
Relationship Between Excitability of Spinal Motor Neurons in Remote Muscles and Voluntary Movements

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Abstract

In physical therapy, it is important to understand the influence of the contraction of a particular muscle on other muscles. The mechanism of the facilitation effect of muscle contraction in healthy subjects has been analyzed in previous studies. These studies indicated that muscle contraction with voluntary movement enhances the excitability of spinal motor neurons and motor areas in the cerebral cortex that are not directly associated with the contracting muscle. Furthermore, it has been reported that the facilitation effects on remote muscles not related to movement are affected by the elapsed time since the start of the movement, the strength of muscle contraction, the number of muscle spindles, and the difficulty of the movement. In addition, the facilitation effects of difficult voluntary movements of the unilateral upper limbs on spinal motor neurons in the contralateral upper limb decrease with motor learning. We expect that these findings will be useful not only for physical therapy evaluation but also for patient treatment.

Keywords: F-wave, spinal motor neuron, arm movement, motor learning

1. Introduction

In physical therapy, it is necessary to understand the influence of the muscle contraction accompanying a movement on the muscles not involved in the movement. For instance, associative reactions observed in patients with hemiplegia due to cerebrovascular disorders (CVDs) are tonic reflexes that originate in the muscles of one limb and act on the muscles of another limb. Associative reactions usually occur prior to or during a behavior and lead to enhancement of muscle tone on the affected side. This phenomenon makes selective movement of the upper limb or the lower limb on the affected side more difficult.

When using exercise and therapy, we have to evaluate the movements responsible for the appearance of associative reactions. It is thus important to understand the neurophysiological effects of the voluntary contraction of a particular muscle on the muscles not involved in the movement.

The mechanism of the facilitation effect on the muscles not involved in the movement (i.e., remote muscles) has been analyzed in studies of motor-evoked potentials (MEPs) evoked by transcranial magnetic stimulation (TMS), H-reflexes, and F-waves [1–6]. These studies indicate that muscle activation enhances the excitability of motor areas in the cerebral cortex and spinal motor neurons that are not directly associated with the activating muscle. Furthermore, it has been reported that the facilitation effects on remote muscles not related to voluntary contraction are affected by the elapsed time since the start of movement [2], the strength of the muscle contraction [5–7], the number of muscle spindles [8], and the difficulty of the movement [9].

One of the objectives of physical therapy is the recovery of reduced function and the relearning of previously learned movement patterns. Various plastic changes occur in the central nervous system during motor learning. Practicing complex movements leads to notable reorganization in the primary motor cortex [10, 11]. Spinal reflexes are reduced following exercise training requiring accurate movements [12]. The performance of exercises requiring high levels of skill involves strong control of the spinal cord from the cortex. Therefore, the gain of spinal reflexes is estimated to decrease in the spinal cord. However, when performing difficult movements, muscles that are not directly involved in the intentional movement may be moved involuntarily. Such a phenomenon is rarely observed in the automatization phase of motor learning. A previous study reported that the facilitation effects of difficult voluntary movements of the unilateral upper limb on spinal motor neurons in the contralateral upper limb decrease with motor learning [13]. These findings will be useful for physical therapy evaluation. In addition, they may help to establish an important index for evaluating the effects of a particular task of different difficulties on muscle groups that are not directly involved in the movement.

2. The mechanism of the facilitation effect of muscle contraction on contralateral spinal motor neurons

It has been reported that the activity of muscle spindles associated with a particular movement may play a role in the facilitation effect of muscle contraction. Delwaide and Toulouse [14] reported that the facilitation effect is not observed after movement attempts when the radial nerve that innervates the muscles of the upper limb involved in the movement is blocked. Hayashi et al. [8] reported the remote facilitation of the soleus H-reflex during contractions of the finger, jaw, and tongue muscles, which have numerous muscle spindles. In contrast, Bussel et al. [1] reported that the H-reflex is facilitated even when the muscle spindle afferent input is blocked by lower limb ischemia. Hess et al. [15] reported the involvement of the facilitation effect in intracortical mechanisms, noting that MEPs following TMS increase in the contralateral limb of amputee patients with phantom limbs when muscle contractions in the amputated limb are imaged. These studies enable us to explain the facilitation of spinal

motor neurons following unilateral arm movement as follows. The excitability of contralateral spinal motor neurons is enhanced when unilateral arm movement is executed. This phenomenon may be attributed to proprioceptive input during unilateral arm movements and the facilitation effect generated by activation of brain regions involved in the planning and execution of movement. We believe that the facilitation effect occurs via commissural fibers and/or uncrossed projections from the ipsilateral brain hemisphere.

The facilitation effects of muscle contraction on muscles other than the contracting muscle are affected by the strength of the muscle contraction. Suzuki et al. [5] reported that as the F/M amplitude ratio for the contralateral F-wave of the opponens pollicis muscle gradually increases with increasing strength of contraction. In particular, F-waves generated at 75 and 100% contraction of the elbow flexor muscles are significantly higher than those generated during relaxation. Muellbacher et al. [6] reported that the F-wave amplitude of the contralateral abductor pollicis brevis (APB) increases at the time of maximum contraction. In contrast, Stinear et al. [7] reported that the maximum contraction of the APB does not alter the F-wave amplitude of the contralateral APB. Therefore, facilitation effects on contralateral spinal motor neurons may occur during contractions of greater than 75%.

3. The influence of movement difficulty on contralateral spinal motor neurons

A few reports have evaluated the effects of qualitative differences in movements, such as task difficulty, on the spinal motor neurons of muscles other than the contracting muscle. We thus evaluated the influence of the difficulty of movement performed with one arm on the excitability of spinal motor neurons in the contralateral arm using F-wave data obtained via electromyography (EMG) [9]. There are only a few reports regarding changes in the facilitation effects of unilateral upper limb movements on spinal motor neurons in the contralateral upper limb associated with motor learning. Therefore, we used F-waves to examine changes in the excitability of spinal motor neurons in the contralateral upper limb following difficult movements performed with the unilateral upper limb [13]. The F-waves measured in these studies are considered to be generated when antidromic impulses induced by motor nerve fiber stimulation excite α -motor neurons in the anterior horn of the spinal cord, and the recurrent discharge generates orthodromic impulses that induce myopotentials [16]. They are used as an index of motor neuron pool excitability in the anterior horn of the spinal cord. The parameters used for analysis were latency, persistence, and F/M amplitude ratio. Latency was the mean time from stimulus pulse to F-wave onset. Persistence was calculated for all ratios that were distinguished on the display. The F/M amplitude ratio was calculated as the ratio of the average peak-to-peak F-wave amplitude to the maximum M-wave amplitude. Latency measures the conduction in motor axons, persistence reflects the state of excitability in the neuronal pool that is examined, and the F/M amplitude ratio represents the percentage of motor neurons activated by antidromic stimulation [17]. F-waves were recorded using a Viking Quest EMG system (Nicolet Biomedical, WI, USA).

3.1. Experiment 1: excitability of spinal motor neurons in the contralateral arm during voluntary arm movements with various levels of difficulty

In this study, we evaluated the influence of movement difficulty in tasks performed with one arm on the excitability of spinal motor neurons in the contralateral arm using F-wave data obtained via EMG (**Figure 1**). Twenty right-handed healthy volunteers (mean age, 26.6 ± 4 years) with no orthopedic or neurological abnormalities were enrolled in this study. The Edinburgh handedness inventory [18] was used to determine the dominant hands of the subjects. The subjects were seated on a chair during the test. The F-waves were recorded from the right APB during the movement tasks and the control task. Movement tasks were executed with the left arm. The F-waves were analyzed for latency, persistence, and F/M amplitude ratio. The index of difficulty was defined by the movement distance and target width [19]. As distance and/or speed of movement can affect the excitability of contralateral spinal motor neurons, tasks with different levels of difficulty were established by altering the target width. Each subject held a pen in his or her left hand and executed repetitive movements between two targets placed on a desk during the movement task (**Figure 2**). The targets were 5×15 cm (width \times length) for task 1, 0.5×15 cm for task 2, and 0.25×15 cm for task 3, and were 20 cm

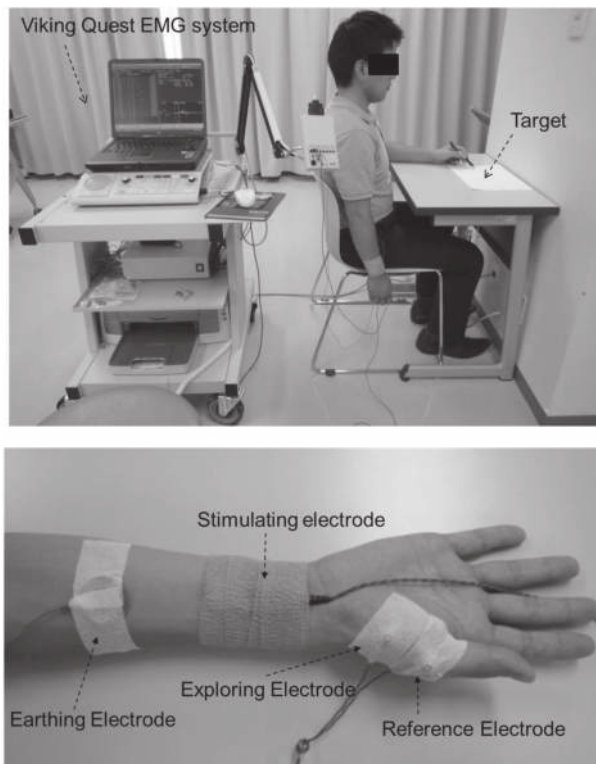


Figure 1. Measurement of the F-wave.

apart for all tasks. The subjects were instructed to accurately touch the target area with the tip of a pen. Each movement task was performed at a frequency of 1 Hz. The tasks were performed in random order. During each task, electrical stimulations were administered when the arm was moving toward the right target (i.e., internal rotation of the left shoulder joint) in order to induce F-waves. The number of times the pen tip deviated from the target was counted and the success rate was calculated after each movement task. The control task comprised remaining in the sitting posture without executing arm movements.

The F-wave parameters (persistence, F/M amplitude ratio, and latency) during the control and movement tasks were compared using Dunnett's tests. The results are shown in **Figures 3–6**. Persistence significantly increased during tasks 1, 2, and 3 compared to the control task. The F/M amplitude ratio also significantly increased during tasks 2 and 3 compared to the control task. The F/M ratio was comparable between task 1 and the control task. There were no significant differences in latency between the control task and any of the movement tasks. The success rates were 100.0% for task 1, 83.3% for task 2, and 52.8% for task 3. The success rates suggested that the tasks had different difficulty levels.

The persistence data suggest that the excitability of spinal motor neurons during movements of the contralateral arm was enhanced during unilateral arm movement. This phenomenon may be attributable to the proprioceptive input during the left arm movement and the facilitation effect generated by the activation of the regions of the brain involved in the planning and

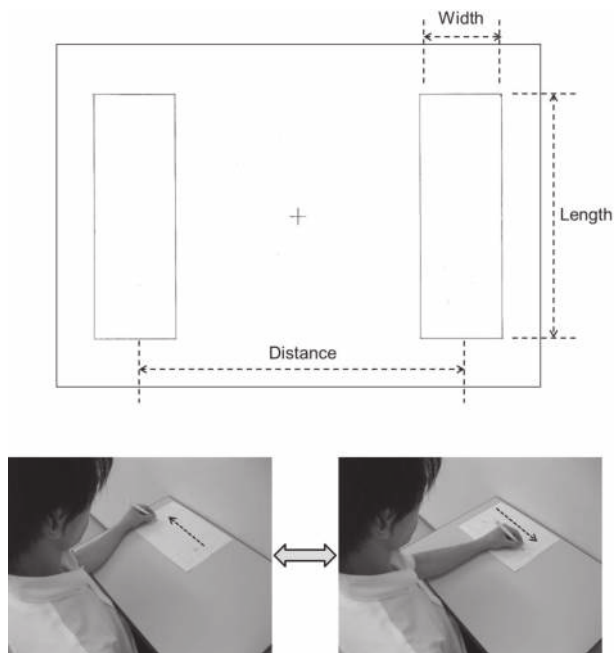


Figure 2. The target and the movement task.

execution of movements. We believe that the facilitation effect occurs via commissural fibers and/or uncrossed projections from the ipsilateral hemisphere.

On the basis of the F/M amplitude ratio data and the success rates, we speculate that task difficulty may have been responsible for the differences observed in the excitability of spinal motor neurons. As the movement speed and range were the same in each movement task, it is unlikely that there were differences in proprioceptive input among the

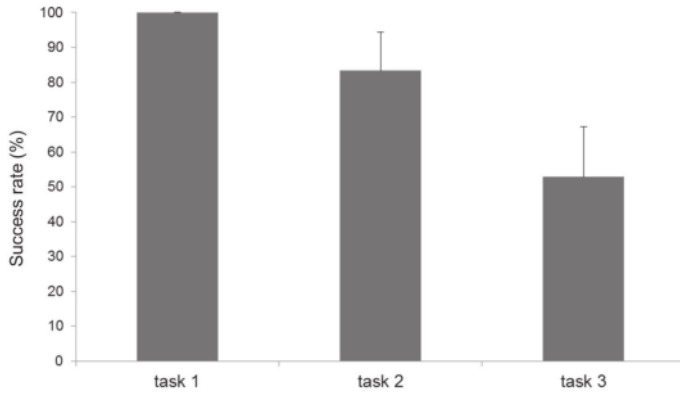


Figure 3. Success rates of the movement tasks.

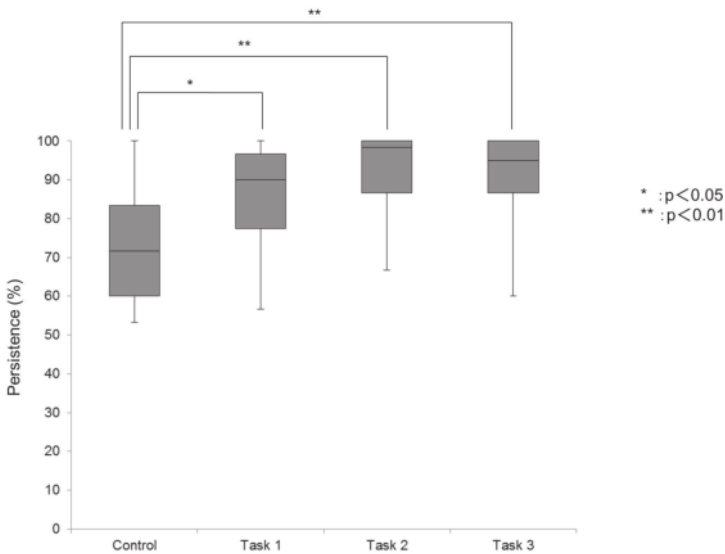


Figure 4. Persistence during the control and movement tasks.

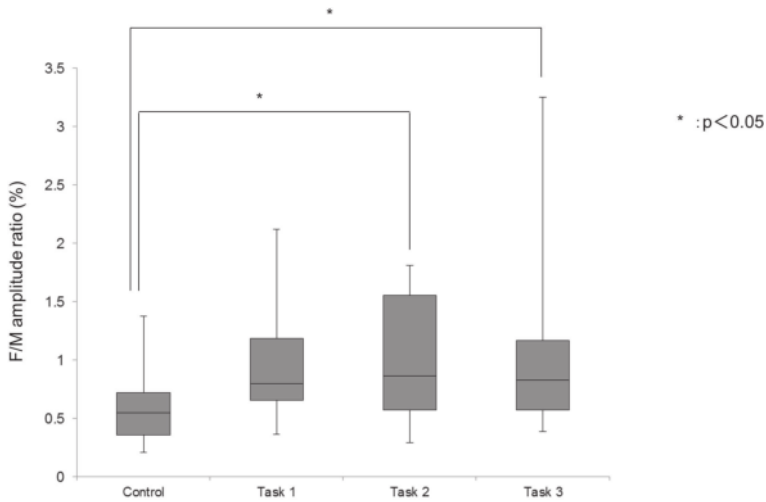


Figure 5. F/M amplitude ratios during the control and movement tasks.

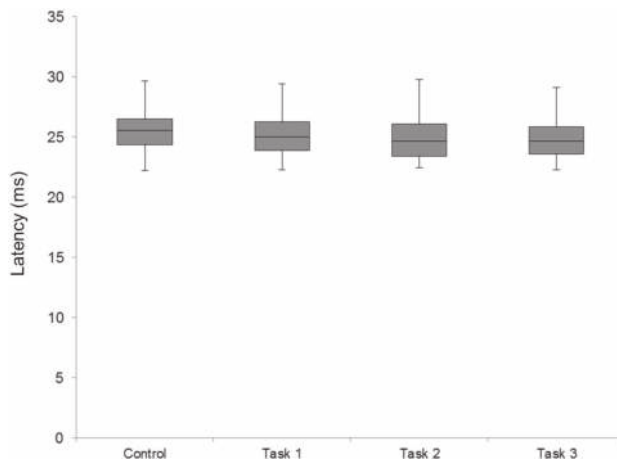


Figure 6. Latency during the control and movement tasks.

tasks. In addition, the success rates indicate that tasks 2 and 3 were more difficult than task 1. According to Shibasaki et al. [20], both the contralateral sensorimotor cortex and the ipsilateral sensorimotor area are activated during the execution of complex sequential finger movements. Winstein et al. [21] examined the relationship between task difficulty and brain activity and reported that activities in areas related to complex movement planning requiring visual motion processing, such as the ipsilateral dorsal premotor area

increase with increased task difficulty. Here, we considered that the excitability of contralateral spinal motor neurons increases during tasks 2 and 3, which have high levels of difficulty and require more accurate movements than task 1. It is possible that the motor-related areas ipsilateral to the movement are activated when difficult movements are performed. This may have led to enhanced excitability of the contralateral spinal motor neurons via projection fibers. Furthermore, although unilateral limb movements are adjusted for by the contralateral motor area, it has been reported that the activation of this contralateral motor area affects the excitability of the ipsilateral motor area via the corpus callosum [22, 23]. We also believe that when difficult movements are performed, motor-related areas contralateral to the movement are strongly activated. This may enhance the excitability of spinal motor neurons contralateral to the movement via commissural fibers. The facilitation effect is described in **Figure 7**. These results suggest that possible differences in the facilitation effects of muscle contraction arising from task difficulty should be considered when evaluating the effects of the contraction of a particular muscle on other muscles.

While we only studied healthy subjects, Eisen and Odusote [24] reported that F-wave amplitudes of patients with spasticity were larger than those in healthy subjects. This result suggests that the influence of the facilitation effect is more remarkable in patients with hemiplegia due to CVDs. Further studies are thus required to investigate the effects of difficult movements of the unilateral limb on the excitability of contralateral spinal motor neurons in patients with hemiplegia.

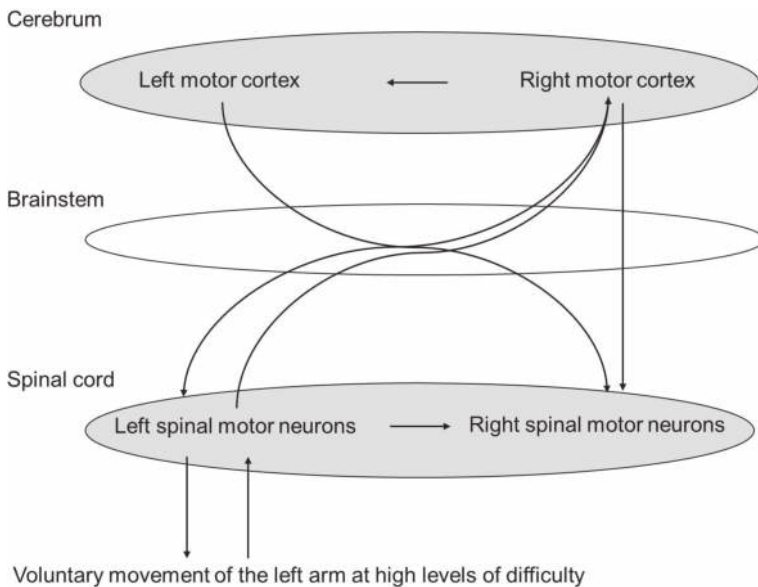


Figure 7. The facilitation effect during voluntary movements with high levels of difficulty.

3.2. Experiment 2: effects of practicing difficult movements with the unilateral arm on the excitability of spinal motor neurons in the contralateral arm

In this study, we used F-waves to evaluate changes in the excitability of spinal motor neurons in the contralateral upper limb caused by practicing high-difficulty movements with the unilateral upper limb. Sixteen right-handed healthy adults (12 men and 4 women; mean age, 26.1 ± 6.0 years) with no orthopedic or neurological abnormalities participated in the study. The subjects were randomly assigned equally to either a control group (6 men and 2 women; mean age, 26.4 ± 7.2 years) or a practice group (6 men and 2 women; mean age, 26.0 ± 4.9 years). The Edinburgh handedness inventory [18] was used to determine the subjects' dominant hands. F-waves were recorded from the right APB during motor tasks performed with the left upper limb before and after the practice task. The subjects were seated on a chair during the test. The limb position was the same as that in experiment 1. The subjects were instructed to not move any body parts other than the left arm throughout the study. The motor tasks used when recording the F-waves were the same as those used in experiment 1. The target width used in the motor task was 0.5×15 cm (width \times length), as this target size led to facilitation effects on spinal nerve function in the contralateral upper limb in a previous study [9]. The number of times the tip of the pen touched a location outside of the target was counted. The practice task consisted of repetitive movements at a frequency of 1 Hz. The practice group performed repetitive movements using the same targets when recording the F-waves, and the control group performed repetitive movements without the targets. The practice task was performed for five sessions with each session consisting of 30 movements. One-minute breaks were provided between successive sessions. F-waves were analyzed to determine latency and the F/M amplitude ratio.

Mann-Whitney tests were used to compare F-wave parameters (F/M amplitude ratio and latency) and the number of failures between the control and practice groups. The Wilcoxon-signed rank sum tests were used to compare F-wave parameters and the numbers of pre- and postpractice failures. The results are shown in **Figures 8–10**. The F/M amplitude ratio during the post-practice session was significantly lower than the pre-practice value. In addition, the postpractice values in the practice group were significantly lower than those in the control group. There were no significant differences in latency pre- versus postpractice in either group. The numbers of failures during the postpractice session were significantly lower than the pre-practice values.

We speculated that the facilitation effects on spinal motor neurons in the contralateral upper limb while performing high-difficulty unilateral upper limb movements could be reduced by practicing the movements. Motor learning is thought to depend on plasticity in motor and sensory areas of the brain. Therefore, facilitation effects during movements of the unilateral upper limb on the spinal motor neurons in the contralateral upper limb can be reduced with motor learning. Suzuki et al. [25] examined the changes that occur in the brain while learning the task of rotating two balls by hand using MEPs induced by TMS. They reported that the excitability of the primary motor cortex ipsilateral to the movements is reduced as performance improves. Winstein et al. [21] examined the relationship between the efficiency of motor tasks and brain activity, and reported that activation of the ipsilateral premotor area is related to motor task difficulty. In addition, Nelson et al. [26] recorded somatosensory evoked potentials (SEPs) during motor tasks, such as adjusting the angle of the joint

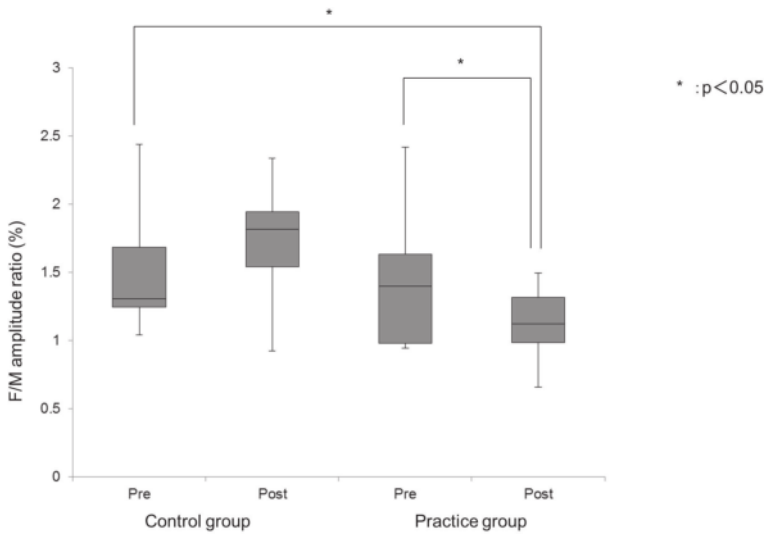


Figure 8. Prepractice and postpractice F/M amplitude ratios in the control and practice groups.

to the correct position. They reported that the input of sensory information to the cerebrum in the central nervous system is reduced when motor tasks are acquired by motor learning. This was reflected in the shorter latency of SEP amplitude decreases with increasing familiarity with the tasks. The results of the present study suggest that the facilitation effects of the sensory input and the upper central nervous system associated with voluntary movements of the upper limb on spinal motor neurons in the contralateral upper limb decrease

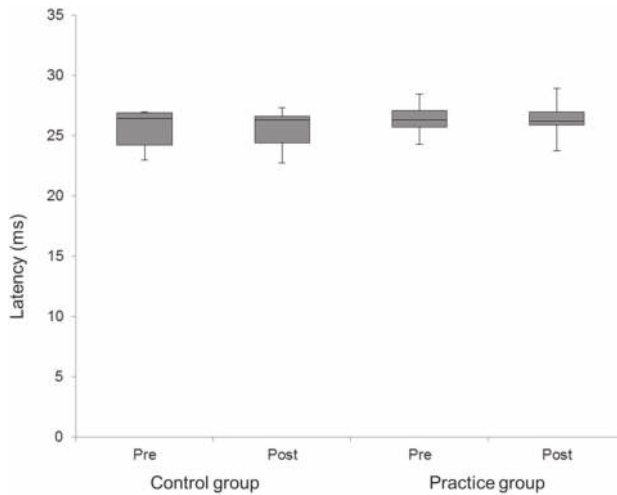


Figure 9. Pre- and postpractice latencies in the control and practice groups.

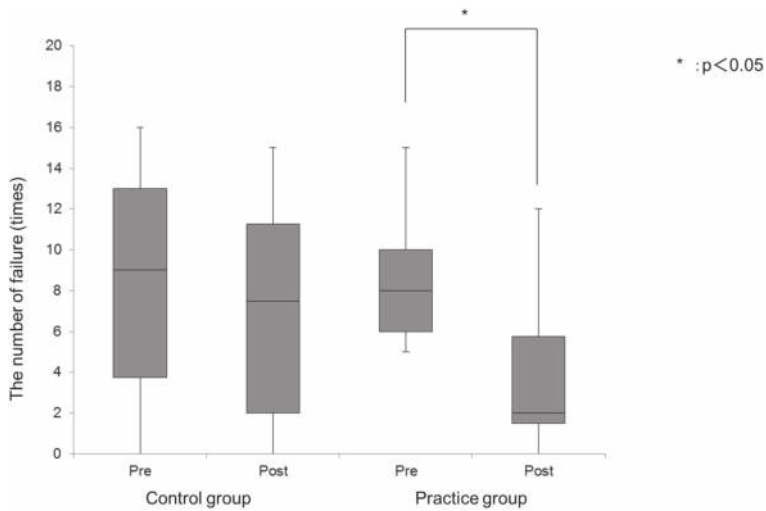


Figure 10. Failures pre- and postpractice in the control and practice groups.

with familiarity with the tasks due to practice. Changes in facilitation effects are described in Figure 11. Thus, the facilitation effects of difficult voluntary movements of the unilateral upper limb on spinal motor neurons in the contralateral upper limb decrease with motor learning.

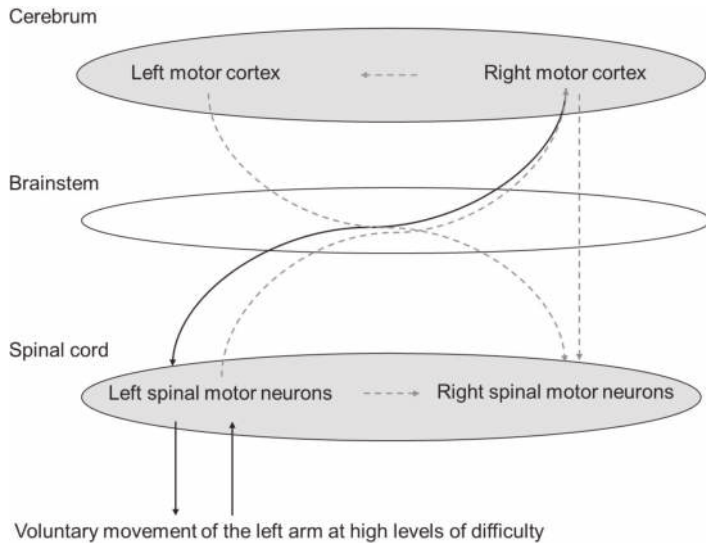


Figure 11. Change in the facilitation effects of voluntary movements after practice.

4. Clinical suggestion

We examined the relationship between the excitability of spinal motor neurons in the upper limb on the affected side and voluntary movements of the lower limb in patients with CVDs and healthy subjects. The voluntary movement performed in this study was simple and consisted of maintaining a straight-leg-raising test position with 30° flexion in the hip joint. No significant differences were observed in healthy subjects, while the excitability of spinal motor neurons in the upper limb on the affected side during voluntary movement was significantly higher than that during rest in patients with CVDs. Patients with CVDs thus experience an increase in the excitability of spinal motor neurons due to the collapse of the regulatory mechanism in the central nervous system. In brief, patients with CVDs are more susceptible to the facilitation effect than are healthy subjects.

In physical therapy, there is a need to evaluate facilitation effects due to the contractions of remote muscles. For example, in hemiplegic patients with CVDs, the associated reaction may disrupt accurate voluntary movement. Neurophysiological interpretations of the facilitation effects of postures and movements are necessary during these evaluations. The facilitation effect may increase with high muscle strength, high movement speed, activity of numerous muscle spindles, and difficult movements, and during the first stages of motor learning. Therapies for patients with hemiplegia with the associated reactions should begin with slow movements requiring low muscle strength. While practicing difficult movements, it is necessary to attenuate the facilitation effect by exercise.

Finally, we will present a related case report. We examined the influence of one physical therapy sessions for trunk muscle function on the function of the affected arm muscles in a patient with left hemiplegia and CVD using surface EMG and H-reflex-evoked EMG [27]. In this study, we compared the H/M amplitude ratio and muscle action potential in the sitting position after physical therapy to those in the sitting position before physical therapy. The H-reflex was recorded from the left APB and muscle action potentials were recorded from both the obliquus abdominis and the iliocostalis lumborum. Physical therapy was performed to improve the alignment of the trunk and the hip joint in a sitting position. We did not perform therapy on the affected arm. The sitting posture improved after physical therapy. The surface EMGs of the obliquus abdominis on the affected side and those of both the iliocostalis lumborum muscles after physical therapy were lower than those before physical therapy (**Figure 12**). The H/M amplitude ratio after physical therapy was also lower than that before physical therapy (**Figure 13**). The results of this study indicate that the excitability of spinal neural function in the affected arm might be decreased after physical therapy for trunk and lower extremity muscles in patients with CVD. The results also suggest that physical therapy on the affected arm in patients with CVD should account for the effects of the contraction of the trunk muscles and the low back muscles. Therefore, evaluation of the facilitation effect due to the contraction of remote muscles requires neurophysiological knowledge. The facilitation effect cannot be interpreted only using knowledge of the kinematic chain. Neurophysiological understanding of the influence of the contraction of a particular muscle on other muscles can be useful not only for evaluation, but also for therapy.

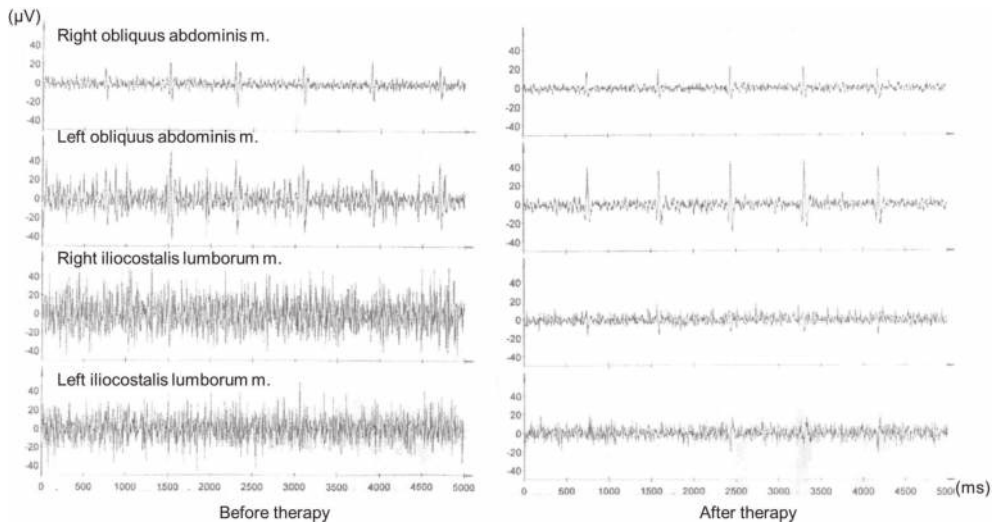


Figure 12. Change in the EMG waveforms before and after therapy.

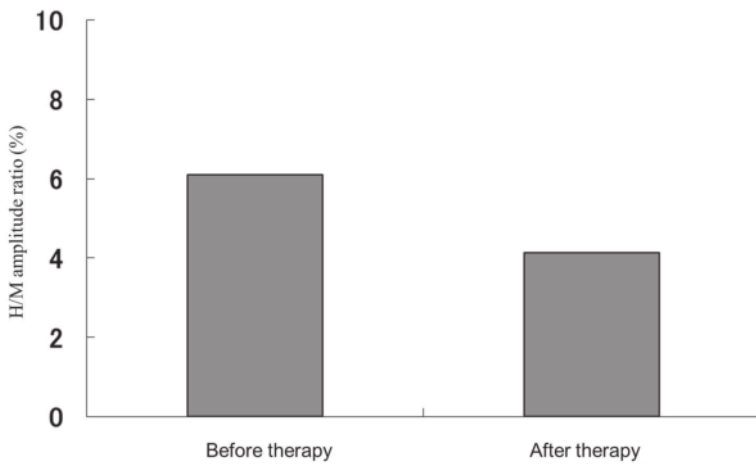


Figure 13. Change in the H/M amplitude ratios before and after therapy.

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