J Rehab Med 2001; 33: 230–234

MODULATION OF CORTICOSPINAL EXCITABILITY DURING IMAGINED KNEE MOVEMENTS

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In this study, we investigated corticospinal excitability during mental simulation of a leg extension movement with the technique of transcranial magnetic stimulation. Motor evoked potentials were recorded in both knee extensors (quadriceps) and flexors (biceps femoris) in 19 trained participants (healthy volunteers). The amplitude and latency of motor evoked potentials were compared in three conditions: (1) at rest, (2) during motor imagery, and (3) at rest, immediately after motor imagery. The results showed a significant effect ($p < 0.001$) of conditions on motor evoked potentials amplitude in the quadriceps but not in the biceps femoris. During motor imagery, the size of motor evoked potentials in the quadriceps increased significantly ($p < 0.001$) compared with rest and post-imagery conditions. Changes in motor evoked potentials latency across conditions were not significant, however. These results are consistent with previous studies in the upper limb and suggest that corticospinal excitability can be enhanced during motor imagery to facilitate responses in specific lower limb muscles.

Key words: transcranial magnetic stimulation, motor imagery, motor evoked potentials, quadriceps, knee.

J Rehab Med 2001; 33: 230–234

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Accepted February 26, 2001

INTRODUCTION

Motor imagery refers to a dynamic state whereby individuals mentally simulate the performance of a specific motor action (1, 2). Although the benefit of mental practice in improving motor performance has been known for years in the fields of sports and coaching, it is only recently that the neural mechanisms of motor imagery have begun to be unveiled. Indeed, neuroimaging studies have provided evidence that both imagined and real movements share, to a large extent, a common neural substrate (see Decety (3) for a review). Regions, like the primary motor cortex and lateral cerebellum that were previously thought to be activated only during executed movements, have now been shown to be activated also during motor imagery (4, 5). Further evidence as to the involvement of motor cortical mechanisms in mental simulation of actions has been obtained recently with the technique of transcranial magnetic stimulation (TMS). This technique consists of stimulating nerve cells by inducing brief currents into the brain using a magnetic coil held over the scalp (see Rothwell (6) for a review). With this technique, many studies have reported selective modulation of motor cortical excitability during imagined wrist and hand movements (7–9). Hashimoto & Rothwell (10), for instance, found that responses evoked in flexor muscles were larger during the phase of imagined wrist flexion than during extension, while the reverse was true for wrist extensors. Thus, it appears that the corticospinal system controlling upper limb muscles can be selectively facilitated when one imagines doing a specific movement. However, at present, there is still limited information as to whether similar findings can be applied to muscles in the lower extremity.

The purpose of the present study, therefore, was to investigate with TMS whether the excitability of the corticospinal system could be selectively modulated during mental simulation of an action that involved the large muscles of the lower extremity.

METHODS

Subjects

Normal healthy volunteers ($n = 19$, 14 males, 5 females, mean (±SD) age: 25.2 ± 8.26 years) were recruited among the population of undergraduate students and faculty members at the Faculty of Health Sciences, University of Ottawa. All subjects were neurologically normal and none reported a recent history of knee injuries. The local institutional Research Ethics Board approved the study and subjects gave their informed consent.

Transcranial magnetic stimulation

For magnetic stimulation, subjects were comfortably seated in a recording chair with the knees slightly extended (~80°) and the feet supported by a bench. A flexible cap, with markings in the anterior and medial-lateral directions (1-cm spacing) was fitted onto their head, so that the zero line corresponded to the vertex. Magnetic stimulation was produced via a Magstim 200 magnetic stimulator (Novametrix Inc.) connected to a 9-cm diameter circular coil. Motor evoked potentials (MEPs) were recorded in the right leg using auto-adhesive surface electrodes (1 cm^2). For optimal recording in the quadriceps (Quad), we followed the procedure outlined by Garland et al. (11) with the proximal electrode placed at the border between rectus femoris and vastus lateralis and the distal electrode placed 10 cm along a line from the center of the patella. A second pair of electrodes was placed over the motor point of the long head of the biceps femoris. The electromyographic signal (EMG) was amplified by 1000 with a time constant of 3 millisecond and a low-pass filtering of 5 kHz using a polygraph amplifier (RMP-6004, Nihon-Kohden Corp.)

To determine the optimal site on the scalp to evoked activity in the contralateral Quad, the coil was displaced in 1-cm step from the vertex while stimulating at high intensity (85% stimulator output). For most subjects, the optimal site was slightly anterior (2 cm) and lateral (1 cm) to the vertex. Once the optimal site was identified, the stimulator output was gradually decreased until MEPs of at least 100 μV could be evoked in the Quad 50% of the time. This intensity was defined as the threshold intensity (6). For the remaining of the experiment, the stimulator output was set at 10% above the threshold intensity.

MEPs were recorded successively in three different conditions: (1) at rest (REST), (2) during mental simulation of leg extension (motor imagery), and, (3) at rest, immediately after motor imagery (POST). A small group of subjects ($n = 5$) was also tested in a fourth condition: active knee extension (ACTIVE). In the first three conditions, subjects were required to remain immobile and fully relax their muscles. For motor imagery, subjects remained seated in the recording chair. They were then trained to perform a simple knee extension movement in response to verbal cues. The movement consisted of a slow concentric contraction to move the leg against gravity from 90° to full extension (0°) with duration of approximately 1 second. One of the investigators provided the instructions for the task and monitored the performance with a stopwatch. After a couple of repetitions, most subjects had no difficulty in performing the leg movement at the prescribed velocity. Subjects were then allowed to practice the movement mentally following the instructions given by the investigator. During practice and testing in the motor imagery condition, EMG activity was constantly monitored to make sure that subjects did not attempt to contract their muscles. When signs of active intervention during imagery were suspected, the trial was simply aborted.

In each condition, 5–10 evoked responses to magnetic stimulation were collected in each muscle with an interval of at least 5 seconds between magnetic stimuli. For motor imagery, TMS was triggered ~1 second after the verbal command to move "mentally". At this interval, most subjects reported that their leg was into the mid-range (60–45°). Accordingly, in the ACTIVE condition, EMG responses were evoked when the leg reached the mid-range (45°) as judged by visual inspection. Data acquisition was controlled using custom software in a PC equipped with a digital interface (Texas Instrument Corp.). All signals were sampled at 2 kHz and saved for later analysis.

Statistics

The peak-to-peak amplitude and latency (see Fig. 2) of each single evoked response were measured in each condition (REST, motor imagery, POST). Then, mean values for amplitude and latency were derived by averaging 5–10 responses in each condition for each subject. To avoid comparison of absolute EMG levels, natural logarithmic transformation was applied to amplitude values in order to normalize data distribution and to make variance more homogeneous (12). [In log transformation, the natural logs of the values ($X = \ln X$) are used in analyses, rather than the original raw values. Because amplitude data tend to have a skewed distribution, such transformation improves variability and results in normal distribution (see Nielsen (12) for further discussion on log transformation).] A one-way repeated-measure ANOVA at $p < 0.05$ was used to test for the effect of conditions (three fixed-levels) on MEPs size (log-amplitude) and latency. A Tukey's post-hoc analysis was performed to test for difference between conditions.

RESULTS

At rest, all subjects exhibited evoked activity in the Quad in response to TMS of the contralateral hemiscalp. The intensity at threshold (see Methods), however, varied considerably between individuals (mean 66%, range: 45–88% stimulator output). While MEPs were relatively easy to elicit in the Quad, responses were more difficult to evoke in the antagonist. Only about half of the subject ($n = 11$) showed detectable responses to TMS in the biceps femoris at rest.

As pointed out in the Methods, EMG signals were closely monitored in the imagery condition to make sure that subjects did not attempt to contract their muscles. In fact, voluntary intervention was seldom seen (only in three cases in which full relaxation was obtained after further practice) and subjects were generally good at maintaining relaxation during mental simulation. Fig. 1 provides two illustrative examples of EMG recordings obtained in the motor imagery condition. These recordings were made in the course of the experiment, with the subjects not being aware that the stimulator output was set to 0% (i.e. no magnetic stimuli was delivered). In both subjects, it can be seen that no significant background EMG activity is present in the knee muscles during mental simulation of leg extension.

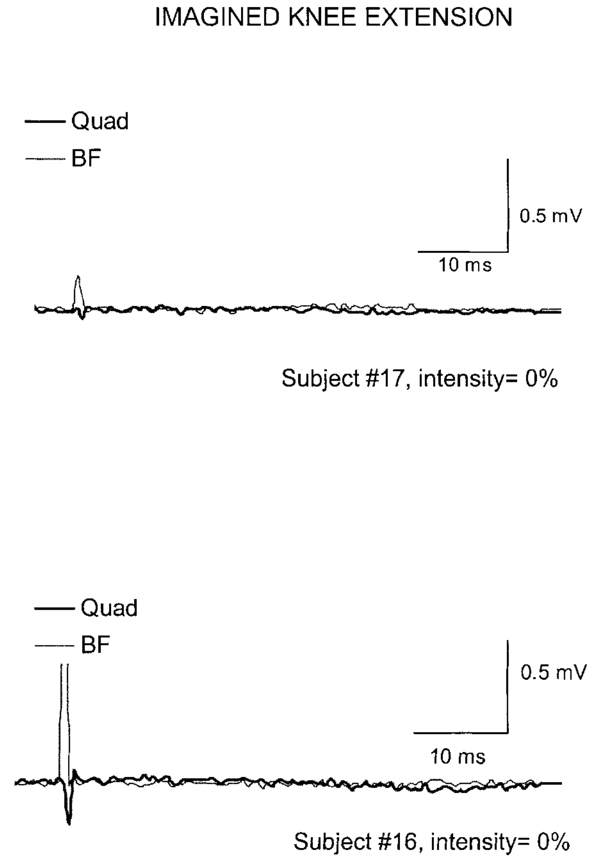

Fig. 1. Examples of individual recordings of background electromyographic activity in the motor imagery condition (i.e. mental simulation of right leg extension). Note that these recordings were made at unpredicted time in the course of the experiment with the subjects not being aware that the stimulator output was set to 0% (no cortical stimuli delivered). Each trace is an average of five trials. Quad: Quadriceps muscle, BF: Biceps femoris.

During imagined knee extension, the size of MEPs in the Quad increased, on average, by more than 250% (mean (±SEM) 279% ± 71%) compared with REST. In the POST condition, MEPs in the Quad tended to return close to their resting values (mean change, 13 ± 16%). Fig. 2 shows two representative examples of the facilitation seen in the Quad during motor imagery. In subjects in whom responses could be evoked in biceps femoris ($n = 11$), the size of MEPs remained

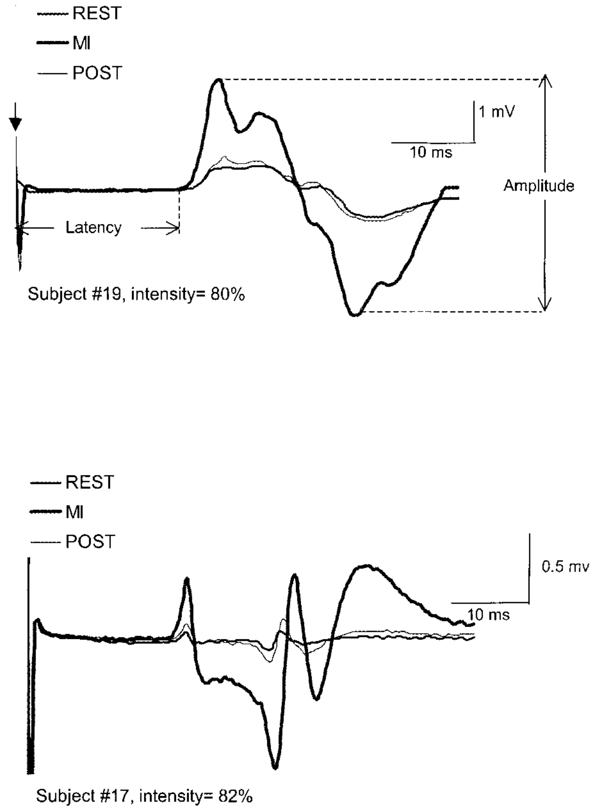

Fig. 2. Individual examples of facilitation of motor evoked potentials (MEPs) in the agonist muscle (Quad) during mental simulation of leg extension (MI). The small arrow indicates stimulus onset. Latency is measured as the difference between the time of the evoked response and stimulus onset. Amplitude is measured from the negative peak (upward deflection) to the positive peak (downward deflection). MEPs recorded at rest (REST) and immediately after imagery (POST) are also shown for comparison. Each trace is an average of five consecutive trials.

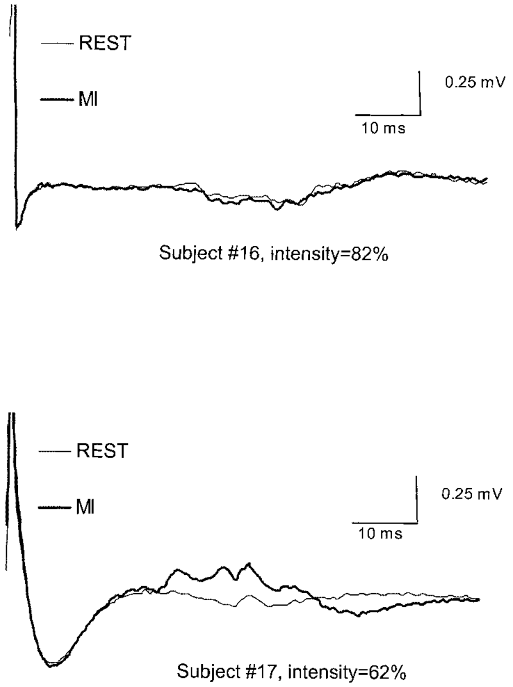

Fig. 3. Individual examples of motor evoked potentials (MEPs) recorded in the antagonist muscle (biceps femoris) during mental simulation of leg extension (MI). MEPs recorded at rest (REST) are shown for comparison. Note the absence of change in MEPs amplitude in one case (above), and the presence of facilitation in another case (below). Each trace is an average of six consecutive trials.

largely unaffected during motor imagery, although three subjects showed evidence of facilitation (mean overall change, 72 ± 55%). Representative examples of responses seen in the biceps femoris are shown in Fig. 3. In the ACTIVE condition, all subjects tested ($n = 5$) showed a considerable facilitation in the Quad (mean change, 492 ± 174%).

Fig. 4 compares the mean (±SD) log-amplitude (A) and latency (B) of MEPs computed in each muscle for all subjects across the three main conditions. The mean values for the ACTIVE condition ($n = 5$) are also shown for comparison. As expected, there was a significant effect of conditions on MEPs log-amplitude in the Quad ($F_{(2,54)} = 10.85, p < 0.001$) but not in biceps femoris. The facilitatory effect of motor imagery on MEPs log-amplitude in the Quad was confirmed by the post-hoc analysis (Tukey, $p < 0.001$) as well as the absence of difference between POST and REST conditions. As evident in Fig. 3B, changes in latency across conditions were comparatively smaller than those measured in amplitude and no significant difference was noted (ANOVA, $F_{(2,54)} = 0.43, p = 0.65$).

DISCUSSION

In the present study, we showed that imagination of a simple leg extension movement is accompanied by a large facilitation of responses evoked by magnetic stimulation of the contralateral motor cortex. The fact that MEPs in the Quad were facilitated, while those in the antagonist biceps femoris remain largely unaffected in the vast majority, indicates that this facilitation is specific to the agonist muscle involved in the task. As mentioned earlier, evidence for such specificity already exists for the upper extremity during tasks involving mental simulation of hand or wrist movements (7, 10, 13). In this regard, our results are entirely consistent with those of previous studies. Thus, the specific central facilitation produced during imagined motor activity seems to be generalized phenomena that can be applied either to upper or lower extremity movements.

As noted in the Introduction, several lines of evidence point out to a change in motor cortical excitability to explain imagery-induced MEPs facilitation. First, observations from functional imaging studies indicate that motor cortical regions normally activated during movement (e.g. supplementary and premotor areas, primary motor cortex) are also activated during motor imagery (14–16). Since these regions are known to contribute to the corticospinal tract, their activation during motor imagery would result in larger descending volleys destined to the agonist

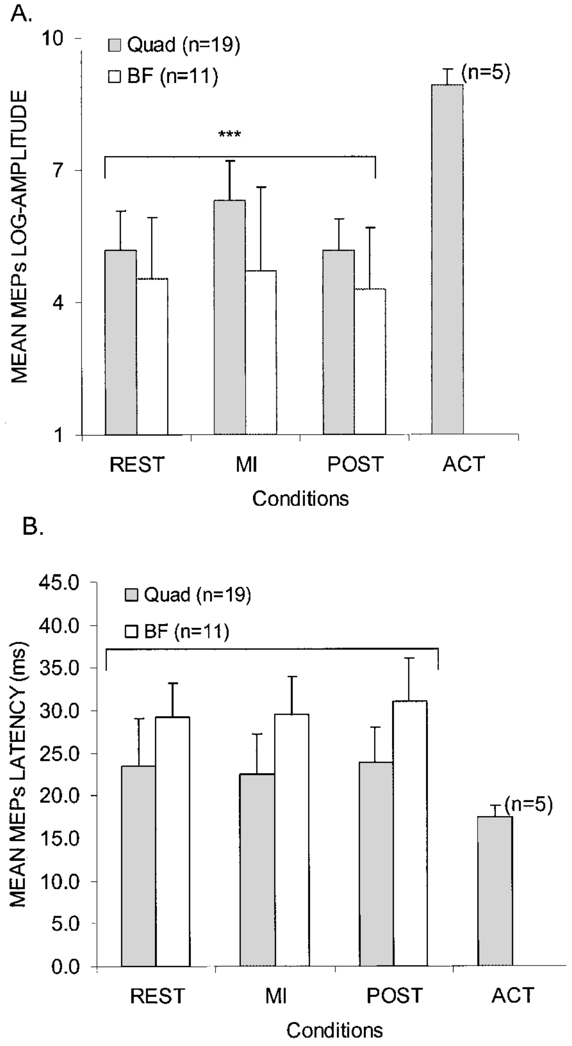

Fig. 4. Mean (±SD) motor evoked potentials (MEPs) log-amplitude (A) and latency (B) computed in each muscle across the three main conditions. The mean values computed in the quadriceps (Quad) for the active (ACT) condition are also shown for comparison. Note that conditions had a significant effect on MEPs log-amplitude in the Quad (ANOVA, F(2,54) = 10.85, $p < 0.001$), but not in biceps femoris (BF). (*** $p < 0.001$, post-hoc Tukey's for multiple comparisons).

motor neurons pool (i.e. the Quad). Second, several studies have described facilitation of EMG responses evoked by cortical magnetic stimulation during mental rehearsal of movements, without concomitant changes in spinal excitability as tested by H-reflex (7, 8, 10). Finally, as shown in a recent report (17), changes in intracortical inhibition that normally occur during movement execution also occur when the same movement is simulated mentally. Thus, an increase in motor cortical excitability during motor imagery offers a plausible mechanism to account for the facilitation observed in the Quad. Such a mechanism would also help to explain why MEPs recorded during actual performance of the movement were larger than those recorded during imagery. Indeed, a recent study by Porro et al. (14) showed that mental rehearsal of a given action produced less activation in primary motor cortex compared with levels reached during actual performance of the action. Thus, a difference in the level of motor cortical activation between imagined and real leg extension movement may account for the difference in the amount of facilitation observed in the Quad in these two conditions.

Although a change in motor cortical excitability seems plausible, an increase in spinal excitability would provide a simpler alternative for the facilitation observed in the motor imagery condition. Indeed, there is evidence that spinal reflex excitability can be modulated during motor imagery, although the sign of this modulation seems to be variable depending upon task conditions (e.g., see results of Bonnet et al. (18) and Oishi et al. (19)). In a recent report, Gandevia et al. (20) used microneurography to seek for evidence of selective fusimotor recruitment during mental rehearsal of motor tasks. While no evidence of such recruitment was found, the authors did notice that mental rehearsal was associated with increased level of background activity in the agonist muscle and increased H-reflex as well. These findings led the authors to conclude that motor imagery involved unintended subliminal performance of the task. In the present study, we found little evidence for the presence of "unintended" voluntary contractions in the Quad in the motor imagery condition (see Fig. 1). However, since we did not measure H-reflex and systematically quantified background EMG activity, we cannot rule out the possibility that changes in spinal excitability may have contributed to the present results.

In conclusion, the present study has extended previous observations on changes in corticospinal excitability induced by motor imagery to show that a specific facilitation can be obtained in the large muscles of the lower extremity. Although this study focused on knee extensors, the present results do not exclude the possibility that other lower extremity muscles (e.g. knee flexors) can also be facilitated via mental simulation. These results have potential applications for rehabilitation specialists as it provides evidence that motor imagery can be used to facilitate motor responses in the lower extremity when real movement is impeded (e.g. cast immobilization) or not possible (e.g. paralysis).

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