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Corticomotor excitability of arm muscles modulates according to static position and orientation of the upper limb

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HIGHLIGHTS

- Multi-joint changes in static, functionally relevant upper limb posture altered the overall corticomotor excitability of the resting target muscles.
- Forearm orientation impacted the overall excitability of both target muscles, but in a more robust manner for the muscle whose length was mechanically altered by forearm posture.
- Posture-mediated changes in overall corticomotor excitability are not likely predominated by variables related to target muscle length alone, particularly for muscles crossing multiple joints.

ABSTRACT

Objective: We investigated how multi-joint changes in static upper limb posture impact the corticomotor excitability of the posterior deltoid (PD) and biceps brachii (BIC), and evaluated whether postural variations in excitability related directly to changes in target muscle length.
Methods: The amplitude of individual motor evoked potentials (MEPs) was evaluated in each of thirteen different static postures. Four functional postures were investigated that varied in shoulder and elbow angle, while the forearm was positioned in each of three orientations. Posture-related changes in muscle lengths were assessed using a biomechanical arm model. Additionally, M-waves were evoked in the BIC in each of three forearm orientations to assess the impact of posture on recorded signal characteristics.
Results: BIC-MEP amplitudes were altered by shoulder and elbow posture, and demonstrated robust changes according to forearm orientation. Observed changes in BIC-MEP amplitudes exceeded those of the M-waves. PD-MEP amplitudes changed predominantly with shoulder posture, but were not completely independent of influence from forearm orientation.
Conclusions: Results provide evidence that overall corticomotor excitability can be modulated according to multi-joint upper limb posture.
Significance: The ability to alter motor pathway excitability using static limb posture suggests the importance of posture selection during rehabilitation aimed at retraining individual muscle recruitment and/or overall coordination patterns.

1. Introduction

Re-educating muscles and learning to control an impaired limb is a common challenge following neurological impairment. Reduced or paralyzed function of the upper limb can dramatically

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encumber one's ability to perform common activities of daily living, and thus functional independence. Under certain circumstances, lost function can be surgically restored by transferring the distal tendon of a non-paralyzed muscle to that of a paralyzed muscle (i.e., tendon transfer). One such procedure involves the restoration of active elbow extension following triceps (TRI) paralysis, which involves transfer of either the posterior deltoid (PD) or biceps brachii (BIC) muscle to the distal tendon of the triceps (Leclercq et al., 2008; Mulcahey et al., 2003). In either case, individuals must learn to recruit the transferred muscle to actuate its new function. Successful training of each muscle as an elbow extensor has been reported, with some evidence that elbow extension against gravity (i.e., overhead) is less successful following PD-TRI transfer (Mulcahey et al., 2003). Mechanical differences exist between the BIC and PD based on musculoskeletal anatomy and muscle architecture (Holzbaur et al., 2005; Langenderfer et al., 2004); however, differences in the ability to voluntarily activate these two muscles during functional tasks (e.g., Johanson et al., 2006, 2011) might also contribute to disparities in performance.

Because the amplitudes of the motor evoked potentials (MEPs) elicited by transcranial magnetic stimulation (TMS) change with joint posture, it has been suggested that limb posture modulates the overall functional state (or excitability) of a motor pathway (i.e., how accessible a muscle is by the motor cortex). For example, changes in the excitability of hand and forearm muscles have been reported to result from static changes in shoulder position (Dominici et al., 2005; Ginanneschi et al., 2005, 2006). Since none of the hand or forearm muscles cross the shoulder joint complex, the authors hypothesized that joint posture modulates excitability according to how relevant the overall limb position is to a particular muscle's function. Other studies have demonstrated that, when a target muscle crosses the joint of interest, MEP amplitudes tend to increase at joint angles that place the muscle at shorter lengths (Lackner and Hummelsheim, 2003; Lewis et al., 2001; Mitsuhashi et al., 2007; Renner et al., 2006). Such results have also been interpreted as posture-dependent changes in corticomotor excitability, and have been used to suggest that a target muscle's length helps to shape its accessibility by the motor cortex.

The hypothesis that muscle length influences corticomotor excitability has not been tested explicitly. Rather it has only been inferred from experiments of a limited scope. Specifically, these experiments have involved a change in position of only a single joint, resulting in a tight coupling between muscle length and joint position. This is problematic since functional behaviors, such as activities of daily living, often involve postural changes at multiple joints. Moreover, because many upper limb muscles (including BIC, for example) cross more than a single joint, muscle length is not always uniquely defined. Thus, how different multi-joint upper limb postures that are adopted during functional use of the hand and arm relate to muscle length is not always intuitive. To complicate matters, apparent length-mediated changes in MEP amplitude parallel length-dependent changes in EMG signal amplitude (Frigon et al., 2007; Hashimoto et al., 1994; Lateva et al., 1996). As such, a strong relationship between posture-dependent changes in muscle length and MEP amplitude could simply reflect electrophysiological changes at the muscle level, rather than central modulation of overall excitability.

The principal aim of the current study was to investigate the effects of multi-joint changes in static upper limb posture on the overall corticomotor excitability of the PD (a muscle that crosses only the shoulder) and BIC (a multi-articular muscle) in healthy, non-impaired individuals. We evaluated the hypothesis that muscle length influences corticomotor excitability, postulating that MEP amplitudes of both muscles would vary with posture, such that the response amplitudes would increase as the target muscles were placed at shorter lengths. To accomplish this, we (1) measured MEP amplitudes in both the BIC and PD in four functionally relevant static upper limb postures, and (2) used a biomechanical model to assess the degree to which changes in target muscle length alone could describe the posture-dependent variations in MEP amplitude. Additionally, we conducted a control experiment, using nerve stimulation to assess the effect of forearm orientation on M-wave amplitude in the BIC, to determine whether muscle electrophysiology alone dictates the recorded changes in MEP amplitude. We chose to focus on the PD and BIC based on our specific interests in tendon transfer surgeries. Consequently, the upper limb postures were selected based on the restoration of voluntary function following cervical spinal cord injury (SCI), and varied in shoulder and elbow angle. In addition, three different forearm orientations were investigated within each functional posture. Since isolated changes in forearm orientation have been reported to modulate MEP amplitude in muscles crossing, and distal to, the elbow (Mitsuhashi et al., 2007), we wanted to evaluate whether forearm orientation has a robust effect in modifying MEP amplitude (and excitability) throughout the workspace.

2. Methods

2.1. Subjects

Twelve healthy subjects, aged 23–35 years (three females and nine males; mean age 26.5 ± 3.3 years), were recruited for this study. Subjects had no neurological impairment or injury to the upper limb. The relationship between corticomotor excitability and arm posture was evaluated in the dominant arm, as self-identified by each subject. All subjects gave their written informed consent to participate in this study and were free to withdraw at any time. The experimental protocol was approved by the Northwestern University Institutional Review Board in accordance with the Declaration of Helsinki.

2.2. Transcranial magnetic stimulation

Responses evoked via the corticospinal pathways projecting to proximal upper limb muscles were assessed using TMS delivered when the muscles were at rest. Single-pulse TMS was delivered to the contralateral motor cortex using a Magstim 200 stimulator (Magstim, Dyfed, Wales, UK) via a 70 mm figure-of-eight coil. The coil was placed tangentially on the scalp with the handle rotated $\sim 45°$ from the midline to induce a posterior-to-anterior cortical current. A single stimulation site, located where the largest peak-to-peak amplitude MEP was evoked in BIC using the lowest stimulation intensity, was marked on the cap and was the coil location used for all subsequent stimulation. The stimulus intensity for experimental trials was set at 120% of the resting threshold (RTh) for the BIC, which was determined with the limb hanging relaxed by the side, and was defined as the stimulus intensity that induced MEPs of $\leqslant 50\ \mu V$ in no more than 5 of 10 consecutive stimuli. Changes in corticospinal excitability were quantified in both BIC and PD simultaneously by the changes in MEP amplitudes across the thirteen postures investigated. During experimental trials, the stimulator was triggered to deliver 20 stimuli at a rate of 0.2 Hz, and the trigger pulses recorded using Spike2 software (Cambridge Electronic Design, Cambridge, UK). The coil position and orientation were maintained manually throughout each trial.

2.3. Electromyography

Surface electromyography (EMG) was used to monitor muscle activity prior to each stimulus event and to record the TMS-induced responses in the target muscles of interest. Recording sites