined two indexes representing the accuracy of motion (**Figure 6**). Since the index representing the accuracy of motion was not defined in the past literature, the first index used herein was correction time, which was the total time for 50 ± 5% MVC. Correction time reflects the ability to control the accuracy of muscle force in the pinch action. Blefari et al. [19] adopted an error range of ±5% as the index reflecting the accuracy of motion. Based on the aforementioned considerations, we adopted an error range of ±5%. We did this because our study and that of Blefari were similar in terms of adopting pinch action. The second index was the 50% MVC error, obtained by subtraction of the relative pinch force value at the 50% MVC from one. In addition, this index was converted to an absolute value, and then expressed as a percentage. The 50% MVC error reflects whether or not there is convergence on 50% MVC. The correction time and the 50% MVC error were calculated for the first trial and the second trial of the pinch task for the motor imagery and control groups. We measured the pinch force value using electromyogram recording software VitalRecorder2 (KISSEI COMTEC). We calculated two indexes reflecting the accuracy of motion using a versatile biological analysis system, the BIMUTAS-Video (KISSEI COMTEC). Provided that the index reflecting the accuracy of motion in the pinch task second trial is significantly improved as compared to that in the pinch task first trial, the effect of motor imagery is confirmed.

We defined two indexes reflecting the accuracy of motion. The first index was correction time (the total time of 50 ± 5% MVC). The second index was the 50% MVC error (derived by subtraction of the relative pinch force value at the 50% MVC from one, followed by conversion to an absolute value, and then expressed as a percentage).

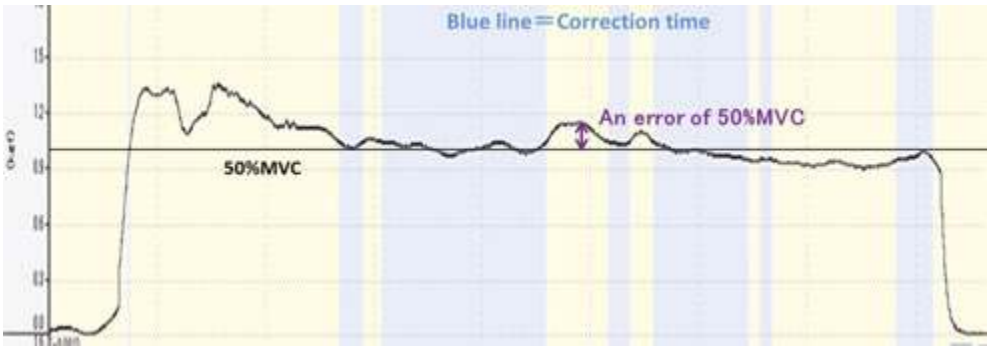

Figure 6. The index for the accuracy of motion.

Data analysis was carried out as follows. Statistical analysis for the normality of the distribution was performed using the Kolmogorov-Smirnov and Shapiro-Wilk tests. Because the data were not recognized as showing a normal distribution, the Friedman test was used to compare F-wave results among the resting, touching a sensor, motor imagery, and without motor imagery conditions. Thereafter, the Scheffe test was used to compare F-wave results across all conditions. Also, the Wilcoxon signed-rank test was used to compare correction time, the 50% MVC error between the first and second trials of the pinch task. The significance level was set at $p < 0.05$. We used SPSS ver. 19 for all statistical analyses.

4. Results

4.1. F-wave results

4.1.1. F-wave results with a 10 s motor learning time

In the motor imagery group when examined for persistence, the resting condition was 63.4 ± 22.7%, the touching a sensor condition was 78.1 ± 17.2%, and the motor imagery condition was 90.5 ± 9.6%. The persistence values under the touching a sensor and motor imagery conditions were significantly increased as compared to that of the resting condition. In addition, persistence was significantly increased in the motor imagery condition than in the touching a sensor condition (*$p < 0.05$, **$p < 0.01$, **Figure 7**). Accordingly, in the control group when examined for persistence, the resting condition was 47.4 ± 19.1%, the touching a sensor condition was 72.1 ± 16.5%, and in the condition without motor imagery was 67.5 ± 17.6%. The persistence values in the touching a sensor and without motor imagery conditions were significantly increased compared to that in the resting condition. However, no significant differences in persistence values were observed between the touching a sensor and without motor imagery conditions (*$p < 0.05$, **$p < 0.01$, **Figure 7**).

Next, in the motor imagery group when examined for the F/M amplitude ratio, the resting condition was 1.2 ± 0.6%, the touching a sensor condition was 1.8 ± 0.8% and the motor

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imagery condition was 2.2 ± 1.5%. The F/M amplitude ratio was significantly increased in the touching sensor and motor imagery conditions as compared to that in the resting condition. However, no significant differences in the F/M amplitude ratios were observed between the touching a sensor and the motor imagery conditions (*p < 0.05, **p < 0.01, **Figure 7**). Accordingly, in the control group when examined for the F/M amplitude ratio, the resting condition was 1.2 ± 0.5%, the touching a sensor condition was 1.9 ± 1.1%, and the condition without motor imagery was 1.8 ± 1.1%. The F/M amplitude ratio in the touching a sensor and without motor imagery conditions were significantly increased compared to that in the resting condition. However, no significant differences in the F/M amplitude ratios were observed between the touching a sensor and without motor imagery conditions (*p < 0.05, **p < 0.01, **Figure 7**).

In the motor imagery group, persistence values when examined in the touching the sensor and motor imagery conditions were significantly increased as compared to that in the resting condition. In addition, persistence was significantly increased in the motor imagery condition compared to that in the touching a sensor condition. The F/M amplitude ratio was significantly increased in the touching a sensor and motor imagery conditions than in the

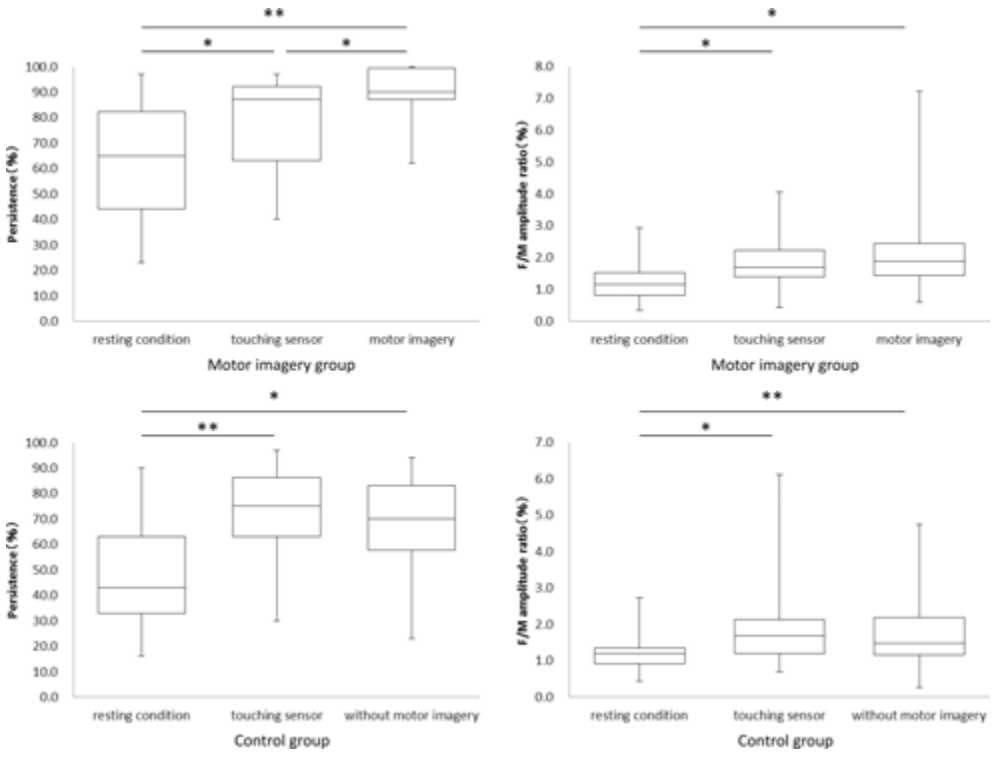

Figure 7. F-wave results.

resting condition. In the control group, the persistence values in the touching a sensor and without motor imagery conditions were significantly increased than that in the resting condition. The F/M amplitude ratios in the touching a sensor and without motor imagery conditions were shown to be significantly increased as compared to that in the resting condition.

4.1.2. F-wave results with a 30 s motor learning time

In the motor imagery group when examined for persistence, the resting condition was 55.6 ± 17.2%, the touching a sensor condition was 72.8 ± 14.3%, and the motor imagery condition was 84.5 ± 12.8%. The persistence values in the touching a sensor and motor imagery conditions were significantly increased as compared to that in the resting condition. In addition, the persistence value was significantly increased in the motor imagery condition than in the touching a sensor condition (**$p < 0.01$, **Figure 8**). Accordingly, in the control group when examined for persistence, the resting condition was 54.3 ± 18.2%, the touching a sensor condition was 70.4 ± 14.4%, and the condition without motor imagery was 70.1 ± 17.7%. The persistence values in the touching a sensor and without motor imagery conditions were significantly increased as compared to that in the resting condition. However, no significant differences in the persistence values were observed between the touching a sensor and without motor imagery conditions (**$p < 0.01$, **Figure 8**).

Next, in the motor imagery group when examined for the F/M amplitude ratio, the resting condition was 1.1 ± 0.7%, the touching a sensor condition was 1.5 ± 0.8%, and the motor imagery condition was 1.7 ± 0.8%. The F/M amplitude ratio was significantly increased in the touching a sensor and motor imagery conditions than in the resting condition. However, no significant differences in the F/M amplitude ratios were observed between the touching a sensor and motor imagery conditions (**$p < 0.01$, **Figure 8**). Accordingly, in the control group when examined for the F/M amplitude ratio, the resting condition was 1.2 ± 0.7%, the touching a sensor condition was 1.5 ± 0.8%, and the condition without motor imagery was 1.6 ± 0.8%. The F/M amplitude ratios in the touching a sensor and without motor imagery conditions were significantly increased than that in the resting condition. However, no significant differences in the F/M amplitude ratios were observed between the touching a sensor and without motor imagery conditions (*$p < 0.05$, **$p < 0.01$, **Figure 8**).

In the motor imagery group, the persistence values in the touching a sensor and motor imagery conditions were significantly increased than that in the resting condition. In addition, the persistence value was significantly increased in the motor imagery condition as compared to that in the touching a sensor condition. The F/M amplitude ratio was observed to be significantly increased in the touching a sensor and motor imagery conditions as compared to the resting condition. In the control group, the persistence values in the touching a sensor and without motor imagery conditions were significantly increased than that in the resting condition. Next, the F/M amplitude ratios in the touching a sensor and without motor imagery conditions were observed to be significantly increased than that in the resting condition.

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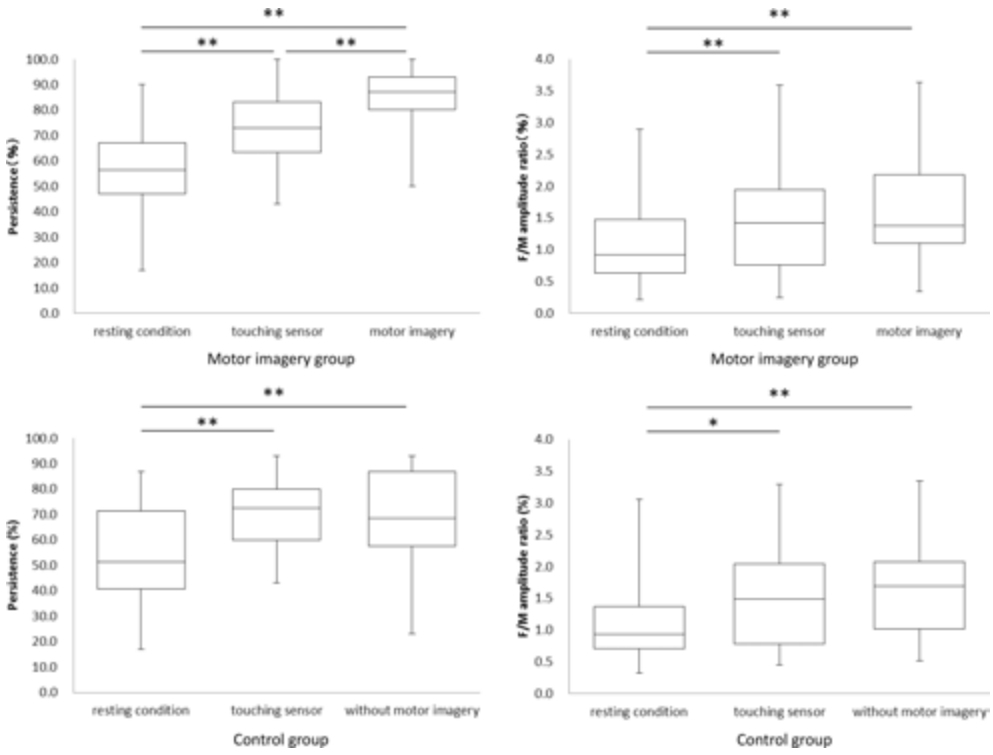

Figure 8. F-wave results.

4.1.3. F-wave results with a 1 min motor learning time

In the motor imagery group when examined for persistence, the resting condition was 48.9 ± 20.3%, the touching a sensor condition was 69.1 ± 13.4%, and the motor imagery condition was 79.8 ± 10.4%. Persistence values in the touching a sensor and motor imagery conditions were significantly increased than that in the resting condition. In addition, persistence was significantly increased in the motor imagery condition as compared to the touching a sensor condition (**$p < 0.01$, $^{\#\#}p < 0.01$, **Figure 9**). Accordingly, in the control group when examined for persistence, the resting condition was 57.6 ± 20.5%, the touching a sensor condition was 74.5 ± 16.7%, and the condition without motor imagery was 68.2 ± 14.9%. Persistence values in the touching a sensor and without motor imagery conditions were significantly increased than that in the resting condition. No significant differences in the persistence values were observed between the touching a sensor and without motor imagery conditions (**$p < 0.01$, **Figure 9**).

Next, in the motor imagery group when examined for the F/M amplitude ratio, the resting condition was 1.8 ± 1.1%, the touching a sensor condition was 2.2 ± 1.2%, and the motor imagery condition was 2.6 ± 2.1%. The F/M amplitude ratio was significantly increased in the

motor imagery than that in the resting condition (**$p < 0.01$, **Figure 9**). Accordingly, in the control group when examined for the F/M amplitude ratio, the resting condition was 1.5 ± 0.7%, the touching a sensor condition was 1.7 ± 0.9%, and the condition without motor imagery was 1.6 ± 0.9%. There were no significant differences in the F/M amplitude ratios among the three conditions (**Figure 9**).

In the motor imagery group, persistence values in the touching a sensor and motor imagery conditions were significantly increased as compared to that in the resting condition. In addition, persistence was significantly increased in the motor imagery condition as compared to the touching a sensor condition. The F/M amplitude ratio was observed to be significantly increased in the motor imagery condition as compared to that in the resting condition. In the control group, persistence values in the touching a sensor and without motor imagery conditions were significantly increased than that in the resting condition. There were no significant differences in the F/M amplitude ratios among the three conditions.

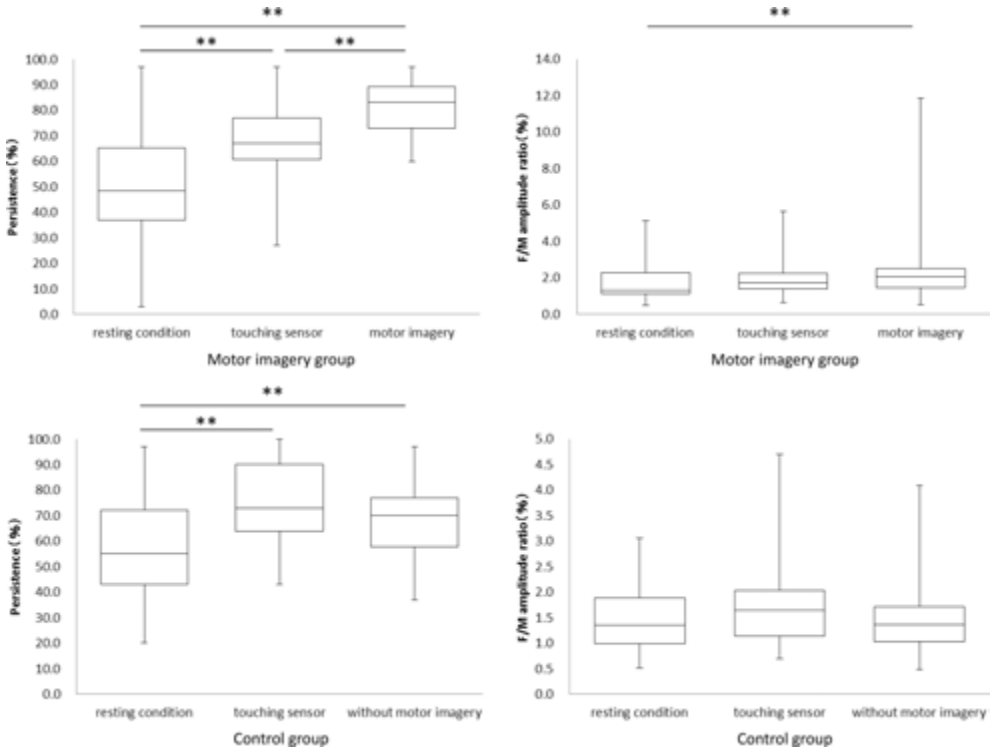

Figure 9. F-wave results.

4.1.4. F-wave results with a 2 min motor learning time

In the motor imagery group when examined for persistence, the resting condition was 63.7±14.2%, the touching a sensor condition was 72.8 ± 15.2%, and the motor imagery condition was 85.2 ± 14.1%. Persistence values in the touching a sensor and motor imagery

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conditions were significantly increased as compared to that in the resting condition. In addition, persistence was significantly increased in the motor imagery condition as compared to the touching a sensor condition (**$p < 0.01$, $^{\#\#}$ $p < 0.01$, **Figure 10**). Accordingly, in the control group when examined for persistence, the resting condition was 58.0 ± 19.9%, the touching a sensor condition was 75.7 ± 15.0% and the condition without motor imagery was 75.6 ± 15.2%. Persistence values in the touching a sensor and without motor imagery conditions were significantly increased than that in the resting condition. No significant differences in the persistence values were observed between the touching a sensor and without motor imagery conditions (**$p < 0.01$, **Figure 10**).

Next, in the motor imagery group when examined for the F/M amplitude ratio, the resting condition was 1.1 ± 0.5%, the touching a sensor condition was 1.3 ± 0.6%, and the motor imagery condition was 1.4 ± 0.6%. The F/M amplitude ratios were significantly increased in the touching a sensor and motor imagery conditions than that in the resting condition. However, no significant differences in the F/M amplitude ratios were observed between the touching a sensor and motor imagery conditions (*$p < 0.05$, **$p < 0.01$, **Figure 10**). Accordingly, in the control group when examined for the F/M amplitude ratio, the resting condition was 1.1 ± 0.7%, the touching a sensor condition was 1.3 ± 0.7%, and the condition without motor imagery was 1.4 ± 0.6%. The F/M amplitude ratios were significantly increased in the

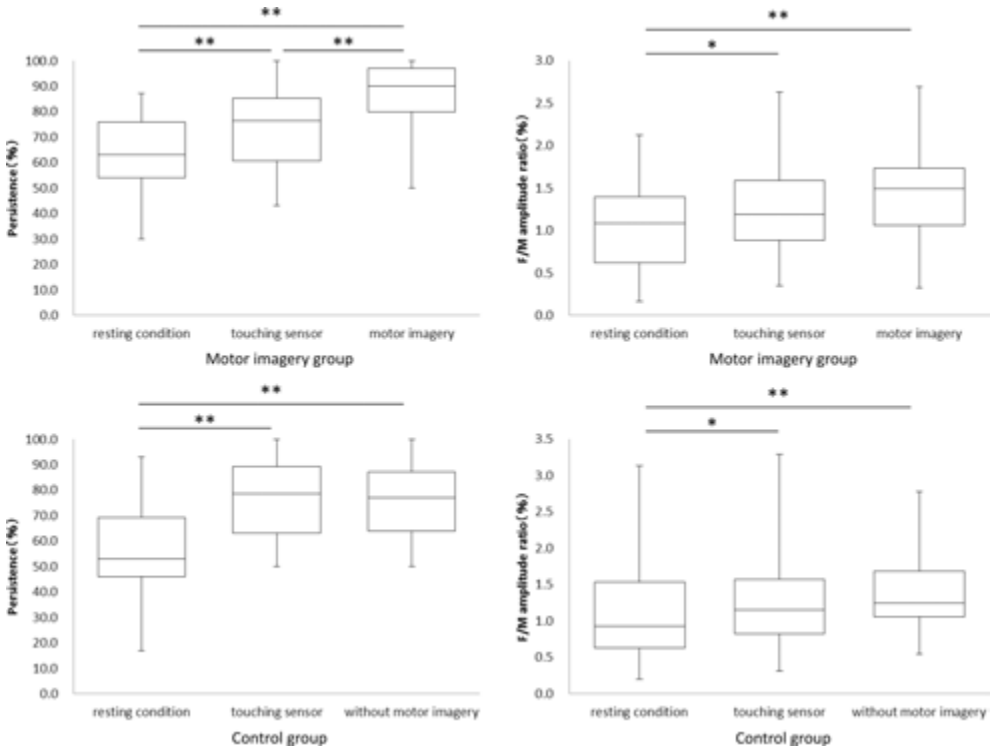

Figure 10. F-wave results.

touching a sensor and without motor imagery conditions than that in the resting condition. However, no significant differences in the F/M amplitude ratios were observed between the touching a sensor and without motor imagery conditions (*$p < 0.05$, **$p < 0.01$, **Figure 10**).

In the motor imagery group, persistence values in the touching a sensor and motor imagery conditions were significantly increased as compared to that in the resting condition. In addition, persistence was significantly increased in the motor imagery condition as compared to the touching a sensor condition. The F/M amplitude ratios were significantly increased in the touching a sensor and motor imagery conditions as compared to the resting condition. In the control group, persistence values in the touching a sensor and without motor imagery conditions were significantly increased as compared to that in the resting condition. The F/M amplitude ratios were significantly increased in the touching a sensor and without motor imagery conditions as compared to the resting condition.

4.2. The index for the accuracy of motion results

4.2.1. The index for the accuracy of motion results with a 10 s motor learning time

In the motor imagery group when examined for the correction time, the pinch task first trial was 1.2 ± 1.5 s and the pinch task second trial was 0.7 ± 1.6 s. No significant differences were observed in the correction time between the first and second trials of the pinch task (**Figure 11**).

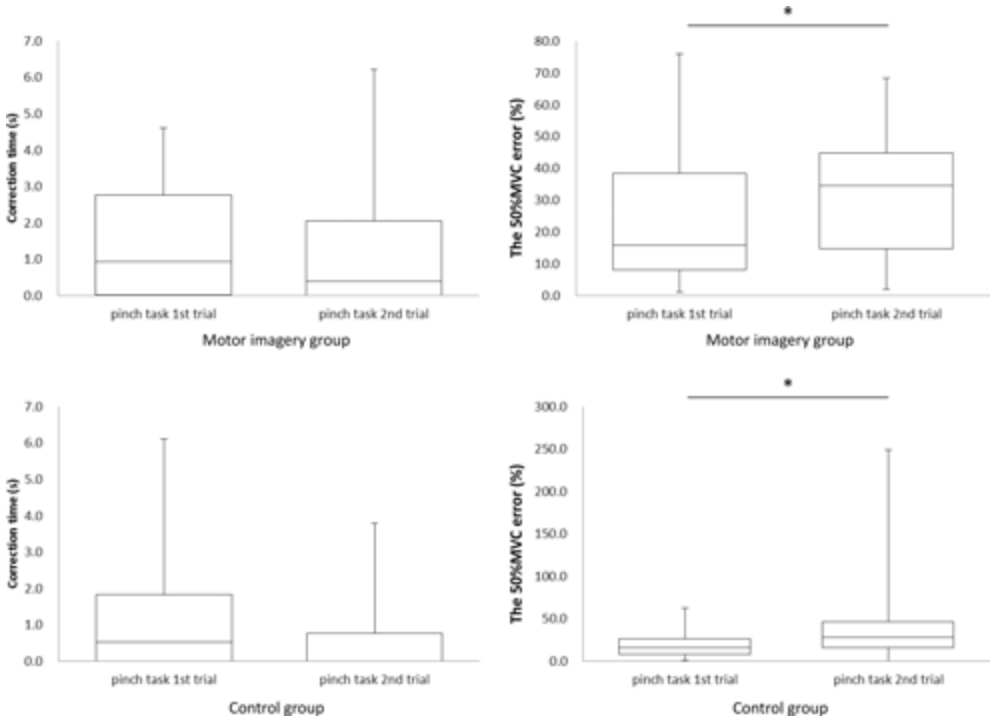

Figure 11. The index reflecting the accuracy of motion results.

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Accordingly, in the control group when examined for the correction time, the pinch task first trial was 1.2 ± 1.7 s and the pinch task second trial was 0.7 ± 1.2 s. No significant differences were observed in the correction time between the first and second trials of the pinch task (**Figure 11**).

Next, in the motor imagery group at the 50% MVC error, the pinch task first trial was 25.7 ± 21.9% and the pinch task second trial was 32.3 ± 18.5%. The 50% MVC error was significantly increased in the second than in the first trial of the pinch task (*$p < 0.05$, **Figure 11**). Accordingly, in the control group at the 50% MVC error, the pinch task first trial was 20.9 ± 17.2% and the pinch task second trial was 36.3 ± 44.3%. The 50% MVC error was significantly increased in the second than in the first trial of the pinch task (*$p < 0.05$, **Figure 11**).

In the motor imagery group, no significant differences were observed in the correction time between the first and second trials of the pinch task. The 50% MVC error was significantly increased in the second as compared to the first trial of the pinch task. In the control group, no significant differences were observed in the correction time between the first and second trials of the pinch task. The 50% MVC error was significantly increased in the second than in the first trial of the pinch task.

4.2.2. The index for the accuracy of motion results with a 30 s motor learning time

In the motor imagery group when examined for the correction time, the pinch task first trial was 1.8 ± 1.9 s and the pinch task second trial was 1.8 ± 1.8 s. No significant differences were observed in the correction times between the first and second trials of the pinch task (**Figure 12**). Accordingly, in the control group when examined for the correction time, the pinch task first trial was 1.5 ± 1.6 s and the pinch task second trial was 0.9 ± 1.3 s. The correction time was significantly decreased in the second than in the first trial of the pinch task (*$p < 0.05$, **Figure 12**).

In the motor imagery group at the 50% MVC error, the pinch task first trial was 25.6 ± 18.8% and the pinch task second trial was 27.4 ± 22.3%. No significant differences were observed at the 50% MVC error between the first and second trials of the pinch task (**Figure 12**). Accordingly, in the control group at the 50% MVC error, the pinch task first trial was 21.1 ± 17.2% and the pinch task second trial was 31.9 ± 28.3%. The 50% MVC was significantly increased in the second than in the first trial of the pinch task (*$p < 0.05$, **Figure 12**).

In the motor imagery group, no significant differences were observed in the correction time or the 50% MVC error between the first and second trials of the pinch task. In the control group, the correction time was significantly decreased in the second than in the first trial of the pinch task. The 50% MVC error was significantly increased in the second than in the first trial of the pinch task.

4.2.3. The index for the accuracy of motion results with a 1 min motor learning time

In the motor imagery group when examined for the correction time, the pinch task first trial was 1.5 ± 1.6 s and the pinch task second trial was 1.3 ± 1.8 s. No significant differences were observed in correction time between the first and second trials of the pinch task (**Figure 13**). Accordingly, in the control group when examined for the correction time, the

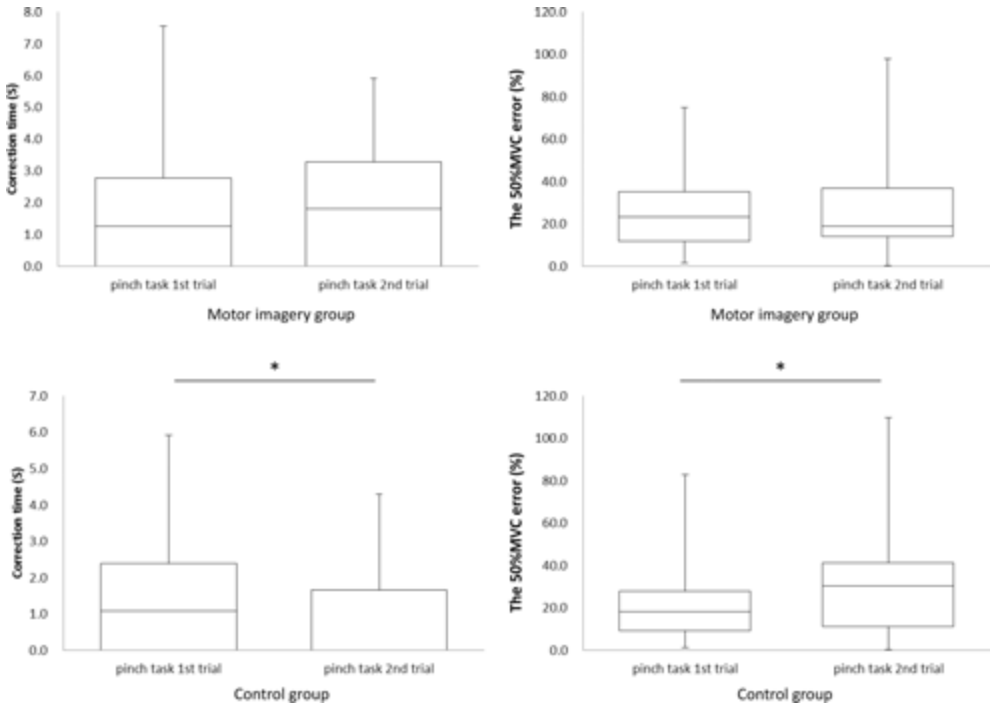

Figure 12. The index for the accuracy of motion results.

pinch task first trial was 1.5 ± 1.9 s and the pinch task second trial was 0.9 ± 1.3 s. Correction time was significantly decreased in the second as compared to the first trial of the pinch task. (**$p < 0.01$, **Figure 13**).

Next, in the motor imagery group at the 50% MVC error, the pinch task first trial was 21.5 ± 16.7% and the pinch task second trial was 24.7 ± 22.7%. No significant differences were observed in the 50% MVC error between the first and second trials of the pinch task (**Figure 13**). Accordingly, in the control group at the 50% MVC error, the pinch task first trial was 28.1 ± 29.1% and the pinch task second trial was 38.9 ± 40.4%. The 50% MVC error was significantly increased in the second than in the first trial of the pinch task (*$p < 0.05$, **Figure 13**).

In the motor imagery group, no significant differences were observed in correction time or the 50% MVC error between the first and second trials of the pinch task. In the control group, correction time was significantly decreased in the second than in the first trial of the pinch task. The 50% MVC error was significantly increased in the second than in the first trial of the pinch task.

4.2.4. The index for the accuracy of motion results with a 2 min motor learning time

In the motor imagery group when examined for the correction time, the pinch task first trial was 1.2 ± 1.7 s and the pinch task second trial was 1.3 ± 1.8 s. No significant differences were

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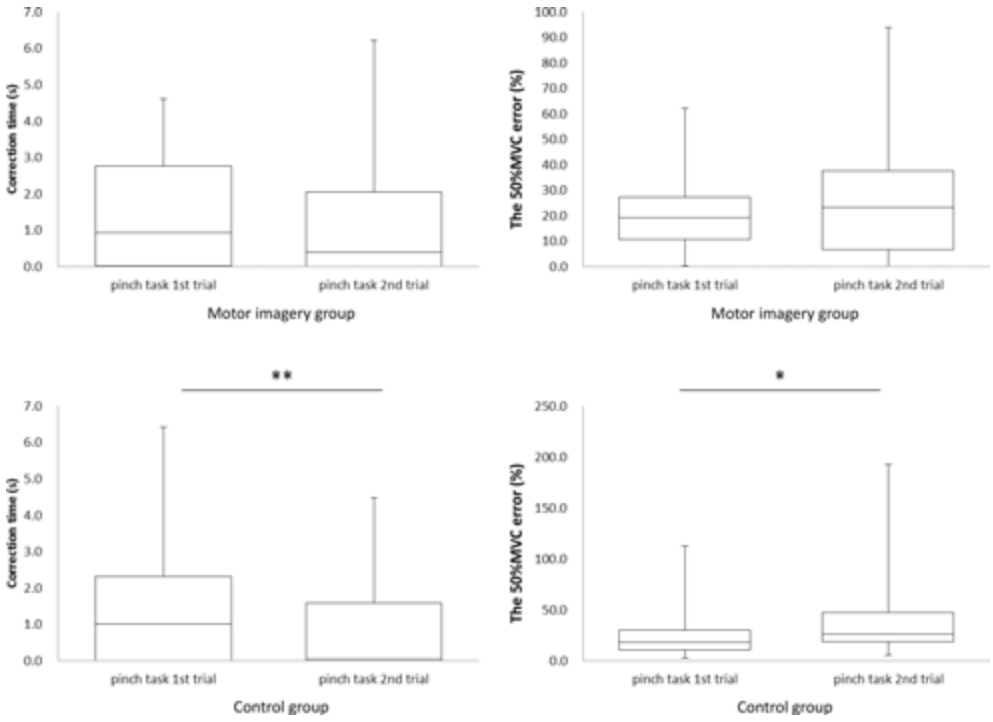

Figure 13. The index for the accuracy of motion results.

observed in correction time between the first and second trials of the pinch task (**Figure 14**). Accordingly, in the control group when examined for the correction time, the pinch task first trial was 1.6 ± 2.2 s and the pinch task second trial was 0.8 ± 1.2 s. Correction time was significantly decreased in the second than in the first trial of the pinch task (*$p < 0.05$, **Figure 14**).

In the motor imagery group at the 50% MVC error, the pinch task first trial was 25.3 ± 26.3% and the pinch task second trial was 36.8 ± 36.8%. The 50% MVC error was significantly increased in the second than that in the first trial of the pinch task (*$p < 0.05$, **Figure 14**). Accordingly, in the control group at the 50% MVC error, the pinch task first trial was 21.7 ± 17.4% and the pinch task second trial was 29.6 ± 25.7%. The 50% MVC error was significantly increased in the second as compared to that the first trial of the pinch task. (*$p < 0.05$, **Figure 14**).

In the motor imagery group, no significant differences were observed in correction time between the first and second trials of the pinch task. The 50% MVC error was significantly increased in the second than that in the first trial of the pinch task. In the control group, correction time was significantly decreased in the second as compared to that in the first trial of the pinch task. The 50% MVC error was significantly increased in the second than that in the first trial of the pinch task.

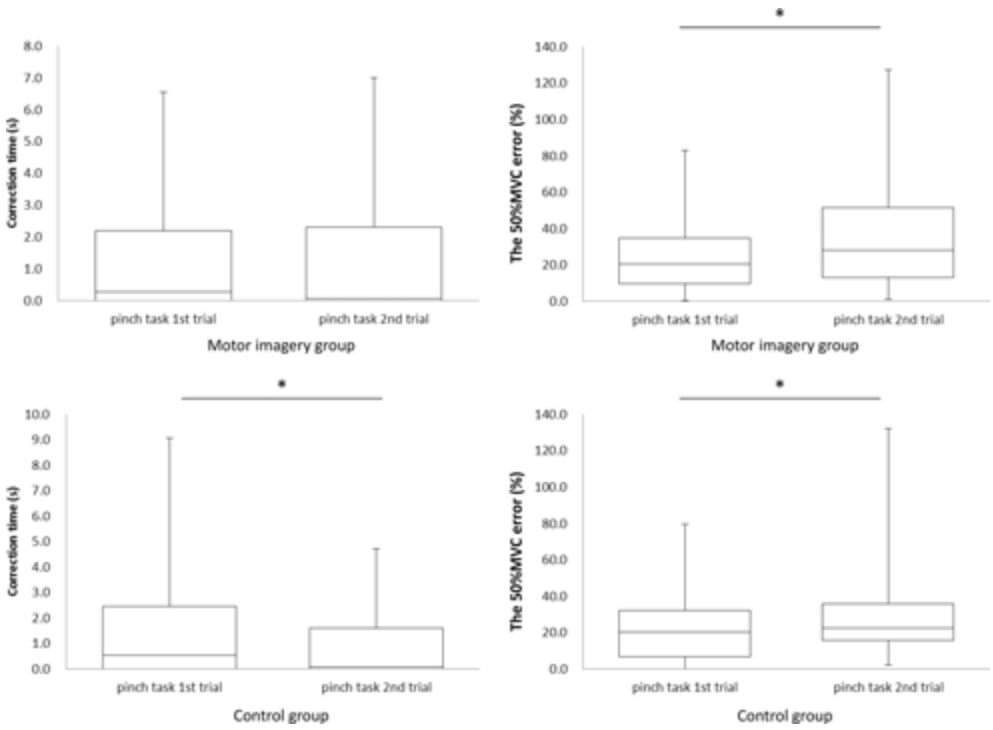

Figure 14. The index for the accuracy of motion results.

5. Discussion

5.1. The factor indicating increased spinal motor neuron excitability

The excitability of spinal motor neurons under the motor imagery condition was increased than that of spinal motor neurons at rest and in the touching a sensor condition. We attribute this to the influence of the descending pathways corresponding to the thenar muscle. In contrast, excitatory inputs travel through the corticospinal pathway and reticulospinal tract and from the corticospinal pathway and extrapyramidal tract to anterior horn cells. Suzuki et al. [11] reported the excitability of spinal motor neurons in the motor imagery condition to be influenced by the descending pathways from the cerebral nervous system. Furthermore, activation of the primary motor area, supplementary motor area, premotor area, primary somatosensory area, dorsolateral prefrontal area, cingulate cortex, and cerebellar regions occurred during motor imagery [4–7]. Therefore, activation of the cerebral cortex in the motor imagery condition presumably increased the excitability of spinal motor neurons via the corticospinal pathway and extrapyramidal tract. The subjects performed motor imagery while touching a pinch meter sensor. Therefore, the influences of tactile and proprioceptive inputs should be considered. Mizuguchi et al. [20, 21] reported that the responsiveness of afferent pathways to the primary somatosensory area during

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motor imagery while utilizing an object was modulated by a combination of tactile and proprioceptive inputs while touching the object. Tactile and proprioceptive inputs from the periphery are integrated after they have been hierarchically processed and then projected to the primary motor area. Furthermore, Suzuki et al. [11] reported that the excitability of spinal motor neurons with motor imagery under the "with sensor" condition was increased than that of the spinal motor neurons with motor imagery under the "without sensor" condition. Thus, tactile and proprioceptive inputs while touching the pinch meter sensor would presumably increase the excitability of spinal motor neurons as part of a synergistic effect. Therefore, we hypothesized that our subjects might perform some form of motor imagery.

5.2. The effect of motor imagery on the accuracy of motion

With a motor learning time of 10 s, no significant differences were observed in the correction times between the first and second trials of the pinch task in either the motor imagery group or the control group. The correction time reflects the ability to control the accuracy of muscle force during the pinch action. We attributed this to numerous zero second correction times from the first trial and to the second trial of the pinch task. Surely, the subject could not be learning 50% MVC with a motor learning time of only 10 s. Accordingly, the correction time was not changed after versus before motor imagery or in the condition without motor imagery. The 50% MVC error was significantly increased in the second than that in the first trial of the pinch task in both the motor imagery and the control group. The error in 50% MVC reflects whether or not there is convergence on 50% MVC. Provided that the pinch value obtained represents convergence on 50% MVC, the 50% MVC error is decreased in the second trial as compared to the first trial of the pinch task. Conversely, provided that the pinch value obtained does not represent convergence on 50% MVC, the 50% MVC error is increased in the second than that in the first trial of the pinch task. Given these observations, our results suggest that motor imagery does not improve the ability to achieve accurate motion after motor learning for 10 s. Mulder et al. [22] reported that motor imagery improved the ability to achieve actual motion only in people with learning that corresponded to the motor imagery task. Accordingly, the subjects might not be able to learn the 50% MVC in only 10 s. Thus, it is necessary for the learning of subjects to correspond fully to the motor task. We conclude that adequate learning time should be provided in future studies.

With a motor learning time of 30 s, no significant differences were observed in the correction time between the first and second trials of the pinch task in the motor imagery group. Accordingly, the correction time was significantly decreased in the second than that in the first trial of the pinch task in the control group. These results suggest that the accuracy of motion was decreased in the control group. If the correction time is increased after motor imagery, the index of the accuracy of motion would be improved in the second trial as compared to the first trial of the pinch task. Conversely, the correction time should be decreased if there is no improvement in the accuracy of motion. Ronsse et al. [23] reported that the effectiveness of motor learning with the use of visual feedback was decreased over time with periodic flexion and extension at both wrist joints. Ohashi et al. [24] reported that the information pertaining to the intensity of force in an isometric contraction task was

decreased over the course of time. In this study, the subjects carried out motor learning with isometric contraction and using visual feedback. Accordingly, if accurate motion was acquired with motor learning for 30 s, it was decreased over the course of time under inactive conditions. On the other hand, the accuracy of motion was not decreased between the first and second trials of the pinch task when performing motor imagery. Therefore, the accuracy of motion might be maintained by motor imagery after motor learning for 30 s. However, in our previous study, motor imagery after motor learning for 10 s failed to maintain accurate motion. It was concluded that a motor learning time of 10 s was insufficient, while 30 s was sufficient. In the motor imagery group, no significant differences were observed in the 50% MVC error between the first and second trials of the pinch task. However, in the control group, the 50% MVC error was significantly increased in the second than that in the first trial of the pinch task. Provided that the pinch value does not represent convergence on 50% MVC, the 50% MVC error would be increased in the second than that in the first trial of the pinch task. Consequently, the accuracy of motion was maintained only in the motor imagery group, results consistent with those for the correction time. Taken together, the present results suggest that motor imagery after 30 s of motor learning is found to be strongly involved in the accuracy of motion. In future studies, it will be necessary to extend the motor learning time before attempting motor imagery. Such a strategy will allow us to study the effects of motor imagery on the accuracy of motion.

With a motor learning time of 1 min, no significant differences were observed in correction time between the first and second trials of the pinch task in the motor imagery group. However, correction time was significantly decreased in the second than that in the first trial of the pinch task in the control group. We obtained the same result in our previous study. This study used isometric contraction and visual feedback at the time of motor learning. Accordingly, the effectiveness of motor learning was maintained only doing motor imagery. Moreover, we compared the pinch force in several pinch tasks between the motor imagery and control groups. In the motor imagery group, we found that the pinch force in the pinch task second trial generated a more authentic 50% MVC than the pinch task first trial in approximately half of all subjects. However, in the control group, the pinch force in the pinch task second trial generated a more authentic 50% MVC than the pinch task first trial in approximately 20% of all subjects. The motor imagery after motor learning for 1 min might show slight improvement in the accuracy of motion. No significant differences were observed at the 50% MVC error between the first and second trials of the pinch task in the motor imagery group. In the control group, however, the 50% MVC error was significantly increased in the second than that in the first trial of the pinch task. The same results were obtained in our previous study. Furthermore, these results were consistent with the correction time results. Taken together, these observations suggest the accuracy of motion to be maintained or even slightly improved by performing motor imagery after motor learning for 1 min. We believe that motor imagery can be adjusted for the variety and total number of mobilized motor units (recruitment), the firing rate of motor units (rate coding), the congruence of each motor unit activity timing (synchronization), the revision of motor programs, and so forth. In conclusion, for successful motor imagery, it is necessary for the subject to completely learn the corresponding motor task.

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Finally, with a motor learning time of 2 min, no significant differences were observed in correction time between the first and second trials of the pinch task in the motor imagery group. In the control group, however, correction time was significantly decreased in the second than that in the first trial of the pinch task. The same result was obtained in our previous study. However, the 50% MVC error was significantly increased in the second than that in the first trial of the pinch task in both the motor imagery group and the control group. These results would appear to contradict the previously mentioned results for the correction time. This apparent contradiction is attributable to the correction time and the 50% MVC error differing slightly in meaning. Specifically, the 50% MVC error was increased in the second than in the first trial of the pinch task. Moreover, the aim of falling within 50 ± 5% MVC on both the first trial and the second trial of the pinch task was missed by many subjects. These subjects maintained accurate motion when viewing the correction time, but did not maintain an error 50% MVC without visualization. These subjects experienced muscle fatigue after motor learning for 2 min. Thus, we compared MVC of the pinch force after versus before motor learning. We found the MVC of the pinch force to be decreased after as compared to before motor learning in most of the subjects experiencing muscle fatigue. Vøllestad [25] reported that muscle fatigue was defined as a decrease in the ability to exert maximum muscle strength with some form of motion. In addition, Higashi et al. [26] reported that the 50% MVC isometric contraction task produced recognizable muscle fatigue over the course of time. In this study, the subjects may have been exerting 50% MVC pinch force for 2 min. In reality, however, the subjects might have gradually exerted 50% MVC with excessive pinch force influencing muscle fatigue. Accordingly, the subjects experiencing muscle fatigue were learning 50% MVC and exceeded the pinch value. Consequently, these subjects might not have been able to maintain accurate motion, because the motor imagery was not correct.

6. Conclusion

Motor imagery increases the excitability of spinal motor neurons. Furthermore, motor imagery may improve the accuracy of motion. In such an event, however, it is important to acquire memory corresponding to the motor imagery task in motor learning. Specifically, it is necessary to take account of the motor learning time. Motor learning times optimally range from 30 s to 1 min. In future studies, it will be important to apply a motor learning method with a motor learning time of 30 s to 1 min. Salmoni et al. [27] reported that motor learning may be impeded by excessive feedback information. It is necessary the concentration time focused on the internal information to be incorporated into a revision of the motor program. In this study, the subjects performed motor learning with continuous visual feedback. Winstein et al. [28] proposed that the learner should gradually be given decreased feedback (Faded Feedback). Also, Lavery et al. [29] proposed that the learner's experience should be combined with summarized feedback (Summary Feedback). Additionally, Sherwood et al. [30] proposed that the learner should be aware of when deviation from the constant bandwidth occurs (Bandwidth Feedback). Schmidt et al. [31] reported that learner paid attention to internal information based on these investigator's methods of motor learning. The above observations highlight

the importance of the motor leaning method. We should thus study the effects of motor imagery on the accuracy of motion.

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