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Massed Practice versus Massed Practice with Stimulation: Effects on Upper Extremity Function and Cortical Plasticity in Individuals with Incomplete Cervical Spinal Cord Injury

Kristina S. Beekhuizen and Edelle C. Field-Fote

Objective. To determine the effect of massed practice (MP) versus massed practice combined with somatosensory stimulation (MP+SS) on cortical plasticity and function in persons with incomplete tetraplegia. Methods. Ten subjects were assigned to either MP or MP+SS. Median nerve stimulation (500 ms train, 10 Hz, 1 ms pulse duration) was delivered at the intensity eliciting a motor threshold response. Training sessions were 5 d/week for 3 weeks at 2 h/session. Outcome measures included 1) motor-evoked potentials (MEPs) elicited via transcranial magnetic stimulation (TMS), motor threshold (MT) and MEP amplitude at 1.2× MT; 2) maximal pinch grip force; 3) Wolf Motor Function Test (WMFT) and Jebsen Hand Function Test. Results. The MP+SS group demonstrated significant improvements (P < 0.05) in pinch grip strength (190%), WMFT scores (52%), and Jebsen test scores (33%), whereas the MP group demonstrated significant improvement (P < 0.05) only in Jebsen test scores (11%). No significant changes were detected in cortical excitability in the MP+SS or MP group. Conclusions. The findings of this preliminary study suggest that MP+SS results in greater increases in pinch strength and timed functional test scores than MP. Optimal stimulation paradigms and training methods are needed to further test this strategy.

Key Words: SCI—Exercise—Electrical stimulation—Constraint-induced therapy—Rehabilitation—Hand function.

Spinal cord injury (SCI) affects 10,000 individuals per year in the United States. The majority of individuals with SCI (~55%) have injuries that are functionally incomplete. In addition, magnetic resonance imaging (MRI) and histopathology indicate that approximately 65% of traumatic injuries classified as “neurologically complete” (absence of sensory and motor function in the lowest sacral segment) actually show some tissue and axonal sparing across the lesion. Therefore, the true number of individuals with anatomically incomplete injuries is much higher than is apparent based on functional testing.

Approximately one half of all individuals with SCI have tetraparesis due to cervical injury. Impaired hand function significantly limits the ability of individuals with cervical SCI to perform manual activities of daily living. Those with complete SCI below the 6th cervical level maintain some hand function and all wrist function, whereas complete spinal cord injury at the C6 neurological level disrupts all hand function except for wrist extension with radial deviation. With complete injuries above the 6th cervical level, no hand function remains. However, individuals with incomplete cervical lesions may have varying degrees of arm and hand function regardless of the level of the lesion.

In incomplete SCI lesions, information may still pass through the lesion on spared fiber tracts, but this information may be fragmented or distorted. Maximizing the function of these spared fibers may be one method to improve motor function. Physiological reorganization of the brain and spinal cord motor networks is a 2nd mechanism underlying recov-
ery of function. Although spontaneous regeneration of lesioned fibers is limited in the adult CNS, functional recovery can occur for several years after injury in incomplete SCI, with the degree of recovery dependent upon the reorganization of circuits that have been spared by the lesion.

Cortical reorganization occurs after SCI, and there is evidence that the sensorimotor cortex may play a role in the recovery of function in individuals with SCI. The results of neuroimaging and neurophysiological techniques such as functional magnetic resonance imaging (fMRI), transcranial magnetic stimulation (TMS), and positron emission tomography (PET) demonstrate that changes occur in the cortex following damage to the spinal cord. The findings of these studies provide evidence of expansion of cortical areas corresponding to muscles spared after SCI into cortical areas previously associated with muscles below the level of the lesion, which is similar to the cortical changes that occur following stroke.

There is evidence in the literature that constraint induced therapy (CIT) promotes cortical reorganization and improves upper extremity function after stroke. Constraint induced therapy, which typically involves constraint of the unaffected upper extremity using a sling to facilitate movement of an affected upper extremity, is a form of massed practice therapy. Studies have demonstrated that the factor underlying the difference in outcomes associated with CIT and traditional therapy is not constraint of the uninvolved limb, but the required frequency of use of the involved limb. Therefore, the term “massed practice” is the more appropriate term to describe an intervention in which repetitive practice is the primary therapeutic factor.

Another intervention that has been shown to improve upper extremity function after stroke is somatosensory stimulation, which is prolonged, repetitive peripheral nerve stimulation. In prior studies investigating the effects of peripheral nerve stimulation on cortical plasticity, the stimulation parameters involved trains of electrical stimuli delivered to the peripheral nerve. The 2-h stimulation protocol consists of 1-ms duration square wave pulses delivered at a frequency of 10 Hz using a duty cycle of 500 ms on/500 ms off. This form of stimulation has been shown to induce changes in cortical excitability and, in individuals with stroke, may promote improvement in pinch grip strength. Two hours of sciatic nerve stimulation in rodents produced an increase in MEPs demonstrated by TMS. Ulnar nerve stimulation in nondisabled subjects for 2 h at the same rate preferentially increased the TMS-induced MEP in the abductor digiti minimi muscle for up to 20 min, whereas the muscles innervated by the median and ulnar nerve were not affected. Similarly, Ridding and others found that 2 h of ulnar nerve stimulation increased the area of the MEPs evoked in the ulnar- but not the median-innervated muscles. There was an increase in excitability of the corticospinal projections accompanied by an increase in the area of the representational cortical maps of the stimulated muscles. Charlton and others, using the same protocol, applied stimulation at 3 peripheral sites, including the combined radial and ulnar nerves, the motor point of the 1st dorsal interossei (FDI), and the FDI paired with TMS over the motor cortex. Although responses varied across subjects, all showed increased excitability of the TMS-induced MEP for at least some of the hand muscles. Confarto and others demonstrated that 2 h of median nerve stimulation for 2 weeks increased pinch muscle strength in the affected hands of individuals with chronic stroke; the increase persisted for 24 h following the stimulation period. Taken together, these studies support the use of prolonged peripheral nerve stimulation for inducing changes in motor performance, most likely via a mechanism related to cortical plasticity. The reorganization of cortical projections has implications for individuals with SCI, as it has been suggested that cortical plasticity, specifically an increased contribution from the somatosensory cortex, plays a role in the recovery of function after SCI.

Massed practice therapy and somatosensory stimulation may be beneficial interventions for individuals with incomplete SCI because information is still passing through the spinal cord, although the information may be fragmented or distorted. The recovery associated with these interventions has been attributed, in large part, to plasticity in the sensorimotor cortex. Given that cortical changes occur after SCI just as they do after stroke, these strategies may also be effective for improving arm and hand function in individuals with incomplete SCI.

The purpose of this investigation was to test the hypotheses that 1) both massed practice and massed practice combined with somatosensory stimulation will increase pinch grip strength, improve upper extremity function, and increase cortical excitability when compared to pretraining measures, and 2) massed practice combined with somatosensory stimulation will result in greater...
increase in pinch grip strength, greater improvement in upper extremity functional test scores, and a greater increase in cortical excitability than massed practice alone in individuals with incomplete cervical SCI.

METHODS

Subjects with cervical SCI were deemed suitable for inclusion if they were between 16 and 70 years of age, demonstrated at least trace evidence of voluntary thumb movement (i.e., twitch), and were diagnosed with spastic paresis (manifesting as spasms, clonus, or hyperreflexia) due to neurologically incomplete SCI of at least 1 year duration. The spinal roots of C8 and T1 supply the main components of the ulnar and median nerves innervating the thenar muscle. Therefore, it was required that the level of injury be at or rostral to C7.

A total of 10 subjects participated in this study (1 woman, 9 men; mean age = 39 years, SD = 10.8, range = 22–63). Subject clinical details are presented in Table 1. Using the American Spinal Cord Injury Association (ASIA) Impairment Scale,21 subjects with SCI had injuries that were classified as either ASIA C (sensory and motor function are preserved below the level of the lesion, but at least half of the muscles below the level of the lesion have a manual muscle test grade of less than 3; n = 4) or ASIA D (sensory and motor function are preserved below the level of the lesion, but at least half of the muscles below the level of the lesion have a manual muscle test grade greater than 3; n = 6). All of the subjects had sustained an SCI at neurological level C7 or above at least 1 year prior to participation in the study (mean time post-SCI = 44 months, SD = 41.2, range = 12–154). All of the subjects were on medications for chronic conditions and were instructed to maintain their daily medication regimen throughout the course of the study. Each subject provided written informed consent consistent with the guidelines established by the Institutional Medical Sciences Subcommittee for the Protection of Human Subjects at the University of Miami.

An upper-extremity motor score was derived from manual muscle testing of motor levels C5 to T1 (Table 1). The ASIA grading criteria were used to assign a grade of 0–5 at each motor level, with a grade of 0 representing no detectable motor function and a grade of 5 representing normal motor function. A maximum score of 50 would be indicative of normal bilateral upper extremity motor function. Sensory function was assessed in the upper extremities bilaterally for light touch (principally testing posterior columns) and pin prick (principally testing spinothalamic pathways) sensitivity over dermatomes C5 to T1. At each level, a score of 2 was given for normal sensation, 1 for impaired sensation, and a 0 for no sensation. A maximum score of 20 was available for each sensory test.

Subjects were randomly assigned (picked a number out of a hat) to 1 of 2 groups: massed practice with somatosensory stimulation (MP+SS) or massed practice training alone (MP). The 2 different groups did not interact with each other; therefore, the MP group was not aware they were part of a “control” group. The subjects received the assigned intervention 5 times per week for 3

Table 1. Clinical Details of the Patients with Incomplete Spinal Cord Injury Taking Part in the Study

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (y)</th>
<th>Sex</th>
<th>ASIA Grade</th>
<th>Neurological Level</th>
<th>Side Tested</th>
<th>Cause of Injury</th>
<th>Duration of Injury (mo)</th>
<th>UE Sensory Score LT (/20)</th>
<th>UE Sensory Score PP (/20)</th>
<th>UE Motor Score (/50)</th>
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<tbody>
<tr>
<td>MP</td>
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<tr>
<td>1</td>
<td>37</td>
<td>M</td>
<td>D</td>
<td>C5</td>
<td>L</td>
<td>T</td>
<td>33</td>
<td>17</td>
<td>20</td>
<td>40</td>
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<tr>
<td>2</td>
<td>40</td>
<td>M</td>
<td>D</td>
<td>C6</td>
<td>L</td>
<td>T</td>
<td>61</td>
<td>13</td>
<td>16</td>
<td>29</td>
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<tr>
<td>3</td>
<td>43</td>
<td>M</td>
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<td>C6</td>
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<td>42</td>
<td>M</td>
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<td>C6</td>
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<td>154</td>
<td>20</td>
<td>16</td>
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<td>MP+SS</td>
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<td>6</td>
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<td>F</td>
<td>D</td>
<td>C7</td>
<td>R</td>
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<td>12</td>
<td>10</td>
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<td>36</td>
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<td>7</td>
<td>39</td>
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<td>C6</td>
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<td>C5</td>
<td>R</td>
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<td>26</td>
<td>15</td>
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<td>22</td>
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<td>10</td>
<td>38</td>
<td>M</td>
<td>C</td>
<td>C5</td>
<td>R</td>
<td>T</td>
<td>43</td>
<td>19</td>
<td>13</td>
<td>37</td>
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</tbody>
</table>

ASIA = American Spinal Cord Injury Association; UE = upper extremity; LT = light touch; PP = pin prick; MP = massed practice; MP+SS = massed practice with somatosensory stimulation; M = male; F = female; L = left; R = right; T = traumatic; NT = nontraumatic.

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weeks, for 2 h per session. The intervention was directed at the upper extremity having the lower motor score. Subjects were tested prior to and following participation in the study.

Testing Procedures

The outcome measures of this study included 1) maximal pinch grip force, 2) Wolf Motor Function Test (WMFT) timed task scores, 3) Jebsen Hand Function Test scores, 4) stimulus intensity required to elicit motor threshold (MT) response (50–100 µV) in thenar muscles, and 5) motor-evoked potentials (MEP) amplitude at 20% over motor threshold intensity (1.2 × MT). The tester was not blinded to group assignment, yet a 2nd individual was always present during testing to ensure accurate and nonbiased measurement.

Pinch grip. Maximal key pinch strength was tested using a MicroFet 4 digital dynamometer (Hoggan Health Industries, West Jordan, Utah). Subjects were seated with the shoulder adducted and neutrally rotated, elbow positioned at 90°, and the forearm and wrist in a neutral position. Subjects held the dynamometer between the lateral aspect of the middle phalanx of the index finger and thumb pad. The subjects were instructed to squeeze as hard as they could for 3 s. Maximal pinch grip force was measured on each trial, and the average of 3 consecutive maximal pinch force measurements was calculated for each subject.

Upper extremity functional testing. The WMFT is a laboratory-based upper extremity function test involving 15 timed measures and 2 force-based measures, which progresses in complexity from engaging individual joints to use of the whole upper extremity. The test was primarily designed to assess, in individuals with stroke, the ability to use combinations of joint movements, and to remediate movement problems based on limitations in the test measures. The WMFT has high interrater reliability ($r = 0.97$, $P < 0.05$), internal consistency, and test-retest reliability in individuals with stroke. Scores in the 15 timed measures were summed to produce a total time score.

The Jebsen-Taylor Hand Function Test (Jebsen) is an assessment of hand disability and improvement in hand function associated with therapeutic procedures. The test is composed of 7 subtests, writing, turning over cards, picking up small common objects, simulated feeding, stacking checkers, picking up large light objects, and picking up large heavy objects. Patients with C6-7 cervical SCI are included in the target population for use of the Jebsen test. The test-retest reliability for the dominant hand in patients with stable hand disorders is high ($r = 0.89$ to $0.99$) with the exception of the writing subtest ($r = 0.67$). Each subtest score is obtained by measuring the time necessary to complete each subtest. Scores in the 7 timed measures were summed to produce a total test score. Administration of the Jebsen test always followed the WMFT on the testing day.

Transcranial magnetic stimulation (TMS). Motor-evoked potentials from the thenar muscles were elicited using TMS applied over the scalp with a Magstim 200 (Magstim Company Ltd., Whitland, Wales, UK) stimulator of maximum magnetic field strength of 2 Tesla, with a figure-8-shaped coil (7 mm). The coil was positioned tangentially to the scalp, directed anteriorly, 45° from the midsagittal axis. The Magstim stimulator produces a damped, polyphasic electric field, about 200 µs in duration. Transcranial magnetic stimulation evokes a contralateral muscle twitch, recorded with surface electromyography (EMG).

The subject wore a tight-fitting plastic cap on which the outline of the coil was traced with a marker once the proper site was found. This controlled for movement of the coil that can occur during testing, thereby reducing measurement error. Outlining the coil on the cap also controlled for coil placement during posttesting. A clamp attached to a tripod supported the figure-8 coil to ensure reproducibility of the testing site.

The amplitude of the MEPs of the thenar muscles was measured with the hand relaxed. EMG recordings from the thenar muscles, obtained from closely spaced pairs of surface Ag-AgCl disc electrodes placed over the thenar eminence of the more affected hand, were used to calculate the amplitude of the MEPs. To measure the MT, the coil was placed over the frontoparietal region contralateral to the target muscle and moved in small increments until the “hot spot” (site at which the threshold is lowest and latency is shortest) was found, using an initial stimulation intensity of 80% of maximum stimulator output (%MSO). The intensity of the magnetic stimulation was decreased progressively in 5% increments until
reaching a level that induced reliable threshold level MEPs of 50 to 100 µV amplitude in approximately 50% of 10 consecutive stimuli. This level of stimulus intensity is considered the MT for the target muscle, expressed as %MSO.\textsuperscript{25}

Motor-evoked potential amplitude at 1.2× MT\textsuperscript{26,27} was the 2nd outcome measure of interest in assessing changes in motor cortex excitability associated with training. The mean MEP amplitude was calculated by averaging 10 TMS MEPs at stimulus intensities at 1.2× MT.

Training Procedures

**Massed practice training.** The subjects in the MP+SS and the MP groups participated in 2 h of massed practice therapy 5 times per week for 3 weeks. The massed practice protocol used was an original training program designed by the authors. Massed practice training focused on continuous repetitions of tasks in each of 5 categories: gross upper extremity movement, grip, grip with rotation, pinch, and pinch with rotation (Figure 1). Each category had approximately 10 tasks focusing on the desired motion of that category. The order of the categories was assigned in random blocks, and the subject repeatedly performed the tasks within that block for 25 min before moving on to the next category. Total training time was 2 h per session. Each category had an associated stack of index cards with a task written on each card. Categories and their associated tasks are given in Table 2. The subjects randomly selected tasks within each category by drawing an index card from the pile. Subjects repeatedly performed 1 task at a time until fatigued. A 2- to 3-min rest break was allowed before the start of a new task within the same category. Feedback was permitted during the training only if the subject was performing the task incorrectly.

**Massed practice + Somatosensory stimulation protocol.** Subjects in the MP+SS group received somatosensory stimulation simultaneously with the massed practice training protocol described in the previous section. Median nerve stimulation was applied at the level of the wrist for the entirety of each 2-h massed practice training session. The protocol for somatosensory stimulation was based on that used by Conforto and others\textsuperscript{20} in patients with stroke. The optimal position to stimulate the median nerve at the wrist was located by identifying the site that elicited in the thenar muscles the maximal motor response to stimulation. Silver-silver surface chloride electrodes were placed on the distal forearm with the anode at the wrist crease and the cathode 2 cm proximal to the anode. Trains of electrical stimulation (Digitimer DS7A, Digitimer Ltd., Welwyn Garden City, England) were delivered at 1 Hz, each train consisting of 5 single pulses at 1 ms duration delivered at 10 Hz. This intensity elicits compound muscle action potentials of 50 to 100 µV from the abductor pollicis brevis in the absence of visible finger movements. This low-stimulation intensity and the stimulus duration of 1 ms preferentially activate large cutaneous and proprioceptive sensory fibers. In addition, this low-stimulation intensity

<Table 2. Massed Practice Categories with Sample Tasks>

<table>
<thead>
<tr>
<th>Gross UE Movement</th>
<th>Grip</th>
<th>Grip with Rotation</th>
<th>Pinch</th>
<th>Pinch with Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balloon swat</td>
<td>Coke can to mouth</td>
<td>Doorknob Deadbolt</td>
<td>Writing—circles and crosses</td>
<td>Flipping cards</td>
</tr>
<tr>
<td>Dart throw</td>
<td>Squeezing toothpaste/glue</td>
<td>Lids on jars</td>
<td>Small object into jar</td>
<td>Key in lock</td>
</tr>
<tr>
<td>Baseball</td>
<td>Slice play dough with</td>
<td>Flipping cups</td>
<td>Pegboard</td>
<td>Lace-up</td>
</tr>
<tr>
<td>Ball bounce</td>
<td>plastic knife</td>
<td>Flipping cans</td>
<td>Coins in change</td>
<td>Beads on string</td>
</tr>
<tr>
<td>Paddle ball</td>
<td>Cutting paper</td>
<td>Screwing in a lightbulb</td>
<td>Connect 4</td>
<td>Twist-tie around bag</td>
</tr>
<tr>
<td></td>
<td>Fold towels/place on shelf</td>
<td>Pitcher pour into cups</td>
<td>Bubble wrap</td>
<td>Screw and</td>
</tr>
<tr>
<td></td>
<td>Shaping play dough—place in</td>
<td></td>
<td>Buttons</td>
<td>screwdriver</td>
</tr>
<tr>
<td></td>
<td>jar</td>
<td></td>
<td>Find small objects in</td>
<td>Nuts and bolts</td>
</tr>
<tr>
<td></td>
<td>Thick paintbrush</td>
<td></td>
<td>rice</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scoop sand and pour</td>
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</table>

**Table 2. Massed Practice Categories with Sample Tasks**

**UE** = upper extremity.
does not interfere with the execution of the massed practice training activities.

Data Analysis

Data analysis was conducted using SPSS 11.0 for Windows (SPSS Inc., Chicago, Illinois). All descriptive data are presented as means and standard error (SE). The Kolmogorov-Smirnov test for normality (with the level of significance set at $P < 0.05$) indicated that the demographic data were normally distributed and the outcome measure data were not normally distributed. Student $t$ tests were used to test for differences in subject demographics between the 2 groups. Because the outcome measure data were not normally distributed, and because the sample size was small, nonparametric analyses were used. The Wilcoxon Signed Ranks test was used to test for significant differences between pretest and posttest scores within each group. The pretraining and posttraining score values were used to calculate percent change scores for each outcome measure for each subject. The Mann-Whitney $U$ test was applied to test for differences in the percent change scores between the 2 groups and to identify differences in pretest values between groups for each of the outcome measures. An a priori level of significance for all analyses was accepted at $P < 0.05$.

RESULTS

Descriptive information for the 10 subjects with incomplete cervical SCI who participated in the
study is presented in Table 1. Student t tests indicated that there were no differences between the 2 groups in terms of age \((t = 2.13, P = 0.066)\), duration of injury \((t = 1.13, P = 0.317)\), light touch sensory scores \((t = 1.37, P = 0.211)\), pin-prick sensory scores \((t = 1.55, P = 0.180)\), or motor scores \((t = 0.513, P = 0.625)\).

Mann-Whitney U tests detected no differences between baseline measures of the MP+SS and MP group for pinch grip force \((Z = -1.358, P = 0.175)\), WMFT timed scores \((Z = -0.731, P = 0.465)\), Jebsen scores \((Z = -0.104, P = 0.917)\), or MEP amplitude \((Z = -0.750, P = 0.453)\). A significant difference was found between baseline measures of MEP threshold in the MP+SS and MP groups \((Z = -2.100, P = 0.036)\).

Pinch Grip

The descriptive statistics for pinch grip are presented in Figure 2. Statistical analyses indicated that the pre- and posttest pinch grip scores were significantly different in the MP+SS group \((Z = -2.023, P < 0.05)\). However, there were no significant differences between pre- and posttest pinch grip scores in the MP group \((Z = -0.405, P = 0.686)\). The MP+SS group \((n = 5)\) demonstrated a significantly greater increase in pinch grip strength than the MP group \((U = 2.0, P < 0.05)\). The subjects in the MP+SS group demonstrated a mean increase in pinch of 190% ± 255% (26% to 642% range), whereas the subjects in the MP group \((n = 5)\) presented a 17% ± 50% mean increase (−76% to 47% range).

Upper Extremity Functional Tests

Figures 3 and 4 present the descriptive statistics for the WMFT and Jebsen test, respectively. A statistically significant difference was detected between pre- and posttest WMFT timed scores in the MP+SS group \((Z = -2.023, P < 0.05)\), with no significant difference between pre- and posttest WMFT timed scores in the MP group \((Z = -0.674, P = 0.500)\). Analysis indicated a statistically significant difference in percent change of WMFT timed test scores between the 2 groups \((U = 1.0, P < 0.05)\). The subjects in the MP+SS group \((n = 5)\) demonstrated a greater improvement in WMFT timed scores (mean decrease in time = 52%, \(SD = 22\%\), range = 17% to 77%) than the subjects in the MP group \((n = 5)\) (mean decrease in time = 6%, \(SD = 21\%\), range = −18% to 23%).

Significant differences were detected between the pre- and posttest training Jebsen test scores in both the MP+SS group \((Z = -2.023, P < 0.05)\) and the MP group \((Z = -2.023, P < 0.05)\). The subjects in the MP+SS group \((n = 5)\) demonstrated a greater improvement in Jebsen scores compared with the
MP group ($U = 3.0, P < 0.05$). The MP+SS group displayed a 33% ± 17% mean decrease in time (range 9%–54%), whereas the subjects in the MP group ($n = 5$) demonstrated an 11% ± 14% mean decrease in time (range = 1%–34%).

Cortical Excitability

The descriptive statistics for the MEP thresholds and MEP amplitudes are presented in Figures 5 and 6, respectively. Two subjects were excluded from
this testing owing to risk factors for use of TMS. No significant differences were detected between pre- and posttest MT measures in the MP+SS group ($Z = -1.069$, $P = 0.285$) or in the MP group ($Z = -1.826$, $P = 0.068$). The subjects in the MP+SS group ($n = 3$) and the MP group ($n = 5$) demonstrated decreases in MT of $14\% \pm 22\%$ and $4\% \pm 20\%$, respectively.

Similarly, the statistical analysis identified no significant difference between pre- and posttest MEP amplitude measures in the MP+SS group ($Z = -1.342$, $P = 0.180$) or in the MP group ($Z = -0.535$, $P = 0.593$).

DISCUSSION

The purpose of this study was to assess the effect of participation in a 3-week training program consisting of MP or MP+SS on grip strength, upper extremity function, and cortical excitability in individuals with incomplete cervical SCI. The results of this investigation indicate that there were significant improvements in pinch grip strength, WMFT, and Jebsen functional scores associated with participation in the MP+SS protocol, whereas the MP protocol was associated with significant improvement in Jebsen functional scores. Neither the MP+SS nor the MP training protocol was associated with measurable changes in cortical excitability.

The findings of this preliminary study suggest that massed practice may be an effective rehabilitative tool for improving strength and function in individuals with cervical SCI and that improvement may be further enhanced by the addition of somatosensory stimulation. The strength and functional gains resulting from the addition of somatosensory stimulation to the massed practice training may be due in part to the involvement of the somatosensory cortex in functional recovery after SCI. Green and others demonstrated that patients that eventually regained function after SCI initially presented with a posterior shift in cortical motor potentials. This posterior shift correlates with somatosensory cortex involvement, thereby suggesting a role of the somatosensory cortex in cortical reorganization after SCI.

Reorganization of the cortex following stroke has been studied extensively in both human and animal models. Cortical territories controlling intact body parts tend to enlarge and invade cortical regions that have lost their peripheral target, yet the remaining intact representation is maintained or enlarged with daily intensive rehabilitative retraining. A study by Darian-Smith concluded that what seems to limit manual performance following spinal section is the rate of transmission of relevant information from the cortex to the cord. Therefore, the potential exists to
maximize the efficacy of this descending information through practice. Because the majority of individuals with SCI (approximately 55%) are functionally incomplete, some information can still pass through the level of the lesion. Prior to this investigation, cortical changes in response to an intervention had not been examined in individuals with incomplete SCI. This preliminary study did not find significant changes in cortical excitability after MP+SS or MP training, and the lack of significant results may be due to the low power (54.3%) to detect differences between the groups in this study. However, further investigation is needed to assess cortical changes in response to MP+SS and MP using a controlled trial with a larger sample size.

The finding that MP+SS improved pinch grip and functional test scores has important implications for the long-term rehabilitation of hand function in individuals with incomplete cervical SCI. The individuals in this study ranged in chronicity from 12 months to 23 years post-SCI, and therefore all were considered to be past the period during which dramatic amounts of spontaneous recovery are expected. None of these individuals was able to receive hand therapy due to the perception that further improvements in hand function were not to be expected. Many were told that it was to their benefit to simply adjust to using adaptive devices. The results of this study, however, indicate that it is possible to achieve additional functional gains even in the chronic stages of injury.

Afferent input, in the form of sensory afferents associated with movement or peripheral nerve stimulation, can induce beneficial neuroplasticity. This plasticity may promote optimal utilization of the remaining pathways conducting neural impulses through the injured regions of the spinal cord in individuals with incomplete SCI. Evidence from animals with cervical hemisection indicates that functional performance is limited principally by the low rate of transmission of information between the cortex and the spinal cord, and the key to recovery of upper extremity function is learning to maximize the available anatomical connections in the spinal cord. Prior to the intervention, the individuals with incomplete cervical SCI may not have been able to activate the remaining connections in the spinal cord to their maximum potential. By galvanizing the nervous system with a barrage of afferent input for 15 two-hour sessions the effectiveness of the existing anatomical connections is likely to have increased, thus making the subjects’ efforts more efficacious in activating these circuits and resulting in improved strength and performance.

There is a possibility that other aspects of cortical excitability not examined in this study may have changed due to the interventions. Changes in cortical maps in response to intervention have not

Figure 6. Motor-evoked potential (MEP) amplitude values at 1.2× motor threshold (MT) before and after training. Data are expressed as mean ± SE. MP = massed practice training alone; MP + SC = massed practice with somatosensory simulation.
been examined in individuals with SCI. If the cortical maps do change, then alterations in cortical excitability may be missed when the posttest measurement is taken in the same location as the pretesting measurement. Green and others\(^3\) used EEG to map the motor potentials associated with movements of the fingers and toes, and to localize the cortical site at which the excitability level of the MP was the greatest. The investigators found that the individuals who exhibited posteriorly shifted cortical motor potentials after SCI were more likely to recover function over time. As the individual recovered function, the motor potential shifted back to the normal anterior position on the cortex.\(^5\) The present investigation used the same measurement site before and after training. Although the TMS coil used in this investigation would certainly evoke responses from a large area, it is likely that in the presence of a shift in the cortical map of the magnitude observed in the EEG studies by Green and others,\(^3\) the site of maximal excitability may well have been missed. Furthermore, 1.2× MT may not be sufficient intensity to distinguish changes in cortical excitability after an intervention in SCI. Input/output curves measuring the amplitude of MEPs at a range of stimulus intensities is more often related to synaptic excitability, which may be a better method to identify changes in cortical excitability than measuring MEPs at a single point along the curve. MEP thresholds have been more often related to membrane excitability in corticomotor pathways than to synaptic excitability as evidenced by how threshold is affected by the administration of CNS-acting drugs that effect membrane excitability, whereas drugs that effect synaptic transmission have little influence on MEP thresholds.\(^30,31\)

The lack of significant change detected in motor threshold in this study may have resulted from threshold measurements occurring with the hand at rest. In this study, motor threshold was measured at rest because it was initially felt that owing to the high degree of variability between subjects, this would provide the most stable baseline measure. Cortical motor threshold is a complex measure because MEPs are evoked only after activation of a sequence of synaptic relays in both cortex and spinal cord. The MEP threshold depends on the excitability of the synaptic relays at the level of the spinal cord in addition to the level of synaptic activity in the cortex. Because the excitability of the spinal synaptic relays is not well defined at rest, threshold may be best measured during active muscle contraction\(^32\) when the synaptic activity is better defined. Therefore, measuring MEP threshold while the subject actively contracts the thumb may produce a superior measure of cortical excitability and should be used in future investigations.

The WMFT and the Jebsen test were the outcome measures of choice because of their ability to detect and quantify improvements in speed of fine and gross motor skill performance in the upper extremity. Pinch grip force was chosen to assess the maximal voluntary activation of the muscles involved in pinching, a practical and important upper extremity activity. The assessments used in the laboratory sessions were selected for their ability to assess changes that would be applicable to meaningful real-world performance. The improvements in functional test scores and grip strength were consistent with anecdotal reports from the subjects in the studies. Subjects reported using the extremity undergoing the intervention more often than they had prior to participation in the study. For example, 1 subject realized he was automatically picking up the telephone with his right (weaker) hand, which he had never done since his injury. Others stated they were more aware of the potential ability of their affected extremity and were more willing to attempt tasks they previously deemed too difficult. The effect of intense, repetitive afferent input on strength and function must be recognized for its potential to impact function, and thereby quality of life, in individuals with incomplete cervical SCI.

Current rehabilitation practices focus on strategies to compensate for, rather than restore, function lost after SCI. While this is due in part to constraints on reimbursement, it is also due to the paucity of evidence supporting the efficacy of restorative strategies. For these strategies to be useful, they must be associated with meaningful change in functional motor performance and incorporate techniques that are widely available in the clinical and home setting. Theoretical and empirical evidence suggest that massed practice and somatosensory stimulation may be appropriate strategies to produce improvements in grip strength and upper extremity function in individuals with incomplete cervical SCI.

The findings of this study indicate that the combination of massed practice with somatosensory stimulation results in significant improvements in pinch grip strength and upper extremity function in individuals with incomplete cervical SCI. MP alone, although appearing to have a less robust effect than MP+SS, also contributes to improved
strength and function. Furthermore, the results of this preliminary study suggest that adding afferent information in the form of median nerve stimulation may enhance rehabilitative interventions that employ task-based training.

LIMITATIONS AND RECOMMENDATIONS

The study sample in this preliminary investigation was limited to 5 subjects in each group, which resulted in low power to detect differences between groups. Future studies should include F wave testing to measure spinal-level excitability in addition to cortical-level excitability. The addition of a 3rd study group receiving only the somatosensory stimulation for the 2-h training period would provide valuable information on the contribution of the somatosensory stimulation on cortical excitability and upper extremity function. Examining cortical excitability in the hemisphere associated with the untreated upper extremity or using a repeated measures approach (subjects serving as their own controls) would provide information regarding how MEP thresholds and amplitudes change over time. These methods can be used to identify the optimal stimulation protocol to combine with MP to achieve the greatest functional benefit.

It would also be beneficial to investigate the effect of somatosensory stimulation of nerves other than the median nerve on pinch grip force and function. The Jebsen test was always administered immediately after the WMFT on the testing day. This may be an explanation for the improvement seen in Jebsen timed scores but not on WMFT scores in the MP group. Randomly assigning the order of functional testing would prevent a learning effect that can result in better scores on the 2nd test.

Examining cortical excitability in the untreated upper extremity's hemisphere or using a repeated measures approach (subjects serve as their own control) would provide information on how MEP thresholds and amplitudes change over time. These methods can be used to identify the optimal stimulation protocol to combine with MP to achieve the greatest functional benefit.

CONCLUSIONS

The findings of this preliminary study suggest that massed practice may be useful to improve upper extremity function in individuals with SCI. Furthermore, it suggests that the combination of massed practice and somatosensory stimulation results in greater increases in pinch strength and timed functional test scores than massed practice training alone. Such a combination may be a beneficial rehabilitation technique to improve strength and function in individuals with incomplete cervical SCI. It is recommended that a randomized controlled study be conducted to investigate the effects of these interventions with a larger sample size, as well as to investigate the effect of somatosensory stimulation alone on cortical plasticity and function in individuals with SCI.

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