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Research Report

Transcranial magnetic stimulation during voluntary action: Directional facilitation of outputs and relationships to force generation

Didier Cros, Oscar Soto, Keith H. Chiappa*

Clinical Neurophysiology Laboratories, Department of Neurology, Massachusetts General Hospital, 3 Hawthorne Place,
Suite 112 Boston, MA 02114, USA

A R T I C L E I N F O

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A B S T R A C T

Single-pulse transcranial magnetic stimulation (TMS) of the human motor cortex evokes simple muscle jerks whose physiological significance is unclear. Indeed, in subjects performing a motor task, there is uncertainty as to whether TMS-evoked outputs reflect the ongoing behavior or, alternatively, a disrupted motor plan. Considering force direction and magnitude to reflect qualitative and quantitative features of the motor plan respectively, we studied the relationships between voluntary forces and those evoked by TMS. In five healthy adults, we recorded the isometric forces acting a hand joint and the electromyographic activity in the first dorsal interosseous (FDI) muscle. Responses obtained at rest were highly invariant. Evoked responses obtained while subjects generated static and dynamic contractions were highly codirectional with the voluntary forces. Such directional relationships were independent of stimulation intensity, stimulated cortical volume, or magnitude of voluntary force exerted. Dynamic force generation was associated with a marked increase in the magnitude of the evoked force that was linearly related to the rate of force generation. The timing of central conduction was different depending on functional role of the target muscle, as either agonist or joint fixator. These results indicate that the architecture of motor plans remain grossly undisrupted by cortical stimulation applied during voluntary motor behavior. The significant magnitude modulation of responses during dynamic force generation suggests an essential role of the corticospinal system in the specification of force changes. Finally, the corticospinal activation depends on the functional role assumed by the target muscle, either postural or agonist.

1. Introduction

From the outset of brain stimulation techniques, researchers have inquired about the relationships between natural voluntary movements and the outputs evoked by artificial stimulation of the motor cortex. Those relationships may be examined under 2 different approaches, which concern either their magnitudes or their spatial attributes. Net changes in the corticospinal excitability induced by voluntary contractions are easily inferred from changes in the size of the stimulus-evoked responses.

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* *Corresponding author*. Fax: +1 617 720 0055.
E-mail address: dcros@partners.org (D. Cros).

Abbreviations: TMS, transcranial magnetic stimulation; MEP, motor-evoked potential; MVC, maximal voluntary contraction; FDI, first dorsal interosseous; MCP, metacarpophalangeal; IC, index of colinearity

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However, the identification of similarities between natural and artificial outputs, a qualitative approach that requires the analysis of their spatial attributes, may prove technically and conceptually more difficult. Until recently, virtually any stimulation technique applied to the motor cortex has failed in producing outputs that resemble natural movements. Indeed, most early studies using intracortical microstimulation of the primate motor cortex, though extremely useful in mapping body parts, elicit brief twitches of muscles or body parts. While these may represent movement fragments, there are difficulties in establishing a meaningful relationship to natural movement. This fact has supported the idea that cortical stimulation, because of its artificial nature, is disruptive of natural neural processing, a notion that extends to transcranial magnetic stimulation (TMS) (Rothwell et al., 1989; Pascual-Leone et al., 1992; Ziemann et al., 1997). However, recent experiments of intracortical microstimulation in monkeys, using longer trains of stimuli than those previously used, were able to evoke complex movements with high resemblance to natural ones (Graziano et al., 2002). That challenges the notion of a disruptive effect of cortical stimulation techniques in general, and of TMS in particular. For practical and safety reasons, in humans, these

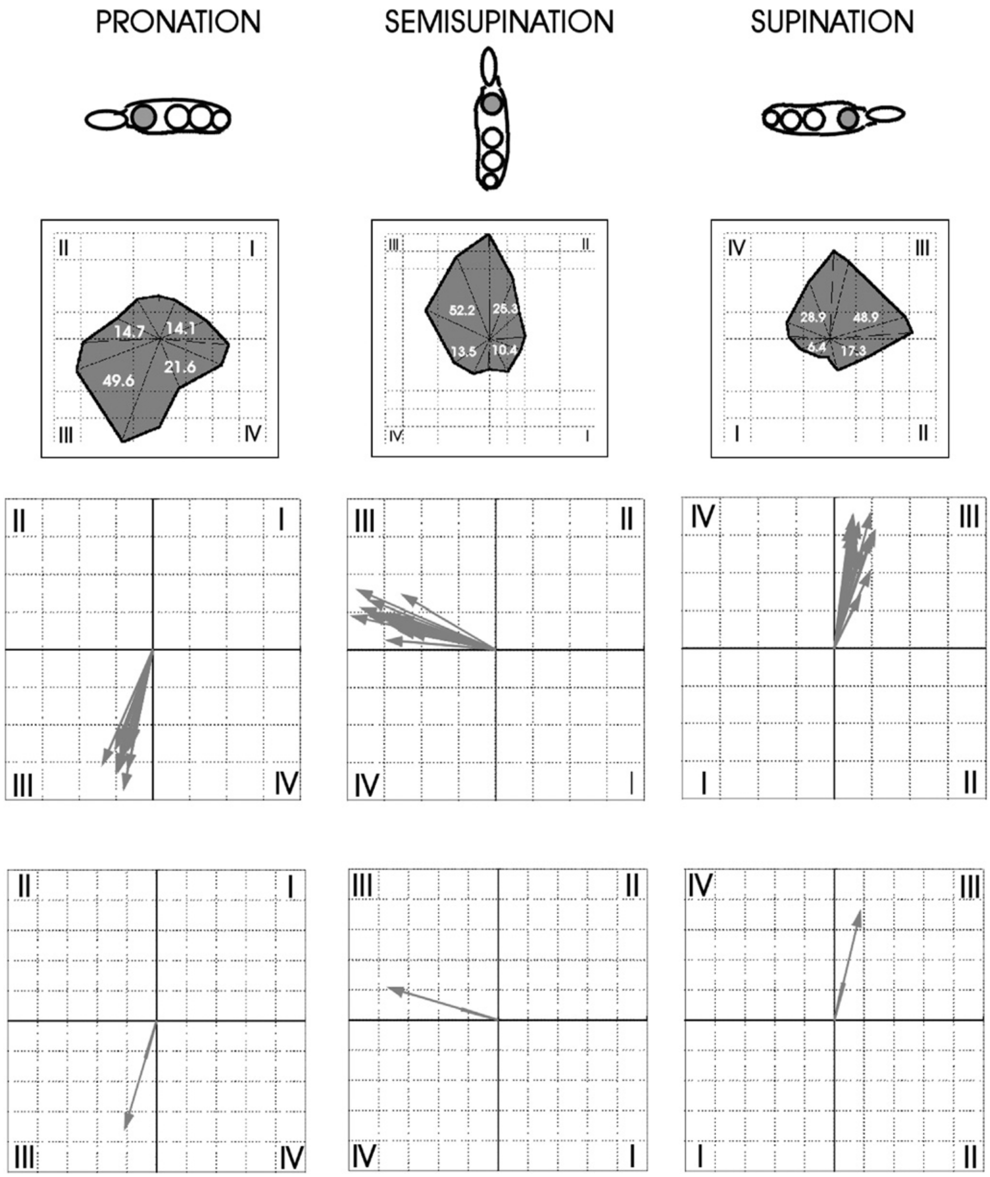

Fig. 1 – No change in the direction of the stimulus-evoked force obtained at rest with different degrees of arm pronation in one subject. On top, a representation of the three hand positions (pronation, semisupination, supination), with the index finger represented as a filled circle. The second row shows the area of the total maximal forces generated at the metacarpophalangeal joint, and displaying the relative contribution of MVC per quadrant to the total MVC (%), 1 division = 5 N. The 2 bottom rows show the stimulus-evoked force vectors obtained at rest [top, individual trials (s_{rest}); bottom, mean vectors (S_{rest})] in each of the hand positions. Note the little variability of the stimulus-evoked force vectors in the 3 positions. It can also be seen that s_{rest} vectors always occur in the quadrant in which the MVC was stronger. Quadrants are labeled in roman numerals, always relative to the plane of the palm. Calibration: 1 division = 1 N.