Effects of transcranial magnetic stimulation of the primary motor cortex on the grip and net forces in the tripod grasp

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Abstract

Transcranial magnetic stimulation (TMS) is a tool of choice to study the functionality of the corticospinal pathway in the intact human. In this study, we used TMS to stimulate the hand area of the primary motor cortex (M1) and measured TMS-evoked forces in a multi-fingered grasp. This short report aims at presenting the experimental setup and some preliminary results. The analysis of the data from one subject suggests that TMS affects differently the grip force (which measures the overall force involved in the grasp) and the net force (which measures the net effect of all contact forces exerted on the object).

1. Introduction

Grasping is a complex motor skill that humans perform with remarkable ease. To date, most studies on the control of the contact forces in the human grasp have focused on the pinch grasp, which involves only the thumb and another finger [1]. In contrast, little is known about the control of contact forces in multi-fingered grasp.

Multi-fingered grasps raise several interesting issues about the manner in which the redundant degrees of freedom of the hand in manipulative actions are controlled [2, 3]. In particular, multi-fingered grasps constrain the direction and magnitude of the contact forces much more loosely than the pinch grasp. It is possible, for example, to vary the internal forces by changing the direction of the contact forces to improve the stability of the grasp without increasing the grip force.

In this report, we provide some preliminary evidence that transcranial magnetic stimulation of the primary motor cortex (M1) affects differently two important characteristics of multi-fingered grasps: the grip force and the net force. The grip force is defined as the sum of the intensities of all contact forces in the plane defined by the contact points while the net force measures the resultant force on the object.

Transcranial Magnetic Stimulation (TMS) is the only technique that allows evaluating the corticospinal pathway functionality in the intact human, from the cortex to the target muscles of the contralateral hemibody.

The technique is based on a brief magnetic pulse which is delivered to the scalp through a coil, and currents induced in the brain may produce excitation or inhibition of superficial cortical neurons: for example, single-pulse TMS applied on the scalp overlying the primary motor cortex (M1) elicits contralateral muscle twitches (called Motor Evoked Potentials, or MEPs) followed by suppression of the voluntary EMG activity (labeled Cortical Silent Period, or CSP), allowing routine evaluations of the excitability and conductivity of corticospinal motor pathways in patients with neurological disorders and on healthy humans for motor control research (see [4,5] for recent reviews).

Indeed, MEPs reflect physiological properties of the corticospinal drive during voluntary [6, 7] or even imagined [8] motor commands. A main limitation of conventional MEPs measurements is, however, the fact that the TMS-evoked EMG activity does not contain any information on the forces produced. One important aim of the current investigation is to compare traditional MEPs characteristics with what we have called "Motor Evoked Forces" (MEFs), as measured by the Grasp Analyzer.

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2. Methods

2.1. Subject

One right-handed 32 years old male subject participated to the study at the moment of the writing of this preliminary report. The subject gave his informed consent to the experimental procedures.

2.2. Experimental setup

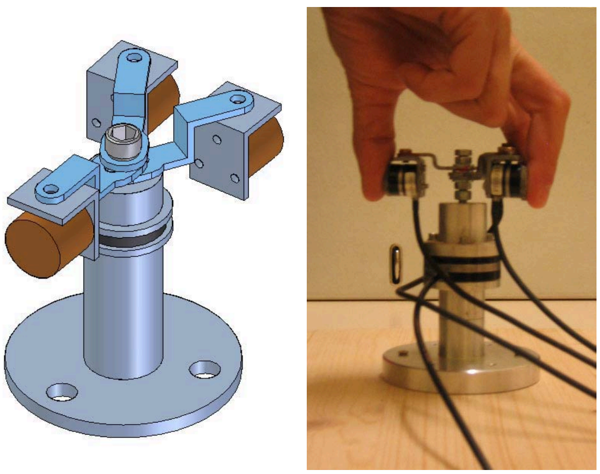

Figure 1. The Grasp Analyzer. Three six DoFs force sensor are mounted the contact surfaces. A fourth one is mounted in the base of the Grasp Analyzer.

2.2.1. The Grasp Analyzer. The main device of the experimental setup is an instrumented object, called Grasp Analyzer that measure the forces and torques at the three contact points during the grasp (Fig. 1). The Grap Analyzer has four six DoFs force/torques (F/T) transducers. The first three F/T transducers (ATI Nano 50, 25 and 12 for the thumb, index and middle finger respectively) are mounted under each contact surface (flat circular vertically oriented contact surfaces with a 16 mm diameter). A fourth F/T sensor (ATI Mini 40) is mounted between the Grasp Analyzer and a fixed base, referred to as the joystick that records the external forces exerted by the hand on the instrumented object. In other terms the joystick F/T sensor measures the net forces generated by the contact forces [9]. The position and orientation of the contact surface can change according to the required grasp or hand configuration required by the experiment.

All the force/torque sensors are connected to the main processing unit via A/D boards (sampling rate was set to 200 Hz). Custom-designed software was used to acquire the data from the force transducers and to visualize the forces and fingertip positions (centers of pressure) on-line.

2.2.2. Transcranial magnetic stimulation (TMS). TMS was carried out with a Magstim Super Rapid machine (maximal output 2 Tesla) connected with an 8-shaped coil. Individual resting excitability thresholds for motor cortex stimulation were firstly determined by measuring the amplitude of motor twitches evoked by single TMS stimuli in the contralateral first interosseous dorsalis muscle. According to International Guidelines [10], motor threshold (MT) was defined as the minimal intensity of the stimulator output capable to evoke a MEP of >50 μV with 50% probability while the target muscle being at rest. The stimulating coil rested tangential to the scalp surface corresponding to the primary motor cortex, with its handle pointing backwards and angled about 45° from the midline. Such position was marked on a strictly adherent bathing cap, so that coil replacement across experimental sessions was accurate.

2.2.3. Motor evoked potentials (MEPs). MEPs were recorded simultaneously, in a standard belly-tendon montage, from three contralateral muscles involved in the grasping task: the right extensor communis digitorum (ECD), the flexor communis digitorum (FCD) and the first interosseous dorsalis (FDI) muscles. Electromyographic signals (from –45 to 155 ms around the TMS instant) were filtered (20 Hz-2 KHz), sampled at 4 KHz and stored for off-line analysis

2.3. Experimental procedure

The participant sat in front of the Grasp Analyzer and extended the right arm toward the device. A cushion supported the weight of the arm and forearm while allowing the hand to hang freely, so that no muscular pre-activation occurred. The position of the Grasp analyzer was adjusted to permit one to grasp it with minimal movements from the relaxed hand position. The participant was instructed to place the fingertips of the thumb, index and middle fingers in the middle of the contact surfaces when grasping the object.

At the beginning of the experimental session, external electrodes were placed on the three aforementioned muscles. The maximum grip force was measured by instructing the subject to squeeze as strongly as possible the object. Then, the motor threshold (MT) was identified as previously described.

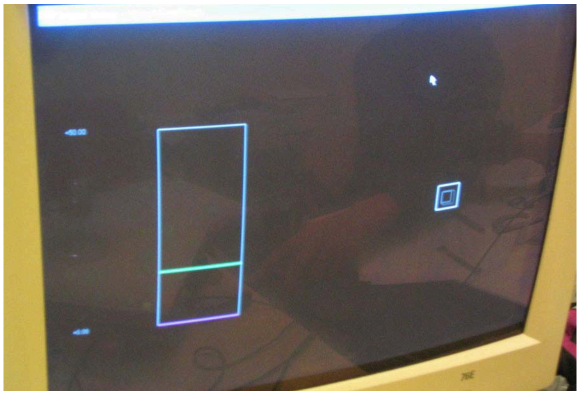

Figure 2. Screen shot of the monitor viewed by the participant during the experiment. The bar (on the right) and the square (on the left) provided visual feedback about the grip and net forces respectively.

2.3.1. The task. The task consisted in controlling the contact forces in order to reach a given magnitude of *grip force*, defined as the sum of the intensities of all the contact forces, and in applying a small vertical force that would lift the object if it were not anchored to the table. A visual feedback was given to the subject to meet the target level of grip and net forces: a horizontal bar indicated the level of grip force while the position, size and orientation of a square depends on the net force produced by the participant (see Fig. 2). At the beginning of each trial, the participant had to use the visual feedback to adjust the grip and net force to match their desired levels. Once both forces had stabilized around their target levels, the force data measured by all four forces transducer were stored in a buffer for 2 seconds. The TMS was automatically triggered after 500ms. The same trigger signal was used to synchronize the force data with the MEPs.

2.3.2 Experimental conditions. Four different intensities of stimulation were applied for each force grip condition, in a random order (12 trials for each condition). Intensities of TMS corresponded to 100%, 111%, 122% and 133% of the individual MT level. The target level of grip force corresponded approximately to 7% 14% 22% and 33% of the maximum grip force. Higher forces were not used in order to avoid both muscular and central fatigue mechanisms due to the required effort along task repetitions.

Preliminary trials indicated that it was easier to maintain the desired level of grip force if a force was applied in the vertical direction at the same time. For this reason, the participant was also required to apply a small upward net force in the vertical that depended on the value of the grip force, while maintaining to zero all other components.

2.4. Data analysis

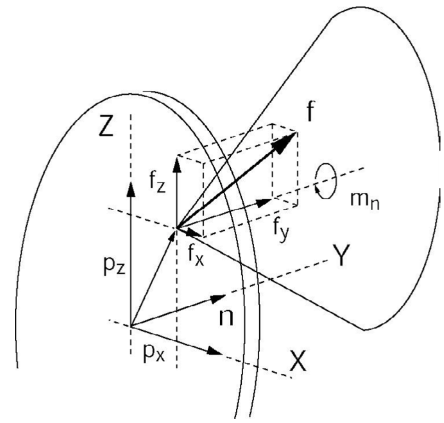

Figure 3. The soft-finger model of the contact forces. The finger applies a force $\boldsymbol{f} = [f_x\ f_y\ f_z]$ and a moment m_n around the direction of the contact surface normal $\boldsymbol{n}$ at the center of pressure (p_x, p_z). By definition, the moments around the X and Z direction are null at the center of pressure. The direction of the contact force must belong to the friction cone to avoid a finger slip.

2.4.1. The contact forces. The mechanical interaction taking place between a finger and the object is best modeled by a force $\boldsymbol{f_i} = [f_x\, f_y\, f_z]$ applied at the center of pressure $\mathbf{r}_i$ and a torque $\boldsymbol{m_i} = [0\ m_n\ 0]$, about the normal $\boldsymbol{n}$ passing through the center of pressure and perpendicular to the surface of the object (the so-called soft-finger model, see Fig. 3). In addition, the contact forces must satisfy the squeezing and frictional constraints. The squeezing constraint

$$\boldsymbol{n}'\boldsymbol{f} \geq 0$$

states that a finger can only push and not pull the contact surface. The frictional constraint

$$\| (I - \boldsymbol{nn}')\boldsymbol{f} \| \leq \mu \boldsymbol{f}'\mathbf{n}$$

states that the contact force must belong to the friction to avoid a finger slip. The aperture angle of the friction cone is

$$\alpha = \tan^{-1}(\mu)$$

where μ is the linear coefficient of friction. The normal torque m_n should also satisfy a similar frictional constraint

$$m_n \leq \mu_{rot}\, \boldsymbol{f}'\boldsymbol{n}$$

where μ_{rot} is the rotational coefficient of friction.

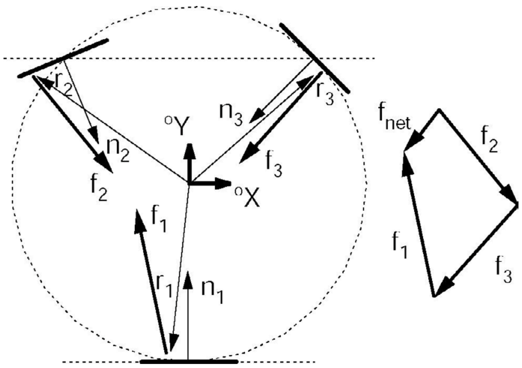

Figure 3. *Left*: Contact forces $\boldsymbol{f}_i$ in the plane defined by the contact points of the tripod grasp. The vectors $\boldsymbol{r}_i$ indicate the position of the contact points on the contact surfaces. *Right*: The net force f_{net} corresponds to the difference between the starting and ending point when the three forces are drawn head-to-tail. The grip force f_{grip} corresponds to the sum of the lengths of three force vectors. When the net force is null, the three contact forces drawn head-to-tail form a triangle and the grip force corresponds to the perimeters of this triangle.

2.4.1. The tripod grasp. In the tripod grasp, the object is grasped by the thumb, index and middle fingers [2]. The net force and moment produced by the contact forces are

$$^0\boldsymbol{f}_{net} = \sum_i {}^0\boldsymbol{f}_i$$

$$^0\boldsymbol{m}_{net} = \sum_i \boldsymbol{r}_i \times {}^0\boldsymbol{f}_i + {}^0\boldsymbol{m}_i$$

where $^0\boldsymbol{f}_i$ and $^0\boldsymbol{m}_i$ are the contact force and moments of the i^{th} digit expressed the object coordinate system system [^{0}X, ^{0}Y, ^{0}Z], and $\boldsymbol{r}_i = [r_{xi}\ r_{yi}\ r_{zi}]$ is the position of the center of pressure relative to center of mass (Fig. 3). In matrix form, the grasp matrix relates the contact forces $F = [\boldsymbol{f}_1\ \boldsymbol{m}_1\ \boldsymbol{f}_2\ \boldsymbol{m}_2\ \boldsymbol{f}_3\ \boldsymbol{m}_3] \in \mathrm{R}^{18}$ to the net force $F_{net} \in \mathrm{R}^6$

$$F_{net} = \begin{bmatrix} \boldsymbol{f}_{net} \\ \boldsymbol{m}_{net} \end{bmatrix} = \left[\begin{array}{cc:c:cc} R_1 & 0 & .. & R_3 & 0 \\ S_1 R_1 & R_1 & .. & S_3 R_3 & R_3 \end{array}\right] \begin{bmatrix} \boldsymbol{f}_1 \\ \boldsymbol{m}_1 \\ \cdots \\ \boldsymbol{f}_3 \\ \boldsymbol{m}_3 \end{bmatrix}$$

$$= GF$$

where the grasp matrix G comprises the skew matrices

$$S_i = \begin{bmatrix} 0 & -r_{zi} & r_{yi} \\ r_{zi} & 0 & -r_{xi} \\ -r_{yi} & r_{xi} & 0 \end{bmatrix}$$

and the rotation matrices $R_i \in SO(3)$ that transform the local coordinate systems associated with each sensor to the object coordinate system and the skew matrices.

In the tripod grasp, specifying the net force F_{net} does not suffice to determine the contact forces F. As matter of fact, the direction and magnitude of the contact can vary while satisfying both the equilibrium conditions

$$F_{net} = G\,\boldsymbol{F}$$

and the frictional and squeezing constraints.

In this study, we used the term *grip force* to designate the sum of the magnitude of the three contact forces in the horizontal plane

$$\sum_i \sqrt{f_{xi}^2 + f_{yi}^2}\ .$$

Intuitively, the grip force represents the level of squeezing used by the participant to grasp the object. We also used the term *net force* to refer to the magnitude of the linear component of the net force F_{net}

$$\sqrt{f_{net_x}^2 + f_{net_y}^2 + f_{net_z}^2}\ .$$

2.4.2. Motor Evoked Forces (MEFs) identification. The presence of MEF in a single trial was detected using the linear components $\boldsymbol{f}_1$, $\boldsymbol{f}_2$ and $\boldsymbol{f}_3$ of the three contact forces. First, we identified the instant in time $t_{df.max}$ at which $\|\delta F/\delta t\|$ (the norm of the time derivative of the vector $F=[\boldsymbol{f}_1\ \boldsymbol{f}_2\ \boldsymbol{f}_3]$) reached its maximum value. Then, we defined the beginning of the MEF, $t_{f.start}$, as the first instant at which this norm reached 1/4 of its maximum value. Finally, we identified the instant $t_{f.peak}$ at which the MEF peaked by finding the largest force difference between t_{TMS}, the moment of the TMS, and any point in time during the trial. A MEF was positively identified only when $t_{f.start} > t_{TMS} + 15$ms and $t_{f.start} < t_{TMS} + 50$ms and $t_{f.peak} - t_{f.start} < 100$ms.

3. Results

The study is still not yet completed and we report only the preliminary analyses of the MEFs for one subject. Table 1 indicates the percentage of trials in which a MEF was detected.

Table 1. Percentage of trials with MEFs

TMS Intensity	Grip Force (N)			
(% of MT)	10	21	33	40
100	17	42	67	42
111	92	100	92	67
122	92	100	100	100
133	100	100	92	100

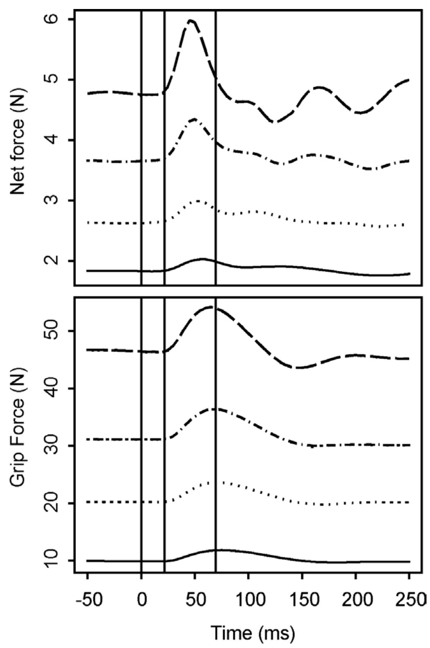

Figure 4. Average MEF for each initial level of grip force: 10N (solid), 21N (dotted), 33N (dash-dot), 50N (dashed). Trials are pooled across TMS intensities. The vertical lines represent the TMS time, the beginning of the MEF and the time of peak MEF (see text).

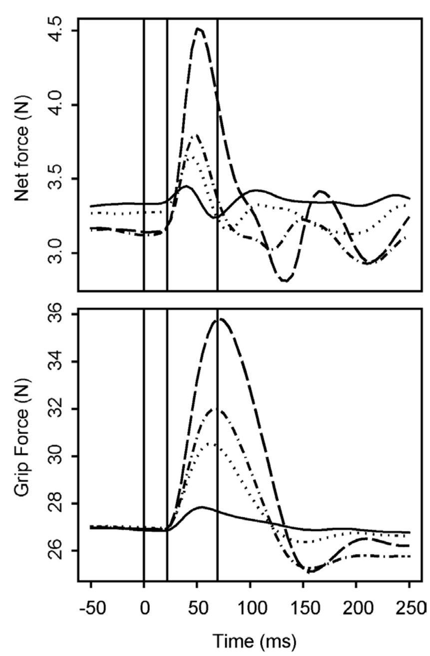

Figure 5. Average MEF for each TMS intensity: 100% (solid), 111% (dotted), 122% (dash-dot), 133% (dashed) of MT. Trials are pooled across initial grip force levels.

In this preliminary report, two indices were analyzed: the grip and net force intensities. Electromyographic data of the simultaneously acquired conventional MEPs are still under investigation.

Figure 4 shows the average MEF for each level of initial grip/net force. At the beginning of the trial, participant was able to use visual feedback to produce the required force level. For both the grip and net force, the amplitude of the MEF increased with the level of excitation as measured by the initial value of grip and net force. The peak of the net force occurred slightly before the peak of the grip force. Figure 5 shows that the size of MEFs also increased with the TMS intensity.

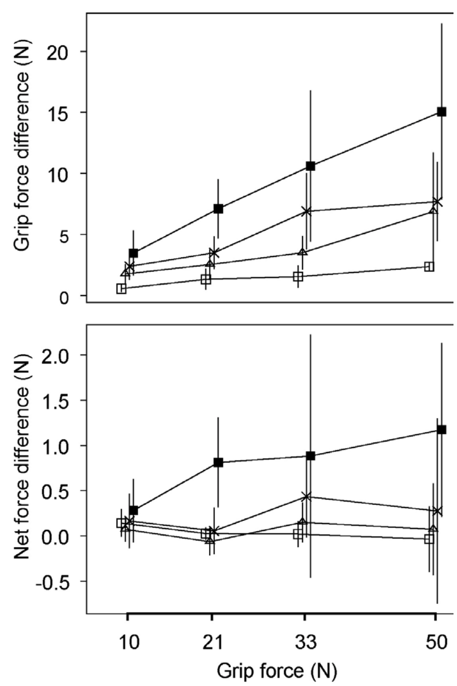

Figure 6. Effect of TMS on the grip and net forces (mean values ± SD). TMS intensity: 100% (empty square), 111% (triangle), 122% (crosses), 133% (solid square).

For each trial in which a MEF could be detected (see Methods), we measured the difference between the grip force at the time of the stimulation (t_{TMS}) and at the time where it peaked t_{fmax}. The top part of Figure 6 shows that grip force scaled with both the initial level of grip force and the level of stimulation. Statistical analysis revealed that both factors and the interaction were statistically significant (P<.01, two-ways ANOVAs; see Table 2).

The bottom part shows a non-linear pattern where only the highest level of TMS seemed to produce a change in the net force. The absence of any statistical effect on the net force when this level of stimulation was removed from the dataset confirmed observation (see Table 2).

Table 2. Statistical analysis results*

Factor	DF	SS	F	P
Net Force				
TMS	3	14.63	13.52	.00
GRIP	3	1.06	0.98	.40
TMS:GRIP	9	3.65	1.12	.35
Residuals	140	50.50		
Net Force (without the highest TMS level)				
TMS	2	0.84	2.20	.12
GRIP	3	0.53	0.92	.43
TMS:GRIP	6	0.43	0.37	.90
Residuals	97	18.58		
Grip Force				
TMS	3	1081.42	360.47	.00
GRIP	3	992.60	330.86	.00
TMS:GRIP	9	258.77	28.75	.01
Residuals	140	1506.03		

*: two-way ANOVAs, type III sum-of-squares.

4. Discussion

The main novel finding of the current investigation is that it is possible to measure complex “motor evoked forces” - such as the ones involved in human grasping - following an external activation of the primary motor cortex. Previous studies measuring relationships between TMS MEPs and twitch force were limited to a single muscle driving a single movement.

This preliminary analysis indicates that the TMS had a different effect on the grip and net components of the MEFs. This result suggests that the grip and net forces might be governed by different neurophysiological mechanisms within the primary motor cortex, the latter being more immune to the external “interference” of the TMS, at least for TMS intensities slightly above MT. In other terms, the effect of the TMS on the net force might be limited by a synergy that would channel the interference into an increase of the self-balanced or internal forces of the grasp. This result shows the potential of the TMS and the MEFs to study the neuro-physiological processes underlying the functional synergies involved in a complex motor skill such as grasping.

Future analysis on additional subjects should be directed to investigate on other aspects of the MEFs such as the direction of the contact forces, the temporal dynamics of the MEFs, and the relationships with TMS-related excitatory (MEPs) and inhibitory (CSP) phenomena.

5. References

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