Concurrent excitation of the opposite motor cortex during transcranial magnetic stimulation to activate the abdominal muscles

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Abstract

The study investigated the potential for stimulation of both motor cortices during transcranial magnetic stimulation (TMS) to evoke abdominal muscle responses. Electromyographic activity (EMG) of transversus abdominis (TrA) was recorded bilaterally in eleven healthy volunteers using fine-wire electrodes. TMS at 120% motor threshold (MT) was delivered at rest and during 10% activation at 1 cm intervals from the midline to 5 cm lateral, along a line 2 cm anterior to the vertex. The optimal site to evoke responses in TrA is located 2 cm lateral to the vertex. When bilateral abdominal responses were evoked at or lateral to this site, onset of ipsilateral motor evoked potentials (MEPs) were ∼3–4 ms longer than contralateral MEPs. The difference between latencies is consistent with activation of faster crossed-, and slower uncrossed-corticospinal pathways from one hemisphere. However, latencies of MEPs were similar between sides when stimulation was applied more medially and were consistent with concurrent activation of crossed corticospinal tracts on both sides. The findings suggest that stimulation of both motor cortices is possible when TMS is delivered less than 2 cm from midline. Concurrent stimulation of both motor cortices can be minimised if TMS is delivered at least 2 cm lateral to midline.

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1. Introduction

The abdominal muscles can be activated by the motor cortex via rapid-conducting corticospinal projections to the spinal motoneurons (Plassman and Gandevia, 1989). One method to investigate excitability of these pathways is transcranial magnetic stimulation (TMS). However, corticospinal cells in the motor cortex that project to the abdominal motoneurons are located medially near the central fissure (Penfield and Boldrey, 1937). Thus it is unclear whether induced-currents from magnetic stimulation over the motor cortex can directly stimulate the opposite hemisphere. If both cortices are stimulated concurrently, it would be impossible to determine the origin of ipsilateral and contralateral evoked responses.

Few studies have investigated the potential for concurrent stimulation of both motor cortices during TMS to elicit activation of muscles with midline motor representations. Several studies have reported that stimulation at scalp sites 2 cm lateral to the midline can evoke responses of the contralateral abdominal muscles with a latency that is ∼2–5 ms faster than responses on the ipsilateral side (Fujiwara et al., 2001; Strutton et al., 2004; Tunstill et al., 2001). The latency of contralateral responses is consistent with activation of crossed corticospinal pathways (Gandevia and Plassman, 1988). The slower ipsilateral responses however are argued to be unlikely due to excitation of the opposite hemisphere as this latency was longer, and more likely due to activation of uncrossed polysynaptic corticospinal fibres from the same motor cortex (Ziemann et al., 1999). However, those studies stimulated 2 cm laterally from the midline where the potential for concurrent stimulation may be minimal. Furthermore, studies to date have used surface electrodes to record responses from the abdominal muscles. As surface electrodes can record myoelectric activity from multiple abdominal muscle layers due to cross-talk, this makes it difficult to be certain that the responses evoked from different stimulation sites involve the same specific abdominal muscles.
Therefore, whether stimulation of sites medial or lateral to the recommended site (2 cm lateral to midline) could induce concurrent excitation of both motor cortices to evoke responses in the abdominal muscles, recorded with intramuscular electrodes, has not been systematically investigated.

The primary aim of this study was to examine the potential for stimulation of both motor cortices during TMS to elicit responses in the abdominal muscles at various distances from the midline. If motor evoked potentials (MEP) contralateral and ipsilateral to the side of stimulation have similar latencies, this could indicate simultaneous stimulation of the faster crossed corticospinal pathways from direct excitation of both motor cortices. However, if the latency of MEPs on the contralateral side of stimulation is faster than those evoked ipsilateral to the stimulated hemisphere, this would suggest that both responses are evoked from the same motor cortex.

2. Materials and methods

2.1. Participants

Eleven right-handed healthy individuals were recruited (4 male, 7 female; age: 23 ± 3 (mean ± S.D.) years; height: 170 ± 10 cm; weight: 67 ± 16 kg). Subjects were excluded if they had a history or family history of epilepsy, any major circulatory, orthopaedic, neurological or respiratory conditions, recent or current pregnancies, previous surgery to the abdomen or back, or if they had undertaken any form of abdominal exercises in the preceding 12 months. Hand dominance was determined by the Edinburgh Handedness Inventory (Oldfield, 1971). The study conformed to the Declaration of Helsinki and was approved by the Institutional Medical Research Ethics Committee.

2.2. Electromyography

Electromyographic activity (EMG) from the deep abdominal muscle, transversus abdominis (TrA), was recorded on both sides using intramuscular fine-wire electrodes (Teflon-coated stainless steel wire, 75 μm with 1 mm of Teflon removed and tips bent back ~1 and ~2 mm to form hooks). Wires were threaded into a hypodermic needle and inserted with ultrasound guidance (Hodges and Richardson, 1997). EMG data were preamplified 2000 times, band-pass filtered between 30 and 1000 Hz and sampled at 2000 Hz using a Power1401 Data Acquisition System and Spike2 software (CED, UK).

2.3. Procedures

Subjects were seated comfortably in a reclined chair with hips flexed to ~70°, knees flexed to ~45°, and both arms well-supported. Magnetic stimulation of the motor cortex was performed using a single-pulse monophasic MagStim 200<sup>2</sup> stimulator (MagStim Company, UK). A 7 cm figure-of-eight coil was used with cross-over position above respective scalp sites and the coil handle positioned at ~45° from the mid-sagittal plane such that the induced current flowed in an anteromedial direction (Sakai et al., 1997). At the midline, stimulation of the motor cortex was performed using two coil orientations: one with induced current flowing towards the left hemisphere, and the other with induced currents towards the right hemisphere. MEPs from stimulation at the midline were averaged across both coil orientations. The figure-of-eight coil provides better focality of stimulation compared to the standard circular coil (Brasil-Neto et al., 1992; Cohen et al., 1990), and has been shown to evoke consistent responses from the abdominal muscles during submaximal voluntary contractions (Tunstill et al., 2001). However, pilot trials showed that ipsilateral responses during voluntary contractions and contralateral responses from relaxed TrA were often difficult to evoke with a figure-of-eight coil, even at maximum stimulator output. Thus, a double-cone coil (MagStim Company, UK) was also used as it produces a stronger magnetic field and can evoke consistent ipsilateral and contralateral responses in the trunk and lower limb muscles at rest and during voluntary contractions. This coil was positioned with the coil handle perpendicular to the scalp site and induced current flowing in an anterior direction.

To determine targets for voluntary contraction of TrA, EMG activity was recorded during maximum voluntary contractions (MVC). Subjects performed a forced expiratory manoeuvre with verbal encouragement (Ninane et al., 1992). No pain or discomfort was reported by any subject during MVC. Three repetitions were completed with 1 min rest between each. The highest root-mean-square (RMS) EMG amplitude over a 1 s interval was recorded (RMS<sub>max</sub>). The target for voluntary contraction of TrA was set at 10% RMS<sub>max</sub> and visual feedback was provided to the subject via a computer screen. Animal and human experiments suggest that normal respiratory drive can modulate excitability of the abdominal motoneurons (Gill and Kuno, 1963; Hodges et al., 1997; Sears, 1964) and thus would be expected to influence the amplitude of MEPs (Lissens et al., 1995). To control for modulation in respiratory drive, subjects kept their glottis opened and ceased breathing at the end of normal expiration prior to stimulation. This was monitored online by measurement of rib cage displacement using a pressure cuff strapped to the chest (Hodges et al., 1997).

A tight-fitting elastic cap was worn and the vertex was located using the International 10/20 system (Jasper, 1958). The optimal location for responses contralateral to the stimulated cortex (i.e. scalp site which induced the largest abdominal response) was determined using the figure-of-eight coil set at suprathreshold intensity (~70–100% maximum stimulator output) during 10% voluntary contraction of TrA. In most subjects, this was found to be 2 cm anterior and lateral to the vertex and is consistent with the location used by previous studies for the obliquus internus and externus abdominis muscles, although the exact location of this position had not been systematically evaluated (Fujiwara et al., 2001; Strutton et al., 2004).

At the optimal location, the following motor thresholds (MT) were identified for the TrA contralateral to the stimulated cortex: active MT using the figure-of-eight coil (cMT<sub>1</sub>); active MT using the double-cone coil (cMT<sub>2</sub>); resting MT using the double-cone coil (RMT<sub>2</sub>). In addition, the active MT for responses ipsilateral to the stimulated hemisphere using the double-cone coil was...
also identified (iMT$_2$). To ensure the responses ipsilateral to the stimulated motor cortex were representative of uncrossed corticospinal projections, the latency of MEPs, which should be $\sim$2–5 ms slower than contralateral responses (Fujisawa et al., 2001; Strutton et al., 2004; Tunstill et al., 2001), was verified visually. All MTs were defined as the minimum intensity that elicited five consecutive abdominal MEPs which were clearly discernible from background EMG activity (Mills and Nithi, 1997).

To determine the potential for concurrent stimulation of both motor cortices, TMS was delivered at 1 cm intervals along a line 2 cm anterior to the vertex and parallel with the coronal plane from the midline to 5 cm lateral. Ten stimuli were delivered $\sim$5 s apart at each site during 10% voluntary contraction (120% cMT$_8$ using the figure-of-eight coil) and when TrA was relaxed (120% cMT$_2$ using the double-cone coil). For the figure-of-eight coil, if 120% of cMT$_8$ exceeded the maximum stimulator output of the TMS, the stimulus intensity was set to the maximum stimulator output. For the double cone coil, the maximum intensity used in this experiment was 90% of the maximum stimulator output. This limit was set because 100% maximum stimulator output was poorly tolerated by our naïve subject group who were not experienced with this type of procedure. Thus, if 120% of cMT$_2$ exceeded 90% of maximum stimulator output of the TMS with the double cone coil, the stimulus intensity was set to 90% of the maximum stimulator output. The procedures were repeated for each hemisphere.

2.4. Data analysis

Data were analysed using Matlab 7 (The Mathwork, USA). Individual trials were full-wave rectified, averaged across trials for each scalp site, and the average background EMG was subtracted (55–5 ms prior to stimulation). For trials in the resting condition, the onset and offset of MEPs relative to the time of the stimulus were visually identified. For trials that involved voluntary contractions, the onset and offset of MEPs (onset of silent period), and the duration of the silent period were visually identified. To minimise bias during visual identification of temporal parameters, data were presented in random order without reference to the identity of the muscle or site of magnetic stimulation. As recordings were made using relatively selective intramuscular electrodes, the peak-to-peak amplitude is variable due to inter-trial differences in the motor units excited by the descending volley. Thus, the amplitude of TrA MEPs from onset to offset was measured using RMS EMG. The RMS EMG was normalised to the peak response for each muscle across all scalp sites. This allowed comparison of the amplitude of MEPs between different scalp sites for the TrA muscle on the left and right side.

2.5. Statistical analysis

Statistical analysis was performed using Statistica 7 (Statsoft, USA). The MTs at the optimal location using the double-cone coil were compared between stimulus paradigms (Condition: cMT$_2$, iMT$_2$ and RMT) and between Muscles (left and right TrA) using repeated-measures analysis of variance (ANOVA). Due to differences in coil properties between the figure-of-eight and double-cone coils, the MTs identified using the figure of eight coil (cMT$_8$) were not compared directly with MTs from the double-cone coil (as this analysis would simply indicate differences in coil properties and not differences in excitability of corticospinal projections to the abdominal responses). Thus cMT$_8$ were compared between the left and right TrA using a Student’s t-test. To evaluate the difference in MEPs with stimulation at different scalp sites, the onset and amplitude of MEPs were compared between Muscles (left and right TrA), Positions (scalp sites), and Activities (resting versus contraction) using repeated-measures ANOVA. Previous studies showed that the onset and duration of silent periods can vary between scalp sites (Wassermann et al., 1993). As silent periods were not induced consistently over all scalp sites, the onset and duration of contralateral and ipsilateral silent periods were unable to be compared across scalp sites. Nevertheless, the onset and duration of the silent period evoked at the optimal location for the muscle contralateral and ipsilateral to the stimulated cortex during trials that involved voluntary contractions were compared using a Student’s t-test. Post hoc testing was performed using Duncan’s multiple range test. Significance was set at $p < 0.05$.

3. Results

3.1. Motor threshold (MT)

Fig. 1 shows group data of each MT for the left and right TrA. MTs could be identified over at least one motor cortex in all subjects at the optimal site. In five subjects, contralateral
responses could not be evoked over one hemisphere using the figure-of-eight coil, even at maximum stimulator output, and in four subjects, ipsilateral responses could not be evoked over one side using the double-cone coil, even at 90% maximum stimulator output.

For the double-cone coil, MTs at the optimal location were significantly different between stimulus paradigms (main effect: condition, \( p < 0.001 \)). The lowest MT was observed for active MT of the contralateral responses (cMT\(_2\); post hoc, \( p < 0.001 \)). The resting MT (RMT\(_2\)) was significantly lower than the active MT for ipsilateral responses (iMT\(_2\); \( p = 0.021 \)). No differences in MTs were found between the left and right TrA for any condition using the double-cone coil (main effect for muscle, \( p = 0.84 \)) or for cMT\(_8\) identified using the figure-of-eight coil (\( p = 0.99 \)). Observation of individual data showed greater differences in iMT\(_2\) between the left and right side compared to MTs for contralateral responses, although the hemisphere with greater MT was not consistently found on the dominant or non-dominant side. The absolute difference of each MT between the left and right TrA in each individual was calculated and comparisons showed that the difference in iMT\(_2\) between sides was greater than the difference in MTs between sides for contralateral responses (active and relaxed, \( p < 0.019 \); Fig. 2).

### 3.2. Motor evoked potential (MEP) across scalp sites

Fig. 3 shows the onset and amplitude of TrA MEPs at rest (Fig. 3A) and during 10% MVC (Fig. 3B). The onset of TrA MEPs was shorter during voluntary contraction than TrA MEPs when the muscle was relaxed (main effect: activity, \( p < 0.001 \)). When stimulation was applied at the vertex and 1 cm lateral to the midline, onsets of MEPs were similar between left and right TrA (interaction—position \( \times \) muscle: \( p = 0.001 \); post hoc: \( p > 0.14 \) for all comparisons of MEPs (at midline and 1 cm) between left and right TrA), and equivalent to the latency of contralateral MEPs at sites further lateral from the midline (post hoc: \( p > 0.09 \) for all comparisons of MEPs evoked at and 1 cm lateral to the midline with those evoked at sites 2–5 cm lateral). This suggests that stimulation at the midline or 1 cm lateral causes activation of contralateral corticospinal pathways, bilaterally. However, the onsets of contralateral MEPs were significantly shorter than ipsilateral MEPs when stimulation occurred at sites at least 2 cm lateral to the vertex and suggests no excitation for all comparisons of MEPs (at midline and 1 cm) between left and right TrA), and equivalent to the latency of contralateral MEPs at sites further lateral from the midline (post hoc: \( p > 0.09 \) for all comparisons of MEPs evoked at and 1 cm lateral to the midline with those evoked at sites 2–5 cm lateral). This suggests that stimulation at the midline or 1 cm lateral causes activation of contralateral corticospinal pathways, bilaterally. However, the onsets of contralateral MEPs were significantly shorter than ipsilateral MEPs when stimulation occurred at sites at least 2 cm lateral to the vertex and suggests no excitation

![Fig. 3. Amplitude and onset of motor evoked potential (MEP) for the left and right transversus abdominis (TrA) at various scalp sites lateral from the midline (Mid) at rest (A) and during 10% voluntary contraction (B). Amplitude is expressed as root-mean-square (RMS) EMG of MEP, normalised to the peak response. When stimulation evoked bilateral responses, the amplitude of contralateral MEPs was significantly larger than ipsilateral MEPs except at midline. In addition, stimulation at sites 2–5 cm lateral to midline evoked contralateral MEPs with significantly shorter onset latency than that for ipsilateral MEPs. This difference was not observed when stimulation was delivered at midline or 1 cm lateral to midline (**\( p < 0.05 \)).](image-url)
Fig. 4. Rectified average motor evoked potentials (MEPs) from a subject during TMS over the midline (A) and at 2 cm lateral (B) at rest (right (R) transversus abdominis (TrA) EMG calibration: 0.2 mV; left (L) TrA EMG calibration: 0.1 mV). Corticospinal pathways activated by TMS are also diagrammatically represented. When TMS was delivered at midline, the latency of TrA MEPs (arrow) was similar between the left and right sides. This suggests activation of crossed corticospinal pathways from both motor cortices (represented as solid and dotted lines on the right hand diagram). When stimulation was delivered at 2 cm lateral to the midline over the left hemisphere, the latency of the MEP on the right side was faster than that on the left side. This suggests activation of crossed and uncrossed corticospinal pathways from the left motor cortex (solid and dashed lines, respectively, on the right hand diagram).

of fast contralateral pathways from the opposite motor cortex (all \( p < 0.045 \)). Representative data from a single subject are presented in Fig. 4.

The amplitude of TrA MEPs was significantly greater during voluntary contraction compared to MEPs at rest (main effect for activity, \( p = 0.0036 \)). Furthermore, for stimulation of scalp sites that evoked bilateral abdominal responses (except at the vertex \( p = 0.33 \)), the amplitude of contralateral MEPs was larger than MEPs on the ipsilateral side (interaction—position \( \times \) muscle: \( p < 0.001 \); post hoc: \( p < 0.046 \)). However as the MT for responses on the ipsilateral side were higher than those on the contralateral side, it is not possible to directly compare the amplitude of MEPs between sides due to optimisation of TMS procedures for contralateral responses.

As stimulation across scalp sites was optimised to contralateral MT, ipsilateral MEPs were not consistently evoked in all subjects. Inspection of individual data showed that a silent period on the ipsilateral side was present in some trials in the absence of observable excitation. This was most commonly observed when TMS was delivered at sites 3–5 cm lateral to the midline. Analysis for responses evoked at the optimal location showed that the duration of silent period was longer in the muscles contralateral to the stimulated hemisphere (73.5 ± 28.2 ms) compared to those ipsilateral to the stimulated hemisphere (37.0 ± 16.8 ms; \( p = 0.018 \)). However, this is again likely to be due to optimisation of magnetic stimulation to the contralateral MT. No differences in onset of silent period were found at the optimal location between responses contralateral (39.7 ± 9.4 ms) and ipsilateral to the stimulated motor cortex (38.2 ± 11.8 ms; \( p = 0.71 \)).

4. Discussion

This study showed that spread of current to excite the corticospinal pathways in the opposite motor cortex is possible when TMS is delivered medially near the vertex. However, magnetic stimulation of scalp sites at least 2 cm lateral to the vertex evokes responses in the contralateral abdominal muscle that were faster than those in the ipsilateral muscle. This is consistent with activation of crossed and uncrossed corticospinal pathways from the same motor cortex without concurrent excitation of fast corticospinal projections from the opposite motor cortex. These results demonstrate that selective activation of the abdominal muscles over one motor cortex is best achieved if TMS is applied at least 2 cm lateral to the vertex. This can be highlighted through analysis of timing of MEPs, which can provide insight into the origin of responses.
4.1. Concurrent stimulation of corticospinal projections to the abdominal muscles from both motor cortices

This is the first study to systematically demonstrate that the largest MEPs of an abdominal muscle, TrA, can be evoked 2 cm lateral to the vertex and that these responses can be recorded with intramuscular EMG electrodes. Stimulation delivered at least 2 cm lateral to midline induced MEPs bilaterally in TrA with distinct differences in latency. The onsets of contralateral responses were found to be ∼3–4 ms shorter than MEPs on the ipsilateral side. This difference in latency is consistent with previous studies that used surface EMG recordings of superficial abdominal muscles (Fujiwara et al., 2001; Strutton et al., 2004; Tunstill et al., 2001). The size of the difference in MEP latencies between contralateral and ipsilateral responses also agrees with data for other axial muscles (e.g., pectoralis major (Quartarone et al., 1999)) and limb muscles (Chen et al., 2003; Colebatch et al., 1990; Wassermann et al., 1991; Ziemann et al., 1999). These findings suggest stimulation of scalp sites at least 2 cm lateral to the midline excites corticospinal pathways from the underlying motor cortex. That is, the faster crossed corticospinal tract (Gandevia and Plassman, 1988) and the slower uncrossed polysynaptic corticospinal tracts (Chen et al., 2003; Ziemann et al., 1999), without concurrent stimulation of contralateral projections from the opposite motor cortex.

When TMS was delivered near the midline, there was no difference in onset between MEPs on the right and left sides. Although it is likely that slower uncrossed corticospinal pathways are also excited and contribute to the later part of the recorded MEP, similarities in latencies between MEPs on both sides is consistent with excitation of faster crossed corticospinal pathways from both motor cortices. These findings are consistent with an earlier study that evoked responses in the rectus abdominis muscles using TMS over the midline and also showed no difference in latency of MEPs between sides (Carr et al., 1994). Although these authors argued that these responses originated from one motor cortex as stimulation of scalp sites further lateral to the midline also elicited bilateral responses, a lack of difference in the latency of abdominal responses between sides in that study would suggest that concurrent stimulation of both motor cortices had occurred.

Interestingly, the average latency for ipsilateral responses evoked at 1 cm lateral to the midline fell between the latency for responses evoked from crossed and uncrossed corticospinal pathways. Observation of individual data showed that in some subjects, TMS delivered at 1 cm lateral to the midline induced faster contralateral MEPs and slower ipsilateral MEPs suggesting activation of crossed and uncrossed corticospinal projections, whereas other subjects showed similar latencies of MEPs between sides when stimulation was delivered 1 cm lateral to the midline. This finding highlights that it is possible to excite motor cortex on one side at 1 cm lateral to the midline in some subjects, but not in others. In addition, abdominal MEPs were smaller in amplitude and slower in latency when stimulation was delivered at rest compared to trials that involved voluntary contractions. This is consistent with facilitation of evoked responses reported in earlier studies (Hess et al., 1986, 1987; Kischka et al., 1993), and is argued to occur at least in part to a greater probability of firing of motoneurons due to increased excitability (Thompson et al., 1991).

As the duration of silent period depends upon stimulus intensity (Triggs et al., 1993) and our procedures were optimised for contralateral MEPs, differences observed in duration of silent period between muscles contralateral and ipsilateral to the stimulated cortex could be explained by higher MT for ipsilateral responses. Differences in duration of silent period could also be attributed to difference in underlying mechanisms. Silent period evoked for muscles on the contralateral side of stimulation are argued to occur through spinal (Fuhr et al., 1991) and cortical mechanisms (Davey et al., 1994). In contrast, ipsilateral silent periods are argued to be mediated at least partly by transcortical pathways that project to and inhibit the opposite hemisphere (Ferbert et al., 1992; Rothwell et al., 1991). Furthermore, as the MT for inhibition of muscle activity is less than that for excitation, it could be possible that silent periods in the ipsilateral muscle may have resulted from current spread to the opposite hemisphere, which was sufficient to inhibit, but not excite the ipsilateral abdominal muscles. Further investigations are needed.

4.2. Greater hemispheric asymmetry in motor threshold (MT) for ipsilateral motor evoked potentials (MEPs)

An interesting finding was that absolute differences in MT between the left and right TrA was greater for longer latency responses elicited by stimulation of the ipsilateral motor cortex compared to the faster crossed pathways from the contralateral motor cortex. This greater asymmetry in MT for ipsilateral corticospinal projections is unlikely to be related to variations in motor unit thresholds between sides, as this would also affect contralateral responses. Asymmetry in ipsilateral MT is consistent with previous studies in other abdominal (Strutton et al., 2004) and axial muscles (Hamdy et al., 1996; MacKinnon et al., 2004; Quartarone et al., 1999). As all our subjects were right-handed, the variability of the side with the highest threshold confirms that this asymmetry is unlikely to be related to handedness (MacKinnon et al., 2004).

Differences in excitability of ipsilateral projections between sides could reflect an asymmetry in motor cortical control of the abdominal muscles. It is unlikely that this asymmetry is related to use-dependent plasticity with one abdominal muscle activated more than the muscle on the opposite side, as this should also be associated with asymmetry in excitability of contralateral corticospinal projections. Instead, these findings could be interpreted to suggest that activation of the abdominal muscles is controlled through descending contralateral and ipsilateral corticospinal projections from predominantly one hemisphere. Control of the trunk muscles in this manner could be argued to be advantageous for midline muscles as it may simplify coordination of muscles that are commonly activated bilaterally during function. This hypothesis is supported by previous studies that showed greater synchronisation
of motor unit firing between bilateral axial muscles (Carr et al., 1994; Marsden et al., 1999). Motor unit synchronisation has been argued to be mediated by common drive to separate motoneuron pools, and this could be simplified by inputs from a single hemisphere. Bilateral drive to the trunk muscles could also explain the observation that patients with unilateral stroke often have deficits in activation of the trunk muscles on both sides (Dickstein et al., 1999, 2004). However, this observation is complicated by compensatory increases in excitability of descending corticospinal projections from the unaffected motor cortex (Fujitawa et al., 2001). Further work is needed to examine the functional relevance of asymmetrical ipsilateral corticospinal projections.

The results suggest that contralateral and ipsilateral corticospinal projections to the abdominal muscles can be discriminated when stimulation is applied at sites at least 2 cm lateral to the midline. TMS delivered in this manner minimises concurrent excitation of corticospinal projections from the motor cortex contralateral to the side of stimulation.

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