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Research Report

Dynamic changes in corticospinal control of precision grip during wrist movements

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ABSTRACT

This work tested the physiological basis underlying the control of a proximo-distal muscle coordination. Using transcranial magnetic stimulation (TMS) of the hand territory within the primary motor cortex (M1), we examined whether the corticospinal excitability of the first dorsal interosseus muscle (FDI, index abductor), engaged in a precision grip, was altered during wrist movements. To this end, 12 seated subjects maintained a pinch between the right index finger and the thumb and FDI motor evoked potentials (MEPs) were elicited under four conditions: (1) during active and (2) passive cyclic wrist flexion/extension, (3) in three positions of static wrist flexion and extension, respectively, and (4) at three levels of isometric force of wrist flexors (FCR) and extensors (ECR) respectively. FDI MEPs were normalized relative to the MEP/EMG linear relationship. They were facilitated during wrist flexion in the active and the passive conditions and this did not depend on FDI background EMG. Interestingly, the occurrence of the most facilitated FDI MEPs was correlated only with the peak of FCR activity. Also, the duration of the post-MEP silent periods normalized to FDI MEP amplitudes was shorter during wrist flexion compared to extension. We discussed the extent to which the dynamic influence of wrist flexion on FDI corticospinal excitability reflects the existence of a proximo-distal synergy between wrist flexion and precision grip and whether this synergy relies on the phase-dependent recruitment of common M1 networks between FCR and FDI muscles and on the salience of proprioceptive afferents from wrist muscles.

1. Introduction

The tendency of hand and wrist muscles to be activated in synergy reflects the inherent process of the brain to restrict the output of the motor system and facilitate the control of complex interjoint movements (Welsh and Llinas, 1997). Controlling the different limb segments as a whole rather than individually (Scott, 2000) thus ensures muscle coordination between the fingers and hand. Writing, pinching or bringing a cup of tea to the mouth represent tasks of manual dexterity that depend on the tuned control of wrist and arm position, thus involving both distal and proximal joints (Kalaska et al., 1997). Because slippage of a held object must be prevented, high-level mechanisms of control were thought to be involved in the adaptation of the coupling between the pinch force and load changes at fingertip when proximal joints (wrist, shoulder) were moved (Flanagan et al., 1993; Flanagan and Wing, 1995; Westling and Johansson, 1984). Furthermore, Rouiller et al. (1998) showed in monkeys that the proximo-distal coordinated activity of wrist and fingers during

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prehension relies on the integrity of the primary motor cortex (M1). Indeed, a fraction of monkeys subjected to a lesion of M1 at an early age presented a remaining deficit in the "synergy of the combined hand orientation with the precision grip" for removing food pellets lodged in a well drilled into a horizontal surface, whereas they succeeded on a vertical surface. The present study further questioned in humans the extent to which the functional organization of M1 contributes to the fine motor control of precision grip during movements at the wrist joint.

It is suggested from studies in animals that the spatial distribution and connection of M1 elements may favor the existence of cortico-cortical networks able to coordinate the recruitment of muscles acting into an interjoint muscle synergy. Intracortical microstimulation and recording experiments have shown that multiple widespread M1 representations of distal upper limb muscles are partly encircled by representations of proximal muscles (Park et al., 2001; Schneider et al., 2001). Experiments combining microstimulation at one site and the injection of a GABA antagonist to induce intracortical disinhibition at a remote site have shown that M1 regions controlling muscles acting at different joints are synaptically connected (Schneider et al., 2002). Also, the existence of long-distance horizontal synaptic connections is supported by neural tracing studies that revealed the presence of large M1 axonal collaterals of up to 3 mm in length in animals (Huntley and Jones, 1991; Landry et al., 1980) and 10 mm in humans (Wangenheim et al., 2002).

In humans, the physiological basis of a proximo-distal muscle synergy was addressed using transcranial magnetic stimulation (TMS) of M1 during a static pointing task (Devanne et al., 2002) and for static and passive positions of the shoulder joint with distal hand and forearm muscles at rest (Ginanneschi et al., 2005; Ginanneschi et al., 2006). Devanne et al. (2002) showed that the motor evoked potentials (MEPs) of the extensor carpi radialis (ECR) increased in amplitude only when shoulder elevators were activated to support the pointing arm compared to the harness-held arm; they proposed that activation of shoulder, elbow and wrist muscles in static pointing tasks involved "common motor cortical circuits" acting into a proximo-distal synergy. Ginanneschi et al. (2005) showed that MEPs of intrinsic hand (abductor digiti minimi, ADM) and ECR muscles were facilitated at 30° shoulder adduction, whereas MEPs of FCR (flexor carpi radialis) were facilitated at 30° shoulder abduction; they proposed that such changes in corticospinal excitability as a function of shoulder position were coherent with the existence of a proximo-distal synergy operating throughout reach-to-grasp tasks. Using the same protocol, Dominici et al. (2005) found that, contrary to ADM, activation of FDI (index finger abductor), whether by TMS or by volition, was not influenced by shoulder position, likely due to a different role in hand function, since the FDI muscle is not engaged in the pre-shaping phase of hand aperture in reach-to-grasp tasks. These TMS studies have provided relevant information on the neural substrates of M1 for synergies and on the influence of afferents from proximal joints on the corticospinal excitability of distal muscles; however, TMS data were obtained during static tasks and the functional organization of M1 for proximo-distal synergies needs to be tested during actual interjoint movements.

Using TMS of FDI M1 representation, we examined in the present study whether the corticospinal excitability of FDI engaged in a precision grip task between the thumb and index finger (distal muscle) could be dynamically influenced by cyclic movements of wrist flexion and extension (proximal muscles). We hypothesized that wrist flexion (compared to extension) should induce an increase in FDI corticospinal excitability. First, wrist flexion is required with precision grip to bring objects closer to the body (as for eating) and biomechanical constraints associated with wrist flexion increase FDI activity (Werremeyer and Cole, 1997) thus reflecting a plausible adaptation of the precision grip command. Second, the hand/wrist synergy we propose for bringing back objects, that consequently links FCR and FDI muscles, is opposite to the synergy proposed in Ginanneschi et al.'s data (2005, 2006) for reaching tasks that link corticospinal excitability of ECR and ADM muscles.

Variations of FDI EMG activity during wrist movement and the influence of static and dynamic wrist afferents and muscle activity on M1 excitability (Asanuma and Rosen, 1972; Lemon and Porter, 1976) were specifically addressed (1) using FDI MEP normalization relative to background FDI EMG and (2) by testing precision grip during passive wrist movements, in different static wrist positions and at different levels of isometric contraction of wrist muscles. Determining whether or not precision grip during wrist flexion is a proximo-distal synergy embedded in M1 circuits is of major importance in stroke rehabilitation to understand whether lesion-induced alteration of wrist control contributes to the severe impairments observed in prehension tasks. A portion of this work has appeared in abstract form (Gagné and Schneider, 2002).

2. Results

2.1. Input/output curves and increase of FDI MEP amplitude with EMG background

Fig. 1A presents the FDI input/output curve of one subject and the TMS intensity chosen (1.14 times the active motor threshold, AMT). Across subjects, TMS intensity was set at 30.7% (S.D. = 6.6%) of the maximal stimulator output (MSO) and this corresponded to 1.26 times the AMT (S.D. = 0.11). Fig. 1B illustrates the increase of FDI MEP amplitude with background EMG for one subject in the control condition (precision grip alone with the hand in the neutral position). For all subjects, the correlation coefficient (r^2) of the linear regression ranged from 0.73 to 0.99 (mean = 0.91, S.D. = 0.08). From Eq. (1) in the Data reduction under the Experimental procedures section, $MEP_{expected}$ (amplitude = m[EMG background] + b) was calculated and the ratio $MEP_{obtained}/MEP_{expected}$ computed for each MEP recorded. The values of m and b correspond to 0.05 and −0.66 respectively for the data presented in Fig. 1B.

2.2. Motor and kinematical patterns

Typical raw traces of FCR, ECR and FDI EMG activity (mean of 10 cycles) collected under non-stimulated conditions are presented in Fig. 2 along with the electrogoniometric trace of