Transcranial magnetic stimulation during resistance training of the tibialis anterior muscle

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Abstract

During the first few weeks of resistance training, maximal voluntary contraction (MVC) force increases at a faster rate than can be accounted for by increases in protein synthesis. This early increase in MVC force has been attributed to neural mechanisms but the sources have not been identified. The purpose of this study was to measure changes in cortical excitability with transcranial magnetic stimulation during 4 weeks of resistance training of the tibialis anterior muscle. Ten individuals performed 6 sets of 10 MVCs 3 times per week for 4 weeks and ten participated as a control group. There were no changes in any parameters tested in the control group over the 4 weeks. In the training group, TA muscle strength increased significantly by 10% at week 2 and by 18% at week 4. As hypothesized, cortical excitability during resistance training also increased. The amplitude of the TA surface EMG motor evoked potential elicited by TMS during a low-level contraction increased by 32% after training with no change in the M-wave. These data indicate that there may be an increase in cortical excitability during the first few weeks of resistance training of the TA muscle.

Keywords: Neural adaptations; Strength training; Motor evoked potentials

1. Introduction

During the first few weeks of resistance training, maximal voluntary contraction (MVC) force increases by 10–35% [for review see Griffin and Cafarelli, 2005]. This increase in MVC force cannot be accounted for by increases in muscle protein synthesis alone. Thus it has been proposed that there must also be changes within the central nervous system (CNS) that increase maximal force output (De Lorme and Watkins, 1951; Moritani and DeVries, 1979). Neural adaptations to resistance training have been identified as increases in initial motor unit firing rates (Keen et al., 1994; van Cutsem et al., 1998), reductions in motor unit recruitment thresholds (Keen et al., 1994; van Cutsem et al., 1998), increases in maximal surface EMG area (e.g., Komi et al., 1978; Hakkinen et al., 2000; Pucci et al., in press) and decreases in agonist-antagonist coactivation (Carolan and Cafarelli, 1992; Hakkinen et al., 1998, 2000). In these studies, resistance training involved several weeks of isometric or dynamic exercise that induced an increase in isometric MVC force output. Many of the observed ‘neural adaptations’ to resistance training are indicative of an increase in the excitability of upper or lower motoneurons as an adaptation to resistance training. Thus it is possible that just as an individual modifies motor programs to learn a new skill, one may also ‘learn’ to increase maximal muscle force output. This type of learning may be different than modifying a motor program to learn a new skill. Nonetheless it is quite possible that there would be an increase in the excitability of the motor areas of the cortex to allow for greater and faster command to the lower motoneuron pool following resistance training.

Transcranial magnetic stimulation (TMS) was first developed by Barker et al. (1985) and involves the painless application of magnetic stimulation to the cortex. TMS is thought to activate neurons presynaptic to the primary motor cortex (Day et al., 1987) and has been
used extensively as a technique to map changes in the excitability of the human motor cortex under a variety of conditions, including hand motor tasks (Abbruzzese et al., 1994; Datta et al., 1989; Nielsen et al., 1993) postural control (Lavoie et al., 1995), neuromuscular fatigue (c.f. Taylor and Gandevia, 2001), limb immobilization (Liepert et al., 1997), spinal cord injury (Topka et al., 1991) and limb amputation (Hall et al., 1990; Cohen et al., 1991). In general, these studies have shown that motor evoked potential (MEP) amplitude increases with activity and decreases with disuse and fatigue.

TMS is commonly used as an independent measure to demonstrate that an increase in cortical excitability occurs during repetitive contractions (Grafton et al., 1992; Bonato et al., 1996; Iacoboni et al., 1996; Ljubisavljevic et al., 1996; Sacco et al., 1997; Samii et al., 1996, 1997; Aranyi et al., 1998; Shadmehr and Holcomb, 1997; Tinazzi and Zanette, 1998; van Mier et al., 1998; Caramia et al., 2000). Methods of investigation typically involve stimulation using multiple stimulator intensities during rest or a low-level (5–10% MVC) baseline contraction or, alternatively, using one stimulation intensity (usually 20–30% above threshold) at multiple levels of muscle contraction. Threshold is typically defined as the percent maximal stimulator intensity that elicits MEPs on 50% of the trials. Both the MEP amplitude – stimulator intensity and the MEP amplitude – background muscle contraction level plots produce sigmoidal distributions. The most sensitive ranges of these distributions is at approximately 20% above excitability threshold and at a baseline contraction of 10% MVC (Devanne et al., 1997; Han et al., 2001). Thus, these were the parameters selected for the present investigation.

To date, only two studies have investigated how cortical excitability may adapt to isometric resistance training in humans and both involved muscles of the upper extremity (Carroll et al., 2002; Jensen et al., 2005). Carroll et al. (2002) investigated the changes in MEP amplitudes before and after 4 weeks of resistance training of the first dorsal interosseous (FDI) muscle. They found that MEP amplitudes did not change when elicited at near threshold levels of stimulation but the force at which maximum MEP amplitude occurred significantly shifted from approximately 50% MVC before training to 30–40% MVC after training. They concluded that “...the level of contraction at which the entire population of motor units receiving input from the transcranial volley had been recruited was lower after training.” This is consistent with previous findings of reductions in motor unit recruitment thresholds following resistance training (Keen et al., 1994; van Cutsem et al., 1998). In another study involving the upper extremity, Jensen et al. (2005) found that at rest and during a baseline contraction of 5% MVC, the maximal MEP amplitude increased with motor learning but not with resistance training. To date no investigations of this nature have involved the human lower limb.

The purpose of this study was to test the hypothesis that since several indications of increased descending drive to the tibialis anterior muscle following resistance training have been found (van Cutsem et al., 1998), an increase in cortical excitability would also be apparent. We hypothesized that in the tibialis anterior muscle, MEP amplitudes evoked by TMS elicited in the optimal range of stimulation (20% above threshold) and during the optimal baseline contraction (10% MVC) would increase following 4 weeks of isometric resistance training. We further sought to determine if these changes would be associated with increases in MVC force, M-wave amplitude and maximal surface EMG area.

2. Methods

2.1. Participants

Twenty individuals (19 male, 1 female) age 18–32 years participated in this study. All were healthy and reported no history of metabolic or neuromuscular disorder. Ten individuals performed resistance training of the tibialis anterior muscle and ten participated as a control group. All participants were familiarized with the experimental procedures during an orientation session prior to the experiment and signed consent forms. All procedures were in accordance with the Declaration of Helsinki, 1975 and were approved by the York University Human Participants Review Committee.

2.2. Experimental set up

Participants were seated in an adjustable chair with hip, knee and ankle joint angles of 90°. The right knee and ankle joints were immobilized with a padded clamp positioned proximal to the knee joint and the right foot was strapped to an aluminum plate attached to a strain gauge. Bipolar surface Ag–AgCl recording electrodes with a 0.8 cm diameter and interelectrode distance of 2 cm (EQ Inc., Chalfont PA, USA) were centered over the tibialis anterior muscle to record the surface electromyogram (EMG). The area of electrode placement was first shaved and cleaned with 70% isopropyl alcohol. The site was marked with permanent marker to ensure no differences in electrode placement relative to the innervation zone occurred before and after training. The markings were maintained by the experimenter and the participants throughout the 4 week period for both training and control groups.

In order to measure changes in cortical excitability with resistance training, MEPs were recorded from the surface EMG of the tibialis anterior muscle and were elicited with a transcranial magnetic stimulator (Cadwell, MES-10, Kennewick, WA) through a figure-8 angled coil (Caldwell Laboratories Inc., Kennewick WA) placed over the cortical motor area of the tibialis anterior muscle. Measures of maximal force output were done with the twitch interpolation technique which involved the placement of an electrical stimulating electrode with an anode–cathode distance of 2 cm placed over the common peroneal nerve just distal to
the neck of the fibula. A ground strap electrode was placed between the stimulating and recording electrodes. A schematic of the experimental set up is displayed in Fig. 1.

2.3. Procedures

Three maximal voluntary contractions (MVC) were performed first. Participants were instructed to perform the MVCs as fast as possible. They were provided with visual feedback of the force to assist with motivation for obtaining maximal force output and were also provided with verbal encouragement. Superimposed shocks were delivered during and immediately after each MVC with a 50 μs pulse from an electric stimulator (Digitimer DS7A) to determine the degree of maximal voluntary contraction according to the twitch interpolation technique (Belanger and McComas, 1981). If a superimposed twitch was visible during the contraction this indicated that the contraction was not maximal and participants were asked to repeat the MVC. Three maximal M-waves were recorded during rest after the performance of the MVCs with supramaximal stimulation. Supramaximal stimulation was defined as the current that was 15% above the intensity at which the maximal M-wave occurred.

Following the recording of MVC force and M-wave, motor evoked potentials (MEP) were elicited with TMS. The best site for stimulation was determined by delivering low intensity stimuli through the angled-coil at multiple locations in the general area of representation of the tibialis anterior muscle. When the location over the scalp that produced the largest MEP was identified, the coil was secured in place by clamping it to a device on the back of the chair. TMS stimulator intensity was set to 20% above excitability threshold. Threshold was defined as the intensity which evoked visible (>100 μV) MEPs on 50% of 10 consecutive trials. MEP thresholds were determined at rest and during a baseline contraction of 10% MVC. There was no significant difference in background levels of EMG during the baseline contractions before and after training. Ten percent MVC was chosen as a baseline contraction level because this is the contraction intensity most sensitive to changes in MEP amplitude (Han et al., 2001). Ten MEPs were elicited at rest followed by ten during a baseline contraction of 10% MVC. All procedures were repeated on the trained group prior to training on the 6th (2 weeks) and the 12th (4 weeks) training days. The control group was tested on Day 1 and the day corresponding to the 12th training day (4 weeks).

2.4. Resistance training

All training was performed with the experimenter present and the participant was positioned in the same dynamometer used during data collection. In previous studies of the quadriceps muscle we found that resistance training with 3–5 sets of 10 MVCs for 5–8 weeks of training increased MVC force by 16–36% (Cannon and Cafarelli, 1987; Carolan and Cafarelli, 1992; Rich and Cafarelli, 2000). In the present study, training consisted of 6 sets of 10 MVCs of the tibialis anterior muscle performed 3 times per week for 4 weeks. All MVCs lasted 5 s and the participants typically rested 10 s between each MVC with 2 min rest between each set of 10 contractions. Force recordings were made on every training day.

2.5. Data collection and analysis

The signal from the strain gauge load cell was amplified (custom amplifier, York Electronics Shop), analog to digital converted (Cambridge Electronic Design MICRO 1401, Cambridge UK) and low-pass filtered at 100 Hz. Surface EMG data were first filtered at 5–1000 Hz and then sampled at 2000 Hz. All data were analyzed using Spike 2 for Windows (Cambridge Electronic Design, v4.0). The average maximal force and maximal instantaneous rate of rise of torque (dT/dt) were averaged over the three MVCs. The root mean square (RMS) of the surface EMG during maximal voluntary contractions was calculated from a 1 s segment occurring during the peak asymptote of MVC force. The peak-to-peak amplitudes of the MEPs were averaged over the 10 stimuli obtained at rest and during 10% MVC on each day of data collection. Ten MEPs collected during one train of stimulus pulses collected during a baseline contraction of 10% MVC are displayed in Fig. 2.

2.6. Statistics

MVC torque, peak slope, EMGmax RMS, peak-to-peak M-wave amplitude and peak-to-peak MEP amplitude were
compared across testing days with a two-way (treatment × day) repeated measures analysis of variance (ANOVA). Tukey’s post hoc analysis was used to determine differences between cells when significant main effects were observed. In all cases, an alpha level of 0.05 or less was accepted as a significant difference. All data are reported as mean ± standard error.

3. Results

3.1. Maximal voluntary contraction

Mean maximal voluntary contraction torques (MVC) from each of the 12 training days are displayed in Fig. 3. There was no significant difference in the MVC torques between training (272.2 ± 8.5 N m) and control (262.3 ± 13.1 N m) groups on Day 1. The MVC for the control group did not change by the end of the 4 week training period (263 ± 12.6 N m). There was a main effect of training day in the trained group. At 4 weeks, the trained group increased their MVC torque significantly ($p < 0.05$) to 321.5 ± 10.3 N m.

Mean maximal instantaneous rate of rise of MVC was significantly higher at the end of the 4 weeks (1451.6 ± 127.9 N m s) than on Day 1 (921.4 ± 95.0 N m s) in the training group. Fig. 4 shows the $dT/dt$ from the trained group’s MVC following training. These two variables showed no relation prior to training, but there was a modest correlation between them after 12 days of isometric resistance training ($r = 0.65$, $p < 0.05$).

3.2. Motor evoked potentials

The mean peak-to-peak amplitudes of MEPs evoked during a baseline contraction of 10% MVC, did not differ significantly between training (2.15 ± 0.3 mV) and control (1.91 ± 0.2 mV) groups on Day 1, nor was there a difference between Day 1 and Day 12 (1.75 ± 0.2 mV) values in the control group. Stimulator intensity is reported as % maximal stimulator output. The stimulator intensity required to elicit MEPs 50% of the time (defined as threshold) did not differ across training days. During the baseline 10% MVC, mean stimulator thresholds were as follows, Day 1 (55 ± 2%), 2 weeks (54 ± 3%) and 4 weeks (54 ± 3%) in the training group. MEP thresholds for the control group also did not significantly differ between Day 1 (46 ± 3%) and 4 weeks (47 ± 3%).

During active contractions, MEP amplitudes were significantly higher than initial at 2 weeks and 4 weeks when normalized to the maximal M-wave. MEP/M values for Days 1, 6 and 12 were 38.2 ± 2.4%, 42.2 ± 2.6% and 50.0 ± 2.8%.
43.0 ± 2.3%, respectively. Un-normalized MEP amplitudes for the trained group were also significantly higher than Day 1 (2.15 ± 0.3 mV) on Day 6 (2.83 ± 0.5 mV) and Day 12 (2.50 ± 0.3 mV). Fig. 5 displays the raw data for the MEPs during a 10% MVC baseline contraction for training and control groups at Day 1, Day 6 (2 weeks) and Day 12 (4 weeks). During rest, there was no significant difference in MEP amplitudes from Day 1 (0.65 ± 0.11) to Day 6 (0.56 ± 0.11) to Day 12 (0.56 ± 0.08).

3.3. M-waves

Peak-to-peak maximal M-wave amplitudes were not significantly different between groups or across testing days. Training group peak-to-peak M-wave amplitudes were 7.11 ± 1.0 mV, 7.24 ± 0.8 mV and 7.43 ± 0.9 mV on Days 1, 6 and 12, respectively. M-wave amplitudes did not change between Day 1 (5.75 ± 0.6) and Day 12 (6.02 ± 0.7) in the control group.

3.4. Surface EMG

Maximal surface EMG RMS of the training group increased significantly from Day 1 (0.86 ± 0.10 mV) to Day 6 (1.12 ± 0.14 mV) but did not increase significantly further by Day 12 (1.14 ± .18 mV). Maximal surface EMG RMS did not change in the control group between Day 1 (0.58 ± 0.05 mV) and Day 12 (0.60 ± 0.05 mV).

4. Discussion

Transcranial magnetic stimulation has been used extensively to explore the excitability of the human motor cortex in response to various types of activity. Significant increases in MEP amplitude occur prior to movement initiation (Starr et al., 1998; Reynolds and Ashby, 1999), during task performance (Ljubisavljevic et al., 1996; Sacco et al., 1997; Aranyi et al., 1998; Tinazzi and Zanette, 1998) and following cessation of muscular activity (Bonato et al., 1996; Samii et al., 1996, 1997; Caramia et al., 2000). These studies typically use levels of stimulation intensity of approximately 20–30% above threshold during rest or low-level background contractions. Similarly, in the present study, we found an increase in MEP amplitude following 4 weeks of resistance training of the tibialis anterior muscle at a stimulation intensity of 20% above threshold during a baseline contraction of 10% MVC. However, no changes in MEP amplitude occurred when MEPs were evoked at rest before and after training. No changes in any of the parameters measured occurred in the control group over the 4 weeks. In the biceps brachii muscle, Jensen et al. (2005) found significant increases in maximal MEP amplitude at rest and at 5% MVC following a motor learning task but not following resistance training. In the FDI muscle, Carroll et al. (2002) found no change in MEP amplitudes at near threshold levels of intensity at multiple contraction levels. However, there was a significant shift toward lower contraction levels (from 50% MVC to 30–40% MVC) at which MEPmax occurred. The differences in these studies and the present study may involve differences in neuroplasticity of the cortical areas serving the upper and lower extremities. Individual muscle groups can respond differently to TMS (Schieppati et al., 1996; Tergau et al., 2000). For example, input–output relations of MEP amplitude as a function of background muscle activity are approximately linear in the tibialis anterior muscle (de Noordhout et al., 1992), but not in the FDI muscle which saturates rapidly (Hess et al., 1987).

There is also evidence that muscles differ in their response to resistance training. For example, some muscles are predisposed to increases in EMG activity while others are not (Rabita et al., 2000). In the present study, we found an increase in MEP amplitude in the tibialis anterior muscle, indicating an increase in central drive with resistance training. These findings are consistent with those of van Cutsem et al. (1998), who showed an increase in the initial firing rates of single motor units, decreases in motor unit recruitment thresholds and an increase in the maximal surface EMG following resistance training of the tibialis anterior muscle, whereas in the first dorsal interosseous muscle, maximal surface EMG does not change with resistance training (Keen et al., 1994).

In the present study, the increase in MEP amplitude occurred very early, at least by the 6th day of training (2 weeks). Increased MEP amplitudes are known to return to baseline after learning a new skill (Muellbacher et al., 2001). Since the MEP amplitude of the trained group remained high at 4 weeks and did not change in the control group, it is likely that the increase in MEP amplitude was related to the CNS adaptation to create repeated forceful contractions rather than to merely learning the task.

Increases in neuronal excitability following repetitive motor tasks have been attributed to intracortical synaptic reorganization (Buonomano and Merzenich, 1998) and short term and long term potentiation (Keller et al., 1990; Asanuma and Pavlides, 1997; Benke et al., 1998). An increase in motor unit synchronization with resistance
training (Semmler and Nordstrom, 1998) could also increase both the amplitude of the MEP and the surface EMG area (Milner-Brown et al., 1975). It is likely that the increase in CNS excitability during resistance training takes place at the level of the cortex rather than the spinal cord, since H-reflex amplitudes do not change following either repetitive movements (Tinazzi and Zanette, 1998) or resistance training (Casabona et al., 1990; Aagaard et al., 2002a; Scaglioni et al., 1997). However the possibility can not be discounted. There were no changes in the amplitude of the M-wave pre-post training, indicating that there were no changes in sarcolemmal excitability with training. MEP amplitudes were statistically higher following training when compared in absolute values and when normalized to the participants M-waves.

The increase in peak MVC force was correlated with an increase in the maximal rate of rise of that force. Similar findings have been observed in the quadriceps muscle (Rich and Cafarelli, 2000; Aagaard et al., 2002b). An increase in the initial motor unit firing rates at the onset of contraction (van Cutsem et al., 1998), lower motor unit recruitment thresholds (van Cutsem et al., 1998; Keen et al., 1994) and a shift in peak cortical excitation toward earlier phases of contraction (Carroll et al., 2002) could cause the increase in the rate of rise of contraction during training.

In conclusion, the present investigation found an increase in MEP amplitude following 4 weeks of resistance training the tibialis anterior muscle during a 10% MVC background contraction. Increases in CNS excitability following repetitive contractions have been proposed to involve changes in synaptic input, synchronization, and enhanced short-term and long-term potentiation. These increases in the excitability of the motor system may manifest as higher initial motor unit firing rates and lower motor unit recruitment thresholds resulting in a faster rate of rise and higher overall muscle force output following resistance training.

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References


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