The Effect of Motor Imagery on Spinal Segmental Excitability

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The purpose of this study was to investigate the effect of motor imagery on spinal segmental excitability by recording the reflex responses to externally applied stretch of the extrinsic finger flexors and extensors during the performance of an imaginary task. Nine young healthy subjects performed a series of imagined flexion-extension movements of the fingers. Muscle stretch was imposed concurrently by applying rotations of the metacarpophalangeal joints at 100, 300, or 500°/sec. Three of the nine tested subjects also generated 0.2 Newton meter voluntary flexion torque in preloading tasks before stretch.

At 300°/sec stretch, electromyogram (EMG) and torque reflex responses, which were observed in the finger flexors in four of nine subjects during motor imagery, were activated at a short latency (38.6 ± 10.6 msec). This latency was similar to that recorded during a stretch of preactivated flexor muscles (34.4 ± 3.6 msec), in which motoneurons are already suprathreshold and in which monosynaptic effects of muscle afferents are likely to be discernable. In a similar manner, for stretches imposed at 500°/sec, responses to stretch of the flexors were observed in all five tested subjects in imaginary flexion tasks at very short latencies (26.4 ± 3.7 msec), again similar to those induced by tendon taps (22.8 ± 1.2 msec). No EMG response was observed at rest during stretches.

These observations support the view that effects must have been mediated by imagery-related subthreshold activation of spinal motoneurons and/or interneurons, rather than by long-latency transcortical reflex responses. We conclude that motor imagery has a potent effect on the excitability of spinal reflex pathways.

Key words: motor imagery; stretch reflex; spinal excitability; motor; fingers; human

Introduction

A general feature of motor imagery is that subjects feel they are performing a certain movement without executing it (Jeannerod, 1995; Decety, 1996a; Facchini et al., 2002). Extensive evidence in the literature shows that motor imagery shares a number of neural substrates with those neural centers involved in the actual movement (Decety, 1996a; Grammond, 1997; Abbruzzese et al., 1999). Imaginary movements share additional features with actual movements such as kinematic constraints (Sirigu et al., 1995), temporal properties (Decety et al., 1989; Sirigu et al., 1995), and the effects on motor performance (Yue and Cole, 1992). Furthermore, transcranial magnetic stimulation (TMS) studies have demonstrated an increased excitability in primary motor cortex (M1) and corticospinal pathways during motor imagery when compared with the resting state, as evidenced by a decrease in motor threshold and an increase in size of the motor evoked potentials (MEPs) (Kasai et al., 1997; Kiers et al., 1997; Fadiga et al., 1999; Yahagi and Kasai, 1999; Facchini et al., 2002, Li et al., 2004). However, the MEPs do not provide information about the level of the corticospinal pathway at which these effects arise (Petersen et al., 2003). Contributions to the increased amplitude of the MEPs may arise from the spinal motoneurons (Morita et al., 2000) or from spinal interneurons (INs), which receive direct inputs from M1 or linked premotor areas (Dum and Strick, 1991; He et al., 1995).

Controversy exists in the literature regarding the relative contributions of supraspinal and spinal changes in excitability to the observed increase in the MEP amplitudes. Both H-reflex and F-wave techniques, in combination with TMS stimulation over M1, have been used to explore these contributions. Some researchers have found no effect of motor imagery on H-reflex amplitude [extensor carpi radialis (Kasai et al., 1997; Hashimoto and Rothwell, 1999) and flexor digitorum superficialis (Abbruzzese et al., 1996)], whereas others have found a facilitatory effect (flexor carpi radialis) in half of their subjects, resulting in a statistically significant difference (Kiers et al., 1997). Rossini et al. (1999) reported specific facilitation of the F waves recorded from intrinsic hand muscles (abductor digitii minimi, first dorsal interosseous) during motor imagery. In the soleus muscles, Bonnet et al. (1997) reported a similar increase in excitability (based on H-reflexes and tendon reflexes) during motor imagery. Facilitation of these reflexes suggests subthreshold excitation of the spinal motoneuron pool of the target muscle during motor imagery.

In contrast, there was no change in the F waves in another motor imagery study, also recorded from intrinsic hand muscles (Facchini et al., 2002). One limitation of the F-wave technique is that modulation of F waves may not be representative of the change of the entire α motoneuron pool (Mercuri et al., 1996). Thus, the effect of motor imagery at the spinal level remains unclear.
Excitability than changes in long-loop pathways. Furthermore, examination of the trial-to-trial variation in relative short latencies (average, 26.4 ± 3.7 msec), a time too short to allow significant participation of long-loop pathways. We found that the earliest effects of motor imagery were usually discernable at the segmental level. We examined this effect by comparing reflex responses [electromyogram (EMG) or joint torque] to externally imposed stretches of finger flexors and extensors at rest with those recorded during motor imagery. We found that the earliest effects of motor imagery were usually discernable at relatively short latencies (average, 26.4 ± 3.7 msec), a time too short to allow significant participation of long-loop pathways. Furthermore, examination of the trial-to-trial variation in response showed patterns of EMG response that were more likely to reflect changes in baseline motoneuronal and/or interneuronal excitability than changes in long-loop pathways.

Materials and Methods

Subjects. Nine healthy volunteers, all males, participated in the experiments. All of them were right-handed according to their preferential use of the right-hand during writing and eating. The mean age of the subjects was 30 ± 4.9 (mean ± SD) years. Their weight was 67 ± 10.5 kg, and their height was 1.72 ± 0.04 m. The left arm of each subject was used for testing. All subjects gave informed consent before the experiment according to the procedures approved by the Institutional Review Board at Northwestern University.

Apparatus and recordings. Stretches were provided by a servomotor (1.4 horsepower; PMI Motion Technologies, Radford, VA) as described previously (Kamper and Rymer, 2000). Briefly, the subject was positioned on an adjustable chair such that the shoulder was abducted ~50° and the elbow was flexed ~90°. The forearm and wrist were placed in a fiberglass cast and secured in the neutral position to a clamp attached to the table to which the motor was secured. This arrangement prevented translation and rotation of the arm. The motor shaft extended vertically above the table. The metacarpophalangeal (MCP) joints were aligned with the shaft such that rotation of the shaft produced an equivalent angular rotation of the MCP joints. An aluminum channel was connected to the shaft and to a U-shaped piece into which the fingers were placed. A bead-filled balloon surrounding the fingers was attached to the inner surface of the U-shaped piece. Evacuation of the bladder with a vacuum pump provided a rigid coupling between the fingers and the U-shaped piece and, thus, the motor shaft. A strap kept the thumb extended and abducted from the palm so it did not interfere with finger flexion.

Differential surface EMG electrodes (DelSys, Boston, MA) were mounted above the muscle bellies of the flexor digitorum superficialis (FDS) and the extensor digitorum communis (EDC) of the left arm to record muscle activity. The EMG signals were amplified and low-pass filtered at 225 Hz. The signals from the left forearm (both FDS and EDC) were displayed on-line on an oscilloscope (V per division) to ensure that the EMG silent during motor imagery. EMG silence was defined as the absence of any background activity at the sensitivity of 25 μV per division. Each trial began with a ramp of motor activation and terminated with a ramp of motor inhibition.

Angular position, rotational velocity, and torque were measured throughout the trials with a position encoder (138647; PMI Motion Technologies), tachometer (PMI Motion Technologies), and torque transducer (TRT-200; Transducer Techniques, Temecula, CA), respectively. All signals were sampled at 500 Hz using customized software, and the data were saved for off-line analysis.

Procedures. Two experimental conditions were investigated in all nine subjects: rest (the absence of imagery) and motor imagery. As shown in Figure 1, there were four different motor imagery tasks: ImFlex-EXT, ImExt-EXT, ImFlex-FLEX, and ImExt-FLEX, where ImFlex/Ext stands for the direction of imagery and Ext/FLEX for the direction of stretches imposed by the MCP rotator. Subjects were instructed to keep their muscles relaxed before the stretch. Stretches were performed at 300 or 100°/sec, with a rise time equal to 10% of the total movement time. The range of stretch was from 0 to 30° of flexion of the MCP joints for the FLEX stretch, whereas it was from 30° of flexion to 0° for the EXT stretch. The ranges were selected such that the flexors and extensors were equally stretched with respect to the neutral position of MCP joints. There are no existing data on the respective reflex thresholds of FDS and EDC, but because both muscles are near optimal fiber length for these postures (Kamper et al., 2001), we expected that the effects on the muscles would be similar. In addition, two tasks were also tested in five of nine subjects, ImFlex-EXT and at rest using fast stretches (500°/sec), at which the MCP joints were rotated from 20° of flexion to 0°, resulting in a movement time of 40 msec.

A "ramp-hold- ramp" stretch was used (Fig. 2). In tasks at rest, the EXT stretch was imposed during the first half of the trial, whereas the FLEX stretch was applied during the second half of the trial. The instruction for motor imagery was to mentally extend–flex the secured left fingers against the U-shaped piece as hard as possible and to maintain the imagined contraction until the end of the actual stretch. The stretch was initiated unexpectedly within 3–5 sec after the verbal command to begin the imagery. Subjects were asked to practice the mental tasks for a few minutes before testing to ensure that they were able to keep the EMG silent during motor imagery. EMG silence was defined as the absence of any background activity at the sensitivity of 25 μV per division. During motor imagery, the subject was also instructed to keep the whole body still, including the other hand.

The order of conditions was randomized. Five trials were recorded for each task. The interval between two consecutive trials was ~20 sec. The experimenter discarded a motor imagery trial if EMG activities were detected visually during the experiment and a repeat trial was performed.

Three of nine tested subjects were randomly selected to perform additional preloading tasks in an effort to gauge the magnitude of the imagery effect. In the preloading tasks, subjects generated 0.2 Newton meter (Nm) of flexion torque against the motor (~1.5% MVC). Under the...
Ground EMG (EMGBG) were defined as the mean values calculated from EMGPK was obtained from the rectified, low-pass filtered EMG EXT (ImFlex-EXT, ImExt-EXT) and FLEX (ImFlex-FLEX, ImExt-FLEX) halves separately (Fig. 2) and used as a baseline for imagery tasks with the onset and impact force of the tendon tap. Kistler (Don Mills, Ontario, Canada) force sensor. The tapper allowed the wrist joint, was applied using a customized tapper equipped with a force sensors. The data here are presented as means, whereas the figures show means and SE bars. Repeated measures ANOVAs were used with factors IMAG (three levels: None (rest), ImFlex, and ImExt) and STRE (two levels: flexion and extension). Whenever necessary, post hoc Tukey’s honest significant difference tests were used to compare the various levels of a factor. Paired Student’s t tests were used to test resting conditions.

Results

In the present study, we focused on motor imagery tasks that were accompanied by finger stretches applied at several different velocities. At 300°/sec, the duration of the imposed movement was ~100 msec, a time span less than the minimum required for a voluntary reaction time movement, thereby allowing us to focus on reflex rather than voluntary reaction-time responses. Trials at 100°/sec were also analyzed and revealed a similar pattern of torque and EMG responses. Background EMG and torque values were analyzed and showed no difference across different conditions of imagery tasks and rest within the same subjects, indicating that comparisons of EMG responses across trials were legitimate. High-speed stretches (500°/sec) were used to investigate the effect of stretch velocity on reflex latency during motor imagery.

Effects of motor imagery on reflex EMG responses in forearm muscles

Pattern of reflex EMG responses

In general, reflex EMG responses were recorded during most imagery tasks, whereas no response was recorded at rest in any of the subjects across different stretch velocities (Fig. 2). Furthermore, the EMG responses showed a novel pattern during motor imagery tasks in that the responses were much more evident during the FLEX stretches than during the EXT stretches.

As summarized in Table 1, reflex EMG responses (peak EMG magnitude more than three SDs of background EMG) from EDC occurred in all nine subjects during the ImExt-FLEX tasks and in seven of nine subjects during the ImExt-FLEX tasks. In these tasks (FLEX stretches), reflex EMG responses were present when EDC was stretched, regardless of the direction of imagined movements. In contrast, reflex EMG responses from FDS were observed in four of nine subjects during the ImExt-EXT tasks in which this muscle was the putative primary mover in the imaginary movement and was stretched (EXT) by the actuator. No reflex responses were observed in the ImExt-EXT tasks where FDS was stretched when EDC was the putative primary mover of the imagined movement.

Magnitude of EMG response

Magnitudes of responses were quantified by repeated-measure ANOVAs. A 2 × 3 two-way ANOVA (STRE×IMAG) was performed to compare the magnitude of EMG responses (EMGPK – EMGBG) in EDC within the same subject across different conditions (motor imagery, rest). The results showed a significant effect of IMAG (F(2,16) = 4.13; p < 0.05) and a significant interaction of IMAG×STRE (F(2,16) = 4.14; p < 0.05), indicating that the latency by signal processing, only rectified, but unfiltered, signals of raw EMG data were used. A reflex EMG response was considered to have occurred when the peak EMG magnitude (EMGPK) during the stretch exceeded three SDs of the EMGBG. The latency of the stretch reflex was computed as the time interval from the movement onset (t0) to the moment when the EMG magnitude exceeded two SDs of the baseline. EMG responses were analyzed for extensors (EDC) and flexors (FDS) separately. Similarly, the latency for the tendon tap tests was calculated as the interval between the onset of the tap (t0) and the EMG onset. The EMG response was also visually inspected trial by trial.

Statistics.

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EMG responses from EDC were significantly larger during motor imagery in the flexion stretch (ImFlex-FLEX, 0.29 V; ImExt-FLEX, 0.25 V) than in other conditions (ImFlex-EXT, ImExt-EXT, Rest, 0.01 V). The same type of ANOVA was performed for EMG responses from FDS and only showed a significant effect of IMAG ($F_{(2,16)} = 3.85; p < 0.05$). Tukey's post hoc test revealed that the EMG response in FDS was significantly larger in ImFlex-EXT tasks (0.15 V) than in other tasks (ImExt-EXT, 0.04 V; ImExt-FLEX, ImFlex-FLEX, 0.01 V; Rest, 0.01 V).

When normalized by the EMG response obtained from the voluntary preloaded condition in which the joint was stretched at 300°/sec, the averaged EMG magnitude in three subjects was 48.7% for the ImFlex-EXT tasks. The averaged magnitude of EMG response was 89.5% for the preloading tasks stretched at 100°/sec.

The onset latency of stretch reflex

Latency of EMG onset for stretch reflex was dependent on imagined movement and muscle (Table 1); it was shorter in FDS than in EDC. Furthermore, the reflex responses were seen in both FDS and EDC during imagined flexion, whereas only responses in EDC were observed for imagined extension. For stretches imposed at 300°/sec, the latency of onset for stretch responses ranged from 22 to 72 msec in the finger flexors and from 35 to 83 msec in the finger extensors (Table 1). On average, the EMG latency was 38.6 msec (SD, 8.1 msec) in the finger extensors (Table 1). The averaged EMG magnitude in three subjects was 30.2% (SD, 10.6%) in the FDS for the ImFlex-EXT tasks, 58.1 msec (± 11.5) in the EDC for the ImFlex-FLEX tasks, and 65.4 msec (± 9.8) in the EDC for the ImExt-FLEX tasks. The averaged latency was 34.4 msec (± 3.6) in the FDS during the preloading tasks, ranging from 25.8 to 50 msec. As shown in Table 1, the latency varied across trials within a subject. The shortest latencies for the ImFlex-EXT tasks in each subject (22 to 34 msec) (Table 1) were comparable with those observed during preloading tasks in which the same muscles were stretched (34.4 ± 3.6 msec). If only the shortest latency was considered for each subject, the average was 29.5 msec.

To assess the effects of stretch velocity on the onset latency, the latencies were compared at different movement velocities. Unlike the responses for 300°/sec stretch, EMG responses in FDS were observed at stretch velocities of 500°/sec in all five tested subjects in the ImFlex-EXT task, whereas no EMG response was observed at rest. Interestingly, in one of the five subjects, EMG response in FDS was elicited during fast stretch (500°/sec) but was not observed in the same ImFlex-EXT task during the stretch at 300°/sec.

Furthermore, the latency decreased substantially below that at 300°/sec, ranging from 21 to 40 msec with an average of 26.4 msec (± 3.7). In addition, the onset latency within a subject was less variable under the 500°/sec stretch (Fig. 3). Of particular interest, this latency was very close to that measured from tendon tap reflex tests (average, 22.8 ± 1.2 msec; range, 20–24 msec).

Effects of motor imagery on reflex torque responses

Predictably, the presence of EMG responses was accompanied by changes in torque responses. As shown in the top panel of Figure 4, the torque response averaged across subjects during the stretch period was larger in the ImFlex-EXT tasks (0.26 Nm) than in the ImExt-EXT tasks (0.2 Nm) and at rest (0.2 Nm) ($F_{(2,16)} = 6.21; p < 0.01$). Note that if the subjects without reflex EMG responses were excluded for the ImFlex-EXT tasks, the averaged peak was even larger (0.36 Nm).

In contrast, no difference in torque responses was observed in motor imagery tasks with FLEX stretches between ImExt-FLEX (0.25 Nm) and ImFlex-FLEX (0.23 Nm) tasks. However, the

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**Table 1. Patterns of EMG response to 300°/s stretches**

<table>
<thead>
<tr>
<th>No.</th>
<th>Rest</th>
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<th>ImExt-EXT</th>
<th>ImFlex-FLEX</th>
<th>ImExt-FLEX</th>
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<td>FDS</td>
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<td>9</td>
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<td>61–77</td>
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</table>

The latency (in milliseconds) varies across trials within a subject. No., Subject number; ImFlex/Ext, imagined flexion/extension movements; FLEX/EXT, flexion/extension stretches; FDS, flexor digitorum superficialis; EDC, extensor digitorum communis; numbers range of the latency (in milliseconds); –, no reflex response. Note that the criterion for reflex response is peak EMG magnitude > 3 SDs of background EMG.

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![Figure 3](https://via.placeholder.com/150)
torque responses during imagery tasks with FLEX stretches were both significantly larger than those at rest (0.15 Nm) during the second half of the tasks ($F_{1,2,16} = 7.04; p < 0.006$) (Fig. 4, bottom panel). Based on Student’s $t$ tests, the torque response at rest was larger in the first half (0.2 Nm) than in the second half (0.15 Nm) of the trial ($p < 0.001$).

The torque responses observed during motor imagery tasks were small in comparison to those that could be seen during the preloading conditions in three tested subjects. Averaged peak torque responses in three subjects were 0.73 Nm for trials stretched at 100°/sec and 0.92 Nm at 300°/sec.

Discussion

Effects of motor imagery on the stretch reflex

We focus discussion on the imagery-related modulation of stretch reflex in the finger flexors, because reflex responses in the flexors were compared during motor imagery, muscle activation, and tendon taps. The results obtained from this study show clear-cut modulation of stretch reflex excitability during motor imagery. EMG responses and accompanying torque responses to the muscle stretch during motor imagery were greatly enhanced when compared with the responses collected without imagery (Figs. 2–4). Additionally, the latency of the response was quite short and similar to that observed during 300°/sec stretch of voluntarily preactivated muscle. This indicates that there was unlikely to be sufficient time for voluntary reaction time responses to influence the EMG response. More importantly, the shortest latencies for the imaginary tasks observed during fast stretches at 500°/sec was similar to those induced by tendon taps, thus providing compelling evidence that imagery-related modulation of stretch reflex occurs at the spinal level. Furthermore, close similarity in reflex responses recorded during tasks performed using preloading, and during motor imagery tasks supports the notion that motor imagery shares many features with actual movements and tendon taps. The results obtained from this study show clear-

![Figure 4. Torque responses to external stretches at rest and during motor imagery tasks are presented with SEs. When the flexors were stretched (left), torque responses in the ImFlex-EXT tasks were significantly larger than those in the ImExt-EXT and at rest. As shown to the right, torque responses to the stretch of the extensors were significantly larger in motor imagery tasks than at rest. No difference was found between ImFlex-FLEX and ImExt-FLEX tasks.](image)

ject, in which reflexes were examined using 300°/sec stretches. Furthermore, the shortest response latencies in FDS in the ImFlex-EXT tasks were comparable with those observed in the preloading tasks at the same stretches (300°/sec) to the same muscle (FDS). During stretch of preactivated muscle, motoneurons are already suprathreshold, and monosynaptic effects of muscle afferents are likely to be discernable. Therefore, the results of within-subject variation at 300°/sec stretch could best be explained by hypothesizing that motoneuron and/or interneuron pools of the target muscle are excited to different and potentially time-varying subthreshold levels during motor imagery. Consequently, stretch-induced afferent inputs elicit reflex responses at different latencies in different trials. In contrast, within-subject variations could also be partly attributed to possibility of nonhomogeneous mental performance of the subjects because of the lack of external cueing (e.g., modulated pitch) (cf. Fadiga et al., 1995).

More importantly, the onset latency discerned during 500°/sec provides convincing evidence that the imagery-related modulation of stretch reflex responses most likely occurs at the spinal level. During fast stretches (500°/sec), the earliest discernable onset latencies in FDS (average, 26.4 msec, from 21 to 40 msec) were close to those induced by tendon taps (22.8 msec, from 20 to 24 msec). The difference is presumably attributable to the fact that the angular joint perturbation was not as abrupt as that achieved during tendon tap and to the fact that excitability may vary throughout the imaginary task. Furthermore, short onset latencies (26.4 msec) of EMG responses during fast stretches in the imagery tasks were similar to those for short latency reflexes or so-called M1 in other hand and forearm muscles [flexor pollicus longus, 24 ± 2 msec (Marsden et al., 1976); flexor carpi radialis, 17–26 msec (Lewis et al., 2004); 20–40 msec (Lin and Sabbahi, 1998)]. Thus, such latencies appear too short for potential involvement of cortical long-loop pathways [≤55 msec in the wrist flexor (Dick et al., 1987)]. Our results support the hypothesis of subthreshold activation of spinal circuitry during motor imagery. This is also consistent with previous reports of facilitatory effects during motor imagery using F-wave and H-reflex techniques (Bonnet et al., 1997; Kiers et al., 1997; Rossini et al., 1999).

Potential mechanisms for enhanced spinal excitability

There are several potential explanations for this imagery-induced modulation of stretch reflex at the spinal level. First, as indicated above, it could be because of subthreshold activation of motoneurons during motor imagery (cf. Gandevia et al., 1997). Because of the existence of direct corticomotoneuronal connections, especially for finger muscles (Porter and Lemon, 1993), it is possible that the excitability of spinal motoneurons is modulated directly by the motor cortex outflow.

Second, contributions may also arise from analogous modula-
tion of spinal INs. These INs also receive direct inputs from M1 and higher premotor areas (Dum and Strick, 1993; He et al., 1995) as well as from brainstem nuclei under cortical control. Modulation of activities in INs was reported during an instructed delay period (an interval between a transient instruction cue and a subsequently triggered movement) in monkeys (Prut and Fetz, 1999). Specifically, approximately one-third of these INs showed significant delay modulation in the absence of EMG activities, a condition potentially analogous to that occurring during motor imagery tasks. Thus, an increase in the IN activities may occur during motor imagery. Last, a combination of the previous two mechanisms could potentially contribute to the observed effect.

Another possibility is that there is an enhanced excitability of
the γ-motor system during motor imagery. Even without changes in the excitability of motoneurons and interneurons, the effect of an external stretch would thus be magnified and could trigger a stretch reflex during motor imagery. However, this is not likely to happen, because Gandevia et al. (1997) reported no change in spindle afferent discharge (and therefore the γ-motor system) during motor imagery. In contrast, their results showed increased motoneuronal activity and reflex excitability. Besides the above-mentioned possible mechanisms of sub-threshold activation, motoneurons could be actively inhibited from discharging through “parallel inhibitory mechanisms” (Takakusaki et al., 2001) despite increased corticospinal input during motor imagery.

**Comparison with H-reflex and F-wave responses**

Our results are also different from those obtained from H-reflex (Kasai et al., 1997; Hashimoto and Rothwell, 1999) and F-wave (Rossini et al., 1999; Facchini et al., 2002) techniques. The difference may lie in different techniques. The F wave is caused by antidromic activation of the motoneurons by strong electrical stimulation of peripheral nerves. Modulation of F waves may not be representative of the change of the entire α motoneuron pool (Mercuri et al., 1996). H-reflexes are evoked by electrical stimulation of peripheral group Ia afferents and recorded in the EMG from the muscle innervated by the stimulated nerve (Berardelli et al., 1987). They are thought to be mainly monosynaptic in origin and thus reflect the excitability of the spinal motoneurons as well as the transmission over the group I a synapses on the motoneurons. Stretch reflexes originate primarily from spindle afferents (Ia and II) and also involve input from skin and subcutaneous nerves (Corden et al., 2000). Therefore, it appears that stretch reflexes use both monosynaptic and polysynaptic connections within the spinal cord, and some contributions may even be transcortical in origin (Goodin et al., 1990).

Together, it could be easier to detect changes in mechanically evoked stretch reflexes than electrically evoked H reflexes and F waves during motor imagery. Thus, the experimental paradigm used in this experiment has some advantages over previous approaches to test changes in spinal excitability during motor imagery.

**Differential effects on finger flexors and extensors**

The observation of different effects of motor imagery on the finger flexors and extensors is also of particular interest. Responses in the EDC were present in almost all cases (both ImFlex-FLEX and ImExt-FLEX) when this muscle was stretched. In contrast, responses in the FDS depended on the direction of the imagined movement: observed only in some subjects in the ImFlex-EXT tasks, not in the ImExt-EXT tasks at all. Differences in EMG responses were also accompanied by differences in torque responses. Furthermore, the onset latency of EMG responses was longer in EDC than in FDS. These differential effects suggest that imagined finger flexion and extension are not symmetrically controlled activities. This is similar to what has been observed during actual voluntary movements (Yue et al., 2000; Nakazawa et al., 2001).

**Conclusion**

Given general agreement regarding the involvement of primary motor cortex and the resulting enhanced corticospinal excitability in motor imagery tasks, our results of reflex response to stretches at the latency close to that induced by tendon taps provide evidence that motor imagery increases the excitability of spinal reflex pathways in a sustained subthreshold manner. We conclude that motor imagery exerts significant effects on spinal segmental circuitry.

**References**


