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Measurement of voluntary activation of the back muscles using transcranial magnetic stimulation

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Objective: Twitch interpolation using transcranial magnetic stimulation (TMS) has recently been used to measure the level of drive from the motor cortex to contracting muscles of the upper and lower limbs, termed voluntary activation. It has yet to be used to assess voluntary activation in trunk muscles. The aim of this study was to assess the feasibility of using TMS to measure voluntary activation in back muscles.

Methods: Sixteen healthy subjects performed a series of brief maximal and submaximal isometric contractions of the back extensors during which TMS was delivered to the motor cortex. The evoked (superimposed) twitch was measured using dynamometry and simultaneous surface electromyographic (EMG) recordings were taken from the left and right erector spinae at vertebral level T12. Voluntary activation was derived using the expression: (1-superimposed twitch amplitude/resting twitch amplitude) $\times$ 100. The resting twitch amplitude was estimated by extrapolation of the linear correlation between voluntary torque and superimposed twitch amplitude to zero torque.

Results: The relationship between superimposed twitch size and voluntary contraction strength for contraction strengths of 50–100% MVC was linear but regression revealed variability between subjects. When data were included from those subjects with a good linear regression fit a strong linear relationship was found for the group means between voluntary contraction strength and voluntary activation ($r^2 = 1$) and superimposed twitch size ($r^2 = 0.99$) for contraction strengths of 50–100% MVC. Voluntary activation was found to be less than maximal (67.71 ± 5.22%) during maximal efforts. Time-to-peak amplitude decreased linearly with increasing voluntary torque. The amplitudes of the motor evoked potentials (MEPs) increased with increasing voluntary torque.

Conclusions: Twitch interpolation using TMS can be used to quantify voluntary activation in back extensors. The results of this study reveal that neural drive to the back extensors during strong contractions is submaximal.

Significance: The assessment of voluntary activation of the back muscles may aid our understanding of the mechanisms of alteration in control of these muscles implicated in chronic low back pain.

1. Introduction

Voluntary activation is defined as the level of neural drive to a muscle during exercise (Gandevia et al., 1995) and it is frequently estimated using the twitch interpolation method (Denny-Brown, 1928; Merton, 1954), where a supramaximal electrical stimulus is delivered to the motor nerve during an isometric voluntary contraction. Voluntary activation can be subsequently calculated by expressing the amplitude of the twitch evoked in the contracting muscle to that evoked by the same stimulus in the relaxed muscle (Herbert and Gandevia, 1999). As the force of voluntary contraction increases, the amplitude of the superimposed twitch decreases (Allen et al., 1998; Belanger and McComas, 1981; Herbert and Gandevia, 1999; Merton, 1954). Even during maximal voluntary contractions (MVC), the stimulus can sometimes evoke further increases in force (Belanger and McComas, 1981; Hales and Gandevia, 1988; Herbert and Gandevia, 1999), suggesting that voluntary activation of the muscle was submaximal (Belanger and McComas, 1981; Merton, 1954; Herbert and Gandevia, 1999).

The multisegmental nature of the innervation of the back muscles, coupled with the difficulties with which these nerves can be accessed, precludes the use of electrical stimulation for the purposes of measuring voluntary activation. Transcranial magnetic stimulation (TMS) circumvents this problem by applying stimulation to

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the motor cortex. TMS has been used successfully to assess voluntary activation in other muscles (Lee et al., 2008; Ross et al., 2007; Sogaard et al., 2006; Taylor et al., 1996; Taylor and Gandevia, 2001; Taylor et al., 2006; Todd et al., 2003; Todd et al., 2004b), but its quantification requires an estimation of resting twitch amplitude rather than a direct measurement. The motor neuronal output in response to a cortical stimulus is less at rest than during a contraction since the excitability of the corticospinal system increases with activity (Hess et al., 1987; Ugawa et al., 1995) and makes the normalisation of the superimposed twitch, to that evoked at rest, inappropriate.

If voluntary activation could be feasibly measured in the back muscles, it could be used to further our understanding of how back muscle physiology is altered in sufferers of chronic low back pain. Changes in strength (Lee et al., 1999; Panjabi et al., 1989; Rissanen et al., 1995; Roy et al., 1990), activity (Flor et al., 1983; Hodges and Richardson, 1999; Radebold et al., 2000; Sihvonen et al., 1997), fatiguability (Biering-Sorensen, 1984; Mannion et al., 1998), endurance (Alaranta et al., 1995; Holmstrom et al., 1992; Jorgensen and Nicolaisen, 1986) and motor control (Radebold et al., 2000; Strutton et al., 2005) have all been implicated as mechanisms in the pathogenesis of chronic low back pain.

2. Materials and methods

The study consisted of a series of experiments to assess voluntary activation of the back muscles. Brief contractions of varying torque were performed and simultaneous surface electromyographic (EMG) activity was recorded from the erector spinae (ES) muscles and, in some subjects, from the rectus abdominis (RA) muscles to assess the activation of RA during back extension.

2.1. Subjects

With local ethical approval and written informed consent 16 healthy subjects (11 males and 5 females, mean (±SEM) age 24.1 ± 1.1 years, range 21–37) were recruited into this study.

2.2. Torque recordings

Back extensor torque was measured using a Cybex Norm Isokinetic Testing System (Henley Healthcare, USA) with an extendable input arm. The output from the Cybex was sampled at 4 kHz by a data acquisition interface (1401 plus and Spike2 software; Cambridge Electronic Design, UK) connected to a personal computer.

2.3. Electromyographic (EMG) recordings

Bilateral EMG recordings were obtained from the ES muscles at vertebral level T12 and, in a subpopulation ($n = 6$) of subjects, from RA. Pairs of Ag/AgCl EMG electrodes (self-adhesive, ARBO blue, 2 cm diameter, Henleys Medical, UK) were positioned 3 cm either side of the spinous process at the T12 level in line with the orientation of the muscle fibres for ES and 3 cm lateral to the linea alba at the level of the umbilicus in line with the orientation of the muscle fibres for RA. The EMG signals were band-pass filtered (100 Hz–2 kHz) and amplified (×10,000; Iso-DAM, WPI, UK) before being sampled at 4 kHz by a data acquisition interface (1401 plus and Spike2 software; Cambridge Electronic Design, UK) connected to a personal computer for subsequent offline analysis.

2.4. Transcranial magnetic stimulation (TMS)

TMS was applied to the motor cortex using a Magstim 200 stimulator (The Magstim Company Ltd., Dyfed, UK) connected to an angled double cone coil (wing outer diameter 12.5 cm), which was positioned with its cross-over located over the vertex with the induced current in the brain flowing in a posterior-to-anterior direction.

Threshold to TMS was determined when the subject was lying prone and maintaining a weak contraction (∼10% MVC). It was defined as the lowest stimulus intensity which produced identifiable MEPs in the ES in half of stimulus presentations. Subsequent experimental trials were conducted using a stimulus intensity of 1.2 times this threshold value to ensure adequate physiological response to stimulation (Mills and Nithi, 1997).

2.5. Protocol

Subjects were positioned prone on the dynamometer bench, with their legs and hips strapped securely to help isolate back muscle movements only (see Fig. 1A). The iliac crests were aligned with the pivot of the dynamometer lever arm.

Subjects performed three brief MVCs (approximately 2 s each) and the mean of the three peak torque values was taken as the control MVC. Target torque indicator lines, calculated from the control MVC, were positioned at submaximal levels (90, 75, 50 and 25% MVC) on the computer screen to provide the subjects with visual feedback.

Subjects performed six sets of five contractions. Each set started with one MVC, which was followed by a randomised sequence of 90, 75, 50 and 25% MVC (see Fig. 1B). Each contraction was held for approximately 2 s, or until the correct level had been reached and held stable, at which point TMS was delivered. Consistent verbal encouragement was provided to ensure the required contraction strength was maintained throughout. Approximately 4 s rest was taken between contractions and 2 min between sets to minimise fatigue.

In a subpopulation of subjects, EMG activity was additionally recorded from RA. The purpose of this was to determine whether the trunk flexors were activated with TMS during back extension, which could potentially reduce the TMS-evoked extensor twitch. Subjects were instructed to remain relaxed whilst six single TMS pulses were delivered to the motor cortex. Subsequently, subjects were instructed to maintain a contraction of the back extensors to 50% MVC, during which six single TMS pulses were delivered to the motor cortex.

2.6. Data analysis

Twitches were identified visually with respect to the TMS event. The amplitudes were calculated by subtracting the mean pre-stimulus torque level (from 25 to 5 ms prior to the TMS event) from the maximum torque level obtained during the twitch. The time-to-peak amplitudes of the twitches with respect to the stimulus were also obtained. In order to calculate the voluntary activation, the resting twitch amplitude was first estimated. It has previously been reported that the amplitude of the TMS-evoked superimposed twitch decreases linearly with increasing voluntary torque for contractions of 50% MVC or greater (Todd et al., 2003) and this study utilises this methodology. For each subject linear regression was used to estimate the resting twitch amplitude, which was taken as the *y*-intercept on a line of best fit of voluntary torque against superimposed twitch amplitude for all twitches produced in response to TMS for contractions of 50, 75, 90% and MVC (see Fig. 2B). The amplitude of the twitch was expressed as a fraction of the resting twitch amplitude and voluntary activation was then calculated as a percentage: (1-superimposed twitch amplitude/resting twitch amplitude) × 100.