SHORT REPORT

ABSTRACT: We investigated the efficacy of different frequencies and intensities of magnetic stimulation for activating the quadriceps muscles; a painless method for stimulating the quadriceps would be useful in the rehabilitation of patients who have difficulty in voluntarily activating their muscles after injury or surgery. Eleven subjects underwent magnetic stimulation of the femoral nerve over a range of frequencies and intensities using a MagStim Rapid magnetic stimulator. Magnetic stimulation at 30 Hz at 80% of the power output of the stimulator used was capable of generating 72% of quadriceps maximal voluntary contraction torque. Subjects reported little or no pain during the procedure. Magnetic stimulation of the femoral nerve is a well-tolerated way to activate the quadriceps muscles.

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TRANSCUTANEOUS MAGNETIC STIMULATION OF THE QUADRICEPS VIA THE FEMORAL NERVE

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Muscle stimulation has traditionally been accomplished by electrical means. This technique has proven useful in rehabilitation,[9,10] but the large voltages and currents required may be painful. Peripheral magnetic stimulation is usually painless[1,7] and allows activation of muscles at levels approaching maximal voluntary contraction (MVC); for example, Polkey et al.[7] were able to attain supramaximal twitches in the quadriceps via stimulation of the femoral nerve.

The effectiveness of magnetic stimulation alone in retarding muscle atrophy has not been examined, to our knowledge. For example, training the quadriceps using external stimulation to overcome the profound quadriceps inhibition following reconstruction of the anterior cruciate ligament [6,11] would be useful during rehabilitation following injury or surgery. The purpose of this study was to stimulate magnetically the femoral nerve, in order to determine the optimal stimulus intensity and frequency to maximize both contraction intensity of the quadriceps and patient comfort.

Abbreviations: ACL, anterior cruciate ligament; MRI, magnetic resonance imaging; MVC, maximal voluntary contraction

Key words: anterior cruciate ligament reconstruction; electric stimulation; magnetic stimulation; neuromuscular rehabilitation; weakness

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MATERIALS AND METHODS

Eleven healthy subjects (7 men and 4 women; age range, 21–44 years) participated in this study. All subjects gave written informed consent. Subjects sat in an isokinetic dynamometer (Biodex, Shirley, New York) with their ankles fixed to the arm of the dynamometer. The dynamometer arm was fixed at 90° and subjects reclined with the trunk at 45° in order to facilitate location of the femoral nerve. Three 5-s isometric MVCs were recorded for each subject, with a 30-s rest between each contraction. Maximal torque values were averaged. Magnetic stimulation was then administered using a MagStim Rapid (MagStim Corp., Whitland, Wales) with four "booster units" and a 110-mm double-circular stimulating coil. This unit and coil can generate a magnetic field of up to 2 Tesla. Subjects were tested with 3-s pulse trains at the following frequencies and intensities (expressed as percent of maximum output of the unit), dictated by the maximum output allowed by the controller software: 20 Hz at 60%, 80%, and 100% intensity; 30 Hz at 60% and 80%; and 40 Hz at 60%. All pulses generated by the unit are monophasic in nature. More booster units would allow use of higher intensities at higher stimulation frequencies.

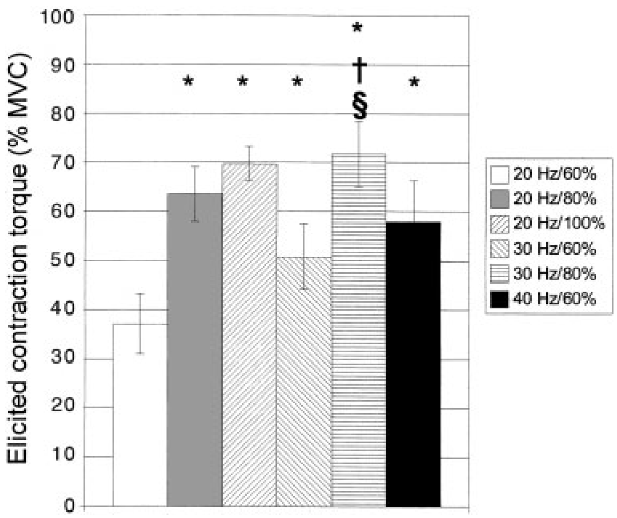

FIGURE 1. Magnetically elicited torque (expressed as percentage of MVC) using various combinations of stimulation intensity and frequency during two different test sessions. (Error bars indicate standard error; *>20 Hz/60%, $P < 0.038$; †>20 Hz/80%, $P = 0.016$; §>30 Hz/60%, $P = 0.021$.)

Optimal placement of the stimulating coil over the femoral nerve was determined by administering single pulses at the femoral crease and finding the location eliciting the greatest twitch response. This was marked using tape, to facilitate consistent coil placement. The coil was oriented tangentially to the surface of the limb, to maximize the elicited contractions, as in previous studies.[4,8] The tester attempted to apply a constant pressure to the coil to minimize its movement during the stimulus trains. Because distance from the stimulating coil to the target nerve affects the magnitude of the elicited contraction, thigh skinfold was measured using calipers.

A repeated-measures analysis of variance with Bonferroni corrections for multiple comparisons was used to assess which combination of stimulus frequency and intensity elicited the most forceful contraction. Pearson product-moment coefficients were used to test the association between the magnitude of magnetically elicited contractions and thigh skinfold. An alpha level of 0.05 was set as the threshold for statistical significance for all analyses.

RESULTS

Some subjects reported discomfort with stimulation at 20 Hz at 100% intensity. Other combinations of intensity and frequency were tolerated without reports of discomfort.

Torque elicited by magnetic stimulation is shown in Figure 1. The combination of 20 Hz at 60% intensity produced the lowest torques ($P < 0.038$). The combinations of 20 Hz at 100% intensity and 30 Hz at 80% intensity produced the largest torques. Thigh skinfold was negatively correlated with the strength of the elicited contraction for stimulation at 20 Hz at 100% intensity ($r = -0.673$, $P = 0.023$).

DISCUSSION

It is thought that contractions of at least 60% MVC are necessary to induce a hypertrophic response.[5] We were able to elicit contractions averaging 72% MVC (range, 35–120%) with high-intensity magnetic stimulation, with several subjects demonstrating magnetically elicited torques greater than MVC. With more booster units for the magnetic stimulator, higher frequencies and intensities can be used and should produce even higher torques.

Eliciting therapeutically useful contractions by electric stimulation is painful. For example, Laufer et al.[3] investigated electrical stimulation of the quadriceps muscles. Maximal torque from electrical stimulation was less than 40% MVC and was limited by the subjects' inability to tolerate the stimulus. Subject tolerance was not the limiting factor in this study, with subjects reporting discomfort only at the highest intensity (100% at 20 Hz) of magnetic stimulation, which generated approximately 70% MVC. Stimulation of 80% intensity at 30 Hz was able to elicit contractions averaging 72% MVC, while being better tolerated than 100% intensity at 20 Hz. Stimulation at higher frequencies allows the intensity of the stimulator output to be reduced, reducing discomfort. The current software causes the contraction to come on suddenly and at full force, which can be uncomfortable; this may be alleviated by software that allows a gradual increase in intensity. Magnetic stimulation offers clear advantages over electrical stimulation.

Intervening tissue (i.e., body fat) was shown to be negatively correlated with the magnitude of contractions at the highest intensity. This is to be expected, as the strength of the magnetic field falls off with distance from the stimulating coil.

Precautions taken for magnetic stimulation should be similar to those for magnetic resonance imaging (MRI). Although the magnetic field generated by the magnetic stimulator was of peak strength similar to that used in MRI, it is much more narrowly focused and will affect only the immediate area near the stimulating coil; for example, for double-circular coils such as that used in this study, magnetic field strength falls off by approximately 50% at 10 mm from the coil.[2]

A limitation to using this device in a therapeutic environment is coil heating, caused by the large currents used, which may damage the coil. Each test session typically involved one or two breaks to allow the coil to cool, which sometimes took 10–15 min. Using a fan to keep a constant stream of air moving over the coil seems the most efficient method for cooling and results in no condensation on the coil. Because the use of lower stimulation intensities and frequencies (thus, less dissipated power) results in less heating, the lowest possible levels providing suitably high contraction levels should be used. Our results show that a stimulus frequency of 20 Hz, at 80% intensity, results in a suitably high (>60% MVC) contraction while minimizing coil heating.

In conclusion, magnetic stimulation of the femoral nerve elicited quadriceps contractions averaging up to 72% MVC and represents a comfortable alternative to electric stimulation. More work needs to be done to understand fully the effects of stimulation intensity and frequency and to test the efficacy of magnetic stimulation as a means of maintaining or restoring muscle strength following injury or surgery.

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