Cortical Reorganization Following Bimanual Training and Somatosensory Stimulation in an Individual With Cervical Spinal Cord Injury: A Case Report

Larisa R Hoffman, Edelle C Field-Fote

Background and Purpose
Deficits in upper-extremity function in individuals with tetraplegia are primarily due to the loss of motor pathways. Detrimental cortical reorganization, however, may create further loss of function. The purpose of this case report is to describe the cortical changes associated with a combination intervention using bimanual massed practice training with somatosensory stimulation.

Case Description
“BR” was a 22-year-old man with C6 tetraplegia and hand impairment who participated in this training intervention for 3 weeks.

Outcomes
BR demonstrated improvements in sensory function, strength (the force-generating quality of muscle), and performance of functional hand skills. Following the training, the cortical motor map of the biceps brachii muscle shifted anteriorly and increased in area and volume.

Discussion
This is the first documented case in which changes in the size and location of the cortical map were associated with an intervention and improvement in function in an individual with tetraplegia. This case suggests that an intensive training intervention may induce both functional and neurophysiological changes.

LR Hoffman, PT, MS, is a doctoral candidate, Department of Physical Therapy, University of Miami Miller School of Medicine, Coral Gables, Fla.

EC Field-Fote, PT, PhD, is Associate Professor, Department of Physical Therapy University of Miami Miller School of Medicine, 5915 Ponce de Leon Blvd, Coral Gables, FL 33146 (USA). Address all correspondence to Dr Field-Fote at: edee@miami.edu.


© 2007 American Physical Therapy Association
I

njury to the cervical spinal cord results in complete or partial loss of hand and arm function, severely limiting the performance of daily activities. Many individuals with tetraplegia cite recovery of arm and hand function as their most important goal during rehabilitation.1,2 Therefore, improving hand and arm function should be a compelling goal in rehabilitation research targeting individuals with cervical spinal cord injury (SCI).

Factors Contributing to Diminished Hand and Arm Function After SCI

Deficits of hand function in individuals with cervical SCI are primarily due to a loss of descending motor pathways that are vital for fine control of the hand and fingers. In addition to these deficits, secondary plastic reorganization may create further loss of function.3–6 Investigations with transcranial magnetic stimulation (TMS) have identified profound cortical reorganization in individuals with SCI whose muscles distal to the lesion have decreased cortical motor representation compared with individuals who are not disabled (eg, a smaller cortical motor hand representation in individuals with cervical SCI).7–10

In addition to the reduction in the size of the hand region of the motor cortex, the cortical area that controls the muscles of the hand (specifically the finger flexors) is shifted posteriorly in individuals with SCI compared with individuals who are not disabled.11–12 Previous investigators11–12 have suggested that this posterior shift provides evidence that individuals with SCI may rely more heavily on other, more posterior cortical areas, such as the sensory cortex, that contribute to the corticospinal tract.

The changes in cortical organization that occur after SCI are not dissimilar to those that occur following stroke. Therefore, we suggest that interventions that are effective in improving hand function in individuals with stroke also might be effective in individuals with SCI. Two interventions that have been shown to be effective in improving cortical control of movement in individuals with stroke are massed practice15,16 and somatosensory stimulation.15

Massed Practice

Massed practice is a form of task-oriented training that involves repetitive practice of discrete motor tasks. In task-oriented training, the goal is to practice the particular task, not just the individual movements required to perform the task. This form of training has been shown to be effective in improving performance of functional skills in individuals with stroke,16 and, furthermore, has been shown to be associated with cortical changes.14,17,18 Beekhuizen and Field-Fote19 have recently shown that subjects with incomplete, cervical SCI who are trained with a combination approach using massed practice with somatosensory stimulation demonstrate improvements in functional skills. In addition, there is a trend suggesting increased cortical excitability following training.

Prior studies of massed practice training have primarily been limited to unimanual task-oriented training.13,14,20 Individuals with SCI frequently have bilateral upper-extremity deficits and, therefore, may benefit from bimanual training. In bilateral upper-extremity tasks, the central nervous system must control a greater number of degrees of freedom than in unimanual tasks, resulting in greater cortical activation.21–23 There is both neurophysiological evidence and clinical evidence to suggest that bilateral movements may increase cortical excitability and thereby facilitate movement both in individuals who are not disabled24,25 and in individuals with impaired movement.26 The response of a muscle is greater when the contralateral homologous muscle is contracted.24,25 In addition, there are more cortical motor areas active during bimanual tasks than during unimanual tasks, even when the tasks are similar.21 Finally, there is clinical evidence that supports the use of training under a bimanual paradigm. In individuals with stroke, the peak velocity of the more involved arm is greater during a bilateral symmetrical reach than the same movement under unilateral conditions.27 If bimanual activities are associated with greater cortical drive, then bilateral massed practice training may be a way to improve functional arm and hand use in individuals with bilateral upper-extremity dysfunction.

Somatosensory Stimulation

The sensory cortex contributes to the corticospinal tract28,29 and contributes to the excitability of the motor cortex.30 Therefore, increasing the excitability of the sensory cortex could plausibly increase the efficacy of the corticospinal tract output. Furthermore, loss of sensory input is associated with decreased excitability of the corresponding area in the motor cortex.31–33 In both individuals without impairment34 and individuals with impaired movement,35 somatosensory stimulation is associated with increased cortical motor excitability. In individuals with weakness due to SCI35 or stroke,15 prolonged application of somatosensory stimulation alone increases pinch grasp force.15,35 It is plausible that, in SCI, somatosensory stimulation can increase the cortical excitability of the motor cortex and corticospinal tract.

The objectives of this case report are to describe the effects of a combined intervention on function and the cor-
This case suggests that an intensive training intervention may induce both functional and neurophysiological changes.

tical neurophysiology in an individual with a chronic, motor complete SCI. We hypothesized that bimanual massed practice training combined with somatosensory stimulation would be associated with increases in the cortical area and volume of the cortical motor map in this individual and thereby improve the ability to perform both unimanual and bimanual tasks.

Case Description

Patient Description and History

“BR” is a 22-year-old man with a diagnosis of chronic, motor complete SCI at the level of C6. According to the American Spinal Injury Association (ASIA) Neurological Classification, BR’s injury would be classified as ASIA B. Immediately following his injury, BR had a tracheotomy and was dependent on a ventilator for respiratory function for 4 months. He was unable to perform any functional activities with his hands or arms. He remained in the intensive care unit for 2 months before he was transferred to inpatient rehabilitation. His inpatient rehabilitation program consisted of two 45-minute sessions of occupational therapy and two 45-minute sessions of physical therapy each day.

After 2 months, BR was discharged home where he received outpatient physical therapy and occupational therapy services 3 days a week for 1 hour each. His therapy programs incorporated upper-extremity strengthening exercises, neuromuscular electrical stimulation (NMES) to the wrist extensors, and learning compensatory strategies such as tenodesis to improve grasping and pinching functions. At the time of discharge from outpatient services, BR required assistance from his mother for upper- and lower-body dressing and for catheterization. He relied on an assistive device to eat independently. At the time of this examination, BR was 1 year after his injury. BR reported that he was right hand dominant both before his injury and during the evaluation. BR stated that his goal was to improve his ability to use his hands and to decrease his reliance on his mother and his assistive devices.

Examination and Evaluation

BR met the screening criteria for participation in this case study, which included a cervical SCI at C7 or above, an intact peripheral median nerve, and the ability to pick up a small object (large paperclip) from the table independently. These criteria were selected in order to ensure that the patient had hand impairment, could perform training and test activities, and had intact innervation of the thenar muscles. BR was interviewed to ensure he did not have a history of brain injury, stroke, seizure, or metal devices in the cranium. A history of any of these conditions increases the probability of seizure associated with the use of TMS.37

After being familiarized with the procedures and risks associated with participating in this case study, BR signed an informed consent statement that had been approved by the Institutional Review Board at the University of Miami, Miami, Fla. BR entered the treatment area in his power wheelchair with his upper extremities resting on the arm rests. The examination focused on upper-extremity function, including sensory function, strength (the force-generating quality of muscle), and performance of unimanual and bimanual fine motor skills. These outcome measures were chosen to include a variety of measures at different levels of the International Classification of Functioning, Disability and Health (ICF).38 Sensory function and strength would fall into the domain of “body functions and structures,” whereas the measures of unimanual and bimanual performance would fall into the domain of “activity limitation.” We did not include a measure of participation or participation restriction.

Sensation. BR’s sensation was impaired throughout his upper extremities. The lowest level of normal sensation was at the C5 dermatome, and his zone of partial preservation extended down to the T8 dermatome bilaterally. He had greater perception of light touch than of pain, and slightly greater sensation on the left than the right (Tab. 1).

Strength. Table 2 lists the ASIA Motor Scores for BR’s upper-extremity muscles. BR was able to abduct his shoulders against gravity and full resistance (5/5) and flex both his elbows against gravity and full resistance (5/5). He was able to extend his right elbow in a gravity-eliminated position (2/5), but had only trace activity in his left elbow extensors (1/5). He was able to extend his wrists against gravity and full resistance bilaterally (5/5), but was not able to flex his wrist in either hand (0/5). He had trace movement in his right finger extensors (1/5) and the right first dorsal interossei in his right hand (1/5). He had no voluntary movement in his finger flexors, thenar muscles, or hypothenar muscles bilaterally (0/5). He also had no voluntary movement in his trunk or lower extremities (Tab. 2).
Unimanual hand function. With the postural support of his trunk strap, he was able to reach using shoulder flexion or abduction without difficulty. To pick up large items, BR preferred to use both upper extremities, holding the object between the volar surfaces of both wrists together. If instructed to lift the object using one hand alone, BR used a tenodesis grasp and, after several attempts, was able to lift the item. His right tenodesis grasp was more effective than his left, which was illustrated by his inability to pick up heavier objects with his left hand. During most lifting tasks, BR would compensate for hand and arm weakness by using shoulder abduction, thereby increasing his wrist extension and the power of his tenodesis grasp.

BR had difficulty picking up smaller objects, and he preferred to use the lateral aspect of his fifth finger to sweep an object across a surface. To pick up the object, BR had to slide it with the ulnar border of his hand to the edge of the table in order to get his thumb on the underside of the object. This strategy was not consistently successful, because BR frequently slid the object off the table onto the floor. During writing tasks, BR used a lateral pinch grasp to hold the pen and used shoulder movements (rather than wrist movements) to control the pen motions. When using a spoon, BR wove it between his fingers to prevent the utensil from dropping when he manipulated it. BR was able to use a tenodesis grasp to pick up empty soup cans.

Bimanual hand function. When performing a bimanual task, BR used his left hand to stabilize the object on the surface, and the ulnar side of his right hand to manipulate the object. For example, when opening a container, BR stabilized it with his left hand using a tenodesis grasp and

---

**Table 1. Individual Preintervention and Postintervention Upper-Extremity American Spinal Injury Association (ASIA) Sensory Scores**

<table>
<thead>
<tr>
<th>Upper-Extremity Dermatomes</th>
<th>Preintervention Light Touch</th>
<th>Preintervention Pinprick</th>
<th>Postintervention Light Touch</th>
<th>Postintervention Pinprick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Upper Extremity</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Left Upper Extremity</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

---

**Table continued**

<table>
<thead>
<tr>
<th>Upper-Extremity Dermatomes</th>
<th>Preintervention Light Touch</th>
<th>Preintervention Pinprick</th>
<th>Postintervention Light Touch</th>
<th>Postintervention Pinprick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Upper Extremity</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Left Upper Extremity</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

---

**Table continued**

<table>
<thead>
<tr>
<th>Upper-Extremity Dermatomes</th>
<th>Preintervention Light Touch</th>
<th>Preintervention Pinprick</th>
<th>Postintervention Light Touch</th>
<th>Postintervention Pinprick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Upper Extremity</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Left Upper Extremity</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

---

**Table continued**

<table>
<thead>
<tr>
<th>Upper-Extremity Dermatomes</th>
<th>Preintervention Light Touch</th>
<th>Preintervention Pinprick</th>
<th>Postintervention Light Touch</th>
<th>Postintervention Pinprick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Upper Extremity</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Left Upper Extremity</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

---

**Table continued**

<table>
<thead>
<tr>
<th>Upper-Extremity Dermatomes</th>
<th>Preintervention Light Touch</th>
<th>Preintervention Pinprick</th>
<th>Postintervention Light Touch</th>
<th>Postintervention Pinprick</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Upper Extremity</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Left Upper Extremity</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
used the ulnar border of his right hand to spin the lid off the container. BR had difficulty with finger isolation required for pressing buttons on a phone, if his other hand was holding the receiver. He was able to complete this task by hyperextending his right thumb to press the buttons. BR did not have sufficient strength in his tenodesis grasp to squeeze the toothpaste tube while stabilizing a toothbrush. Likewise, he was not able to maintain his grasp on both a knife and fork during cutting. BR required the assistance of his right hand during the manipulative portions of dressing tasks such as zipping a zipper and buttoning buttons.

Preintervention testing. The preintervention and postintervention testing procedures, as well as the intervention, were performed by the same physical therapist. The outcome measures were divided into 2 categories: clinical outcome measures and neurophysiological outcome measures. The clinical outcome measures of interest were sensory function, strength, and motor function. The neurophysiological outcome measures were cortical excitability, cortical map area, cortical volume, and center of gravity (COG). Tables 1, 2, 3, 4, and 5 contain the results of preintervention and postintervention testing.

Sensory function was measured by the ASIA sensory score and the Semmes-Weinstein monofilament test. Sensory testing was performed according to the ASIA guidelines. Interrater reliability of the sensory evaluation in individuals with complete tetraplegia, as measured by the intraclass correlation coefficient (ICC), is .94 for pinprick and .93 for light touch. Semmes-Weinstein monofilament testing was used to measure the degree of sensitivity in the median nerve region. The median nerve region was tested at the tip of the thumb, tip of the index finger, and base of the index finger. This test includes 5 monofilaments ranging in diameter from 2.83 mm to 6.65 mm.

With BR’s eyes closed, the smallest monofilament was used first. The monofilament was depressed until it bent and was removed after 1.5 seconds. The subject was instructed to respond verbally when a touch was perceived. If BR did not respond, the next larger monofilament was used. Increasingly larger monofilaments were used until BR responded to at least 5 out of 10 stimuli with the same monofilament. The median monofilament diameter for the 3 sites was determined and this was considered the monofilament test.

Table 2.
Preintervention and Postintervention American Spinal Injury Association (ASIA) Motor Scores for Individual Upper-Extremity Muscles and Total Upper-Extremity Motor Score

<table>
<thead>
<tr>
<th>Key Upper-Extremity Muscles</th>
<th>Right Upper Extremity</th>
<th>Left Upper Extremity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preintervention</td>
<td>Postintervention</td>
</tr>
<tr>
<td>Elbow flexors</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Wrist extensors</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Elbow extensors</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Finger flexors</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Finger abductors</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total UE score</td>
<td>12</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 3.
Summary of Preintervention and Postintervention Results From Sensory Tests, Strength Test, and Jebsen-Taylor Hand Function Test

<table>
<thead>
<tr>
<th>Clinical Test</th>
<th>Right Upper Extremity</th>
<th>Left Upper Extremity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Preintervention</td>
<td>Postintervention</td>
</tr>
<tr>
<td>Semmes-Weinstein monofilament test (median diameter) (mm)</td>
<td>3.61</td>
<td>2.83</td>
</tr>
<tr>
<td>Upper-extremity motor scores</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>Jebsen-Taylor Hand Function Test (s)</td>
<td>172.01</td>
<td>114.97</td>
</tr>
</tbody>
</table>
score. A lower score indicates a smaller median monofilament diameter and, therefore, better sensory function.\textsuperscript{41,42} The interrater reliability of Semmes-Weinstein monofilament testing in individuals with peripheral nerve injury, as well as control subjects without disability, as measured by the ICC is .965.\textsuperscript{41,43} In addition, the responsiveness to change has an effect size of 1.5 in individuals recovering from peripheral nerve damage.\textsuperscript{41,43}

Manual muscle testing of key muscles on the ASIA motor scale was performed in both upper extremities as described by Noreau and Vachon.\textsuperscript{44} The Interrater agreement of manual muscle tests in upper-extremity muscles of individuals who were able-bodied and individuals with reduced muscle strength has kappa values of .54 and .57, respectively.\textsuperscript{45} In individuals with tetraplegia, the correlation (\(r\)) between upper-extremity manual muscle test scores and myometry is between .50 and .95, although there is great variability of muscle force within each manual muscle test grade.\textsuperscript{44}

### Table 4.
Preintervention and Postintervention Scores (in Seconds) on Individual Items on the Jebsen-Taylor Hand Function Test\textsuperscript{a}

<table>
<thead>
<tr>
<th>Task</th>
<th>Preintervention</th>
<th>Postintervention</th>
<th>Preintervention</th>
<th>Postintervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>Writing</td>
<td>39.55</td>
<td>25.44</td>
<td>40.34</td>
<td>38.60</td>
</tr>
<tr>
<td>Page turning</td>
<td>17.45</td>
<td>15.49</td>
<td>20.78</td>
<td>22.01</td>
</tr>
<tr>
<td>Small object</td>
<td>Unable</td>
<td>33.37</td>
<td>Unable</td>
<td>34.48</td>
</tr>
<tr>
<td>Feeding</td>
<td>28.38</td>
<td>19.88</td>
<td>36.79</td>
<td>15.14</td>
</tr>
<tr>
<td>Checkers</td>
<td>17.12</td>
<td>16.33</td>
<td>29.45</td>
<td>27.02</td>
</tr>
<tr>
<td>Lift light object</td>
<td>19.02</td>
<td>18.20</td>
<td>24.07</td>
<td>60.21</td>
</tr>
<tr>
<td>Lift heavy object</td>
<td>50.49</td>
<td>19.63</td>
<td>Unable</td>
<td>23.04</td>
</tr>
<tr>
<td>Total time</td>
<td>172.01</td>
<td>114.97</td>
<td>151.43</td>
<td>162.98</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Total time includes the summated times for all tasks the individual completed independently prior to intervention. Decrease in total time indicates an increase in speed of performing the tasks on the Jebsen-Taylor Hand Function Test.

### Table 5.
Preintervention and Postintervention Scores on Individual Items of the Chedoke Arm and Hand Inventory\textsuperscript{a}

<table>
<thead>
<tr>
<th>Task</th>
<th>Preintervention Score</th>
<th>Preintervention Time (s)</th>
<th>Postintervention Score</th>
<th>Postintervention Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open jar</td>
<td>6</td>
<td>8.90</td>
<td>6</td>
<td>9.27</td>
</tr>
<tr>
<td>Dial 911</td>
<td>6</td>
<td>6.18</td>
<td>6</td>
<td>5.61</td>
</tr>
<tr>
<td>Line draw with ruler</td>
<td>6</td>
<td>3.33</td>
<td>6</td>
<td>7.77</td>
</tr>
<tr>
<td>Toothpaste on toothbrush</td>
<td>4 Requires assistance</td>
<td>108.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cutting with knife/fork</td>
<td>3 Requires assistance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pitcher pour</td>
<td>4</td>
<td>12.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wiring cloth</td>
<td>6</td>
<td>11.74</td>
<td>6</td>
<td>16.81</td>
</tr>
<tr>
<td>Clean eyeglasses</td>
<td>6</td>
<td>24.00</td>
<td>6</td>
<td>117.87</td>
</tr>
<tr>
<td>Zipper</td>
<td>2</td>
<td>Requires assistance</td>
<td>6</td>
<td>Requires assistance</td>
</tr>
<tr>
<td>Do 5 buttons</td>
<td>3</td>
<td>Requires assistance</td>
<td>3</td>
<td>Requires assistance</td>
</tr>
<tr>
<td>Dry back</td>
<td>6</td>
<td>65.94</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>52</td>
<td>117.14</td>
<td>62</td>
<td>117.14</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Total time includes the summated times for all tasks the individual completed independently prior to intervention. Maximum total score is 77. Higher score indicates increased independence. A decrease in time indicates an increased speed of performance.
Upper-extremity motor function was measured using both a test of unimanual hand function (Jebsen-Taylor Hand Function Test) and a test of bimanual hand function (Chedoke Arm and Hand Activity Inventory). The Jebsen-Taylor Hand Function Test assesses the capacity of unilateral hand function and improvement in hand function associated with therapeutic interventions. It is a 7-part, timed test that incorporates writing, turning pages, picking up small objects, feeding, stacking, picking up large objects, and picking up heavy objects. The total score is the sum of the times for each of the individual items. This test has been validated for use in individuals with C6 and C7 tetraplegia. The test-retest reliability (r) is .89 to .99 in individuals with neurological disorders with movement impairment. This measure of unimanual hand function was investigated in both hands individually.

The Chedoke Arm and Hand Activity Inventory was designed to measure the performance of bilateral hand tasks as they relate to functional ability in individuals with stroke. There are 13 items and each item is given a score from 1 to 7, with 1 being dependent or unable to perform the task and 7 being independent. The interrater reliability of the Chedoke Arm and Hand Activity Inventory in individuals with stroke has an ICC of .98. This standardized functional measure has not been validated in individuals with SCI; however, there is currently no standardized measure of bimanual function for use in this population.

A score of 6 (on the Chedoke Arm and Hand Inventory) is defined as modified independent (requiring an assistive device or greater than normal amount of time to perform the task independently), whereas a score of 7 is defined as independent (the ability to perform the task independently in a timely and safe manner). To determine whether the task was done in a timely manner, the time to perform each task was measured in 10 individuals with SCI who scored a 7 on the item. For future trials, the score was defined as 7 if the time to perform the task was within 1.5 standard deviations of the mean time. Furthermore, to determine whether the individual required an assistive device, the task was first attempted without the device, and then with the device if the individual was unable perform the task without it.

The scores alone may not be able to capture improvements in performance of a task for which an assistive device is not required, but additional time is required at preintervention testing. Therefore, in addition to the score provided for each item, the time to perform each task was measured. This was done to provide a measure of change between a score of 6 and 7. The total time score reflects the summated time to complete all items in which the individual scored a 6 or 7. We have found the measures of speed of performance to be reliable and sensitive to change in individuals with SCI (unpublished observation).

We used TMS to assess changes in the neurophysiological measures of interest. Monophasic TMS was delivered by a Magstim 200 stimulator (maximum magnetic field strength=2 Tesla) using a figure-8 coil. To probe for changes in cortical potentials, we tested cortical excitability of the biceps brachii muscle in the dominant arm, as measured by resting motor threshold (MT), cortical map area, cortical map volume, and COG of the cortical map. The biceps brachii muscle was chosen as the representative test muscle because most of the intervention activities were tasks that required use of the elbow flexor muscles. In addition, BR did not have voluntary control of the thenar muscles, which had been the focus of testing in previous studies in this lab. Furthermore, we were unable to evoke a motor-evoked potential (MEP) in other intrinsic hand muscles, even at the highest intensity of TMS. The right side was chosen because this was the dominant hand and performed most of the manipulative portions of the bimanual activities during the evaluation.

The test-retest reliability (ICC) of resting MT of the upper-extremity muscles in individuals without impairment is.90 to .97. The area of the cortical map of upper limb muscles in individuals without impairment is a stable measure having reliability (ICC) of .63 to .86. The location of the COG in individuals without impairment also has reliability (ICC) of .69 to .86, with greater reliability in the medial-to-lateral coordinate than in the anterior-to-posterior coordinate. In individuals with impaired movement due to stroke, Butler et al found no between-session variability over 3 sessions for resting MT, cortical map area, normalized cortical map volume, and shift in COG. For neurophysiological testing, BR sat reclined on a treatment table in a long-sitting position with a headrest to minimize head movement. A pillow supported his upper extremities in a position of slight shoulder flexion and elbow flexion. He was fitted with a tight-fitting cap (Magicap Elite) that was imprinted with a grid marking out 0.65-cm squares. To ensure reliable placement of the cap, marks were placed on the cap indi-
cating the location of the nasion, inion, and ears.

The biceps was palpated and the overlying skin was abraded with an alcohol swab. Two surface silver-silver chloride electrodes were placed 2 cm apart over the lower third of the distal muscle belly of the biceps brachii muscle with a ground electrode over the olecranon. To ensure the muscle was at rest, 10 milliseconds was recorded before and 200 milliseconds was recorded after the stimulus was applied. The electro-myographic signals were amplified and band-pass filtered (Grass S88 stimulator)\(^3\) (10 Hz-2 kHz) and digitized at 2 kHz with an analog-to-digital converter (model 1401).\(^3\) Data was stored using a digital acquisition program and analyzed off-line with customized software (Signal Data Acquisition Software).\(^1\)

The TMS coil was placed directly on the cap over the left hemisphere with the handle pointing 45 degrees posteriorly and laterally, because this position is known to most directly activate the corticospinal tract.\(^50\) The biceps region was estimated to be approximately 5 cm lateral to the central sulcus, along the interaural line. The cortical upper-extremity region was stimulated at 90% of maximal stimulator output (MSO), and the coil was moved in small increments until the “hot spot” (ie, the site at which the amplitude is greatest and latency is shortest) was found.\(^51\) To determine the MT at the hot spot, stimulus intensity was initially set at a level that did not evoke a motor response (30% MSO) and systematically increased in 5% increments. Motor threshold was defined as minimum stimulus intensity at which 3 out of 6 responses of at least 50 microvolts were achieved.\(^52\) To create the motor map, the stimulator intensity was increased to 1.2 times MT. Starting at Cz (the point at which the interaural line and the line connecting nasion and inion intersect), each site on the grid of the cap was stimulated 3 times.\(^51\) The coil was moved laterally by 0.65-cm increments until reaching an area at which no MEP could be evoked at the test intensity. The map area (in square centimeters) was defined as the region encompassing sites from which an MEP of greater than 50 mV could be evoked.

The normalized cortical volume normalized cortical volume was defined as the sum of all active sites normalized to the maximum MEP of the motor map.\(^53\)\(^,\)\(^54\) The COG was found by creating a map representing the amplitude-weighted sites of the excitabale area, according to the procedure described by Ridding et al.\(^34\) To determine whether there was a shift in the excitabale region, the COG of the motor map was determined by weighting the normalized MEP amplitudes according to the distance from the hot spot (\(x=0, y=0\)).

Each site was weighted for both its longitudinal and latitudinal position relative to the hot spot. Using this convention, sites more anterior to the original hot spot had weightings that were increasingly positive; conversely, sites more posterior to the original hot spot had weightings that were increasingly negative. Likewise, sites more distant from the original hot spot in the lateral direction were increasingly negative, whereas sites more medial to the original hot spot were increasingly positive. Therefore, a shift in the anterior direction would be reflected by an increase in the longitudinal or \(y\) values; likewise, a shift to the medial direction would be reflected by a increase in the latitudinal or \(x\) values. The formula for the longitudinal value of the COG calculation is as follows:

\[
X_{COG} = \frac{\sum a_i x_i}{\sum a_i}
\]

Where \(a_i\) is the mean amplitude at an individual scalp site whose coordinate is \(x_i\) centimeters from the hot spot.

Postintervention testing. Postintervention testing was completed 3 days following the intervention. The tests were performed by the same physical therapist and in the same manner as the preintervention testing (Tabs. 1, 2, 3, 4, and 5).

**Intervention**

BR was instructed to maintain his current exercise program and was asked not to participate in any new therapies or exercises during the course of the intervention. The intervention protocol BR performed consisted of bimanual massed practice training in conjunction with somatosensory stimulation, for 2 hours a day, 5 days a week, for 3 weeks. The somatosensory stimulation was applied to only the right hand. Surface silver-silver chloride electrodes were placed on the volar surface of the wrist over the median nerve. The somatosensory stimulation was delivered using a constant current stimulator (Digitimer model DS7A)\(^9\) according to a previously published protocol.\(^15\)\(^,\)\(^19\) The trains were delivered at a frequency of 1 Hz, where one train consisted of 5 pulses of 1-millisecond in duration, at a frequency of 10 pulses per second, with a stimulus intensity just below that which evoked an observable
A twitch in any of the muscles innervated by the median nerve. This type of stimulation is thought to preferentially activate Ia nerve fibers.\textsuperscript{55} The average stimulus intensity was 2.3 milliamperes across the 15 intervention days. The stimulation was applied concurrently with the task training activities.

The bimanual massed practice protocol was modeled after the unimanual massed practice training described in previously published reports from our lab,\textsuperscript{19} with slight modifications so that BR performed bimanual activities throughout the training. These activities were divided into 5 movement categories that focused on the distal extremity (Fig. 1 provides an abbreviated version of the tasks).

**Figure 1.**
Abbreviated list of items and movement categories in bimanual massed practice training. Product manufacturers: Ziploc (SC Johnson, 1525 Howe St, Racine, WI 53403-5011.), Lego (LEGO Co, Global Company Communications, DK-7190 Billund, Denmark), and Rubik’s Cube (Ideal Toy Company, no longer in operation).
The movement categories were grasp, grasp with rotation, pinch, pinch with rotation, and finger isolation.

The tasks were bimanual because BR was asked to use both hands simultaneously throughout the intervention. The tasks were both symmetrical and asymmetrical in nature, meaning that some tasks required both hands to perform a similar movement pattern (such as typing or plugging in extension cords), whereas other tasks required each hand to perform a different movement pattern. In tasks that were symmetrical, BR was encouraged to perform similar movement patterns with both hands simultaneously. For example, in the piano keyboard task, BR was instructed to press the keys using both first fingers simultaneously, then the second fingers, and third fingers. In asymmetrical movement tasks, one hand functions as an assistive or stabilizing hand and the other hand performs the manipulative portions of the task (such as opening a can with a can opener). For asymmetrical tasks, BR was allowed to choose which aspect of the task each hand would perform. For example, when performing the can opener task, it is easier to stabilize the handle of the can opener with the left hand and manipulate the dial with the right hand because of the design of the tool.

The focus of the intervention was restoration of a movement pattern typical of individuals who were not disabled; compensatory strategies were discouraged. For example, BR preferred to grasp writing or eating utensils using either a lateral pinch grasp between his second and third fingers; however, during the training, BR was instructed to use a tripod grasp to grasp the utensil.

Each training session was 2 hours in duration, and each movement category was practiced for 20 to 25 minutes. Each movement category had 5 to 10 associated activities; the subject selected one of these randomly by picking from an associated stack of index cards. The tasks were chosen at random to ensure that a variety of tasks were performed. The intent was to practice a variety of tasks to engage the hand in as many degrees of freedom as possible. During the course of each training session, 2 tasks were performed within each movement category. Considering task set up and rest breaks, approximately 90% of the training session was spent practicing tasks.

Some tasks were more challenging than others for this patient. If BR was unable to complete a task independently, hand-over-hand assistance was provided to ensure he could complete the task successfully (see the grasp with rotation task in Fig. 1). Hand-over-hand assistance is the assistance provided over the patient’s hands (not the object) so that the patient is able to complete the task as independently as possible. Assistance was gradually reduced until BR could perform the task independently. If the task was not challenging for him, the demands of the task were increased by altering the setup. This was necessary in the writing task, in which he was instructed to draw circles and intersecting lines of various sizes using an ink pen. This task gradually became easier and it was necessary to increase the difficulty. We changed the writing utensil from an ink pen to a pencil and finally to a crayon, which require progressively greater force on the writing utensil to mark the paper. This was done to ensure that the tasks were sufficiently challenging because evidence suggests that tasks must be sufficiently challenging to induce cortical reorganization.56

Outcomes
Clinical Outcome Measures
Most of the changes in sensory function were found in the right upper extremity (Tab. 1). BR’s perception of light touch on the right changed from absent (score of 0) to normal (score of 2) after intervention in the 4 dermatome regions of C6–T1. His perception of pinprick on the right changed from absent or impaired to normal in the 4 dermatome regions of C6–T1. These changes in sensation are located both at the level of the injury and in the zone of partial preservation. His sensory scores in the left upper extremity changed only in the distribution for C5 for both light touch and pinprick from impaired (score of 1) to normal (score of 2).

As with the ASIA sensory testing, the changes in Semmes-Weinstein monofilament test score were in the right upper limb. Before intervention, the median monofilament diameter that BR responded to was 3.61 mm for both the right median nerve region and the left median nerve region (Tab. 3). After intervention, BR’s sensation in the right median nerve region improved so that he responded to the smallest monofilament (filament diameter=2.83 mm) at all 3 tested sites; however, the left side remained unchanged.

Strength was measured using manual muscle testing. The only change observed in BR’s motor scores was an increase in the triceps muscle score bilaterally (Tab. 2). On the right he increased from an ability to extend the elbow only in a gravity-eliminated position (2/5) to the ability to extend the elbow against gravity (3/5), whereas on the left he increased from a trace contraction (1/5) to able to extend the elbow in a gravity-eliminated position (2/5).
On the Jebsen-Taylor Hand Function Test, BR improved in his speed of performing unimanual tasks on the right from 172.01 seconds to 114.97 seconds, but did not improve in his speed on the left, where his time increased from 151.43 seconds to 162.98 seconds (Tabs. 3 and 4). At preintervention testing, BR had the greatest difficulty with picking up small items such as paper clips, pennies, and bottle caps. These items would frequently fall to the floor as he attempted to pick up the object. BR also had difficulty with grasping heavy objects, because his tenodesis grasp was not consistently strong enough to overcome the weight of the object. He was not able to complete either of these tasks with his left hand prior to the intervention.

At postintervention testing, he was able to pick up small objects (e.g., pennies and paper clips) with either hand independently, and pick up large heavy objects (e.g., empty and full aluminum cans) with his left hand. BR's total time score on the Jebsen-Taylor Hand Function Test on the right improved by 33.1%, whereas as his total time on the left changed by -0.1%.

On the Chedoke Arm and Hand Activity Inventory, BR's total score improved from 52 to 62 (maximum score = 110), demonstrating a 19% increase in total score (Tab. 5). Before intervention, BR was able to complete 6 out of 11 items independently, but required more than a reasonable amount of time these items. For tasks that required grasp strength, such as squeezing toothpaste onto a toothbrush or cutting with a knife and fork, BR required assistance with setup such as orienting objects in his hands. Finally, dressing tasks were most difficult, because BR required moderate assistance to manipulate the fastener.

After intervention, he improved on the following items: putting toothpaste on toothbrush, cutting with a fork and knife, pouring a pitcher of water, and zipping up a zipper. On these items, BR improved from either a moderate assistance (score of 3) or minimal assistance (score of 4) to requires assistance with setup (score of 5) or modified independent (score of 6). BR improved most on items with which he previously required assistance.

Items in which BR scored 6 out of 7 at the preintervention testing session did not change by the postintervention test. On some of these items (i.e., pressing buttons on a phone, wringing out a washcloth, and cleaning eyeglasses), he improved in the time to complete these tasks; however, this was not reflected in a change of score. On other items, BR increased slightly in time to complete the task, but the movement pattern chosen was more similar to that used by individuals who are not disabled. For example, before the intervention, the line drawing task was performed using a lateral digital grasp with the pencil; however, following training, BR used a tripod grasp. Another example is opening a screw-top container, where, before intervention, he used the ulnar border of his hand and fifth digit to spin the lid off; after intervention, BR used a whole hand grasp on the lid. Of the tasks that BR was able to perform independently, he demonstrated an 11.5% increase in the time to perform these tasks after intervention compared with his times before the intervention.

Finally, BR composed a list of the new functional skills he used in daily life that he was able to perform independently after training that he had not previously been able to perform (Fig. 2). Although some of these items were the same as the training tasks (such as buttons and zippers), other new skills were not included among the training tasks and were unrelated to the specific training tasks such as opening car doors and windows. This demonstrates a transfer of the training tasks to other skills.

**Outcomes for TMS Measures**

There was no change in MT for the cortical representation of the right biceps brachii muscle. Both before and after intervention, BR's MT for the biceps brachii was 57% MSO. However, the area of the cortical map increased by 8 additional sites.
Before intervention, the area of active sites in BR’s right biceps muscle was 43 cm², whereas after intervention, the area increased to 52 cm² (Fig. 3). The normalized map volume increased from 21.1 cm³ before intervention to 28.6 cm³ after intervention. The COG shifted to a more anterior position by 1.56 cm and to a more medial position by 0.30 cm. Before intervention, the COG was posteriorly shifted relative to the location typical of individuals who were not disabled, at a map (x,y) coordinate of (−0.76, −0.46). This coordinate position is 1.30 cm posterior to Cz (i.e., the point at which the interaural line and the line connecting nasion and inion intersect). After intervention, the COG had shifted to a map coordinate of (−0.30, 1.08). This coordinate position is 0.26 cm anterior to Cz.

Discussion

The outcomes of this case report suggest that bimanual training coupled with somatosensory stimulation may induce cortical reorganization that is associated with improvements in function for individuals with chronic cervical SCI. There were gains noted in sensory function, performance of unimanual tasks, and performance of bimanual tasks. These gains were accompanied by increased area and volume of the motor map associated with a muscle (the biceps brachii muscle) that was used to probe the excitability of the cortex, as well as a shift in the COG of the cortical map to a more anterior position.

Improvements in sensory function occurred within the zone of partial preservation, suggesting that improvements in sensory function can occur through activation of spared pathways. Improvements in sensory function are similar to earlier results from our lab,19 in which we found changes in sensory function in individuals with motor incomplete SCI.
who received either somatosensory stimulation or massed practice in combination with somatosensory stimulation.\textsuperscript{19,35} Thus, we are unable to differentiate the improvements in sensory function due to either intervention independently. In prior studies completed in our lab, however, the greatest improvements in sensory function were observed in individuals who were assigned to a combination of somatosensory stimulation and massed practice training.\textsuperscript{19,35}

The improvements in strength of the triceps muscles were surprising, because the triceps were not targeted by the training. In addition, the focus of the training was not on strengthening but on function and skilled movement. We hypothesize that the training led to an increase in upper-extremity use and independence of function, which could account for the increase in triceps strength. Alternatively, training may be associated with a generalized improvement in cortical control, resulting in improved ability to activate upper-extremity muscles.

BR demonstrated improvements in both time to perform tasks and the number of tasks he was able to perform. Although unimanual tasks were not the focus of the intervention, these tasks improved for BR’s dominant hand. Mudie et al\textsuperscript{57} reported similar findings in which individuals with stroke who participated in a bimanual training program demonstrated improvements in unimanual reaching and grasping tasks. Cauraugh et al\textsuperscript{58} investigated the effects of a training program that incorporated either bimanual or unimanual active wrist extension in conjunction with NMES in individuals with stroke; they noted a change in performance of unimanual skills, including greater hand manipulation, faster reaction times, and sustained voluntary muscle contractions. Prior studies comparing the effects of somatosensory stimulation or massed practice alone have shown that individuals who were assigned to massed practice training demonstrated improvements on the Jebsen-Taylor Hand Function Test, whereas those assigned to somatosensory stimulation group did not improve in this outcome measure.\textsuperscript{35} Individuals who participated in a combination approach, however, demonstrated even greater gains in function; therefore, the relative contribution of either intervention alone cannot be revealed in this case.

BR demonstrated greater gains in unimanual hand function in the right hand compared with the left hand. The greater gains on the right are likely due to hand dominance. Both before his injury and before and after training, BR spontaneously used his right hand for unimanual tasks such as writing and picking up small objects, whereas he frequently chose to use his left hand as an assistive hand.

BR’s scores on the Chedoke Arm and Hand Activity Inventory improved on items for which he scored lower than modified independence (a score of 6) before intervention. BR’s speed in performing bimanual tasks improved on some tasks, but not all. The speed of performance of some tasks did not improve, which may be due to a change in strategy to perform the task, a factor that is not measured by this time-based test. For example, before intervention, BR opened the screw-top container by stabilizing the jar with his left hand and spinning the lid with the ulnar border of his right hand and fifth digit using an ulnar deviation motion. This is a very efficient strategy in that it takes little effort and time because it has been well learned; however, this motor strategy is not flexible. If presented with a container without ridges or a container with a lid that was tightly screwed on, this strategy would fail.

After intervention, BR was presented with the same container, which was not tightly screwed on, and he approached it with a new movement pattern. This new pattern may require more energy and time, but works in a variety of circumstances. Likewise, the pencil grasp chosen after intervention had changed from a lateral pinch grasp to a tripod grasp. The tripod grasp allows greater control of the tip of the utensil. Because these movement strategies were new, BR may have taken longer to perform the task, and, therefore, appearing as if he had not improved on the time-based test. Once the strategy becomes well learned, however, it is likely that it will take less time to perform and impart a greater degree of functionality.

The improvements we observed in sensory and motor function coincided with an enlargement of the motor map of a muscle used to probe cortical excitability, as well as a shift in the COG of the map from a posterior position (associated with the sensory cortex) to a more anterior position (associated with the motor cortex). This change in size of the cortical motor area has been shown to be associated with both electrical stimulation as well as skill development.\textsuperscript{17,54}

Somatosensory stimulation has been shown to increase cortical motor excitability in both individuals who are not disabled\textsuperscript{84} and individuals with SCI.\textsuperscript{19,35} This type of stimulation is thought to preferentially activate the large sensory fibers associated with the Ia muscle afferents.\textsuperscript{55} It may be that activity of muscle afferents plays a critical component in inducing cortical reorganization. The disruption of cutaneous and joint afferents alone does not result
in a reduction in the corresponding cortical excitability,\textsuperscript{31} whereas the disruption of muscle, joint, and cutaneous afferents does result in decreased cortical excitability.\textsuperscript{32} Prior investigations\textsuperscript{15,34,59} have examined the immediate effects of providing somatosensory stimulation and shown that this type of input does increase cortical excitability. We measured the more prolonged effects of this type of input and identified no change in excitability, but changes in the location and area of the map. Thus, somatosensory stimulation may increase cortical motor excitability immediately following stimulation, preparing the system for reorganization that occurs during a longer timescale.

In this case report, some measures of cortical motor excitability, such as motor threshold, did not change, but other measures of cortical motor excitability, such as cortical map volume, increased. In other investigations, muscles innervated by the stimulating nerve have increased in cortical motor excitability.\textsuperscript{34} In this case, BR could not voluntarily activate the thenar muscles; however, muscles innervated by the same nerve root also may increase in cortical excitability, because both the rostral contribution of the median nerve and the musculocutaneous nerve both originate from C5-C6.

Despite the lack of change in MT, the size of the cortical representation of the biceps brachii muscle increased, which also was associated with improvements in skill. This association between the size of the cortical representation and skilled performance also has been demonstrated in both animal models and clinical populations. Adult squirrel monkeys with localized infarctions to the cortical motor hand area that undergo intense hand training exhibit an enlargement of the hand region of the motor cortex in conjunction with improvements in hand function.\textsuperscript{60} Although techniques for direct measurement of cortical excitability cannot be performed with human subjects, similar findings have been demonstrated in clinical populations through more indirect methods. Luft et al\textsuperscript{61} investigated the cortical changes associated with a bilateral upper-extremity training program. The investigators found greater activation of the contralateral hemisphere (as measured by functional magnetic resonance imaging) following bilateral training. Liepert et al\textsuperscript{17} investigated the effect of a 2-week intervention using constraint-induced therapy on the cortical motor area associated with the abductor pollicis brevis muscle in individuals with stroke. They also noted an enlargement of the cortical motor area associated with the abductor pollicis brevis muscle, as well as a shift in the COG closer to the expected region with no change in MT.

Likewise, BR demonstrated a shift in COG, with the greatest shift in the anterior direction. Green et al\textsuperscript{11,12} have demonstrated that individuals with SCI have a movement potential in individuals with stroke. They also noted an enlargement of the cortical motor area associated with the abductor pollicis brevis muscle, as well as a shift in the COG closer to the expected region with no change in MT.

Compared with individuals who are not disabled, the cortical map of the patient in this case report was shifted posteriorly. Roricht et al\textsuperscript{62} reported that the COG of the biceps brachii muscle for individuals who are not disabled ranged from 3.2 cm anterior to Cz to 0.3 cm posterior to Cz, with a mean value 1.0 cm anterior to Cz. The COG of the biceps brachii muscle for BR was outside this range before intervention, but within this range after intervention. This case report is the first to show a shift of the cortical potential following training in an individual with chronic SCI.

Although there may be alternative explanations to the shift in COG, we believe the shift is greater than the variability in the cortical map both in individuals who are not disabled and in individuals with disability. Corneal et al\textsuperscript{63} reported a mean shift in the COG of 1.01 cm without intervention in individuals who are not disabled. Investigators using TMS have found greater variability in the anterior-posterior direction than the medio-lateral direction.\textsuperscript{48,63} However, the variability reported by Corneal et al\textsuperscript{63} in individuals who are not disabled is less than shift we found in patient in this case report. Furthermore, it is possible that slight differences in electrode placement may account for some variability in the absolute amplitude of the response in a particular location. However, it is not likely to alter the relative amplitude and, therefore, not likely to account for changes in the COG. In addition, every attempt was made to standardize electrode placement to avoid this source of variability.

Individuals with movement impairment may have greater variability in their response to TMS.\textsuperscript{49} Although the stability of the cortical motor map in individuals with chronic SCI is not known, the average movement
of the COG in the affected hemisphere in individuals with stroke is more variable than individuals who are not disabled. The average movement of the COG in the affected hemisphere in individuals with chronic stroke in the absence of intervention was found to be 1.13 cm,\(^4\) whereas the same investigators found the average shift in the COG in the less-affected hemisphere to be 0.68 cm.\(^6\) Despite this variability, the investigators found no significant difference in the movement of the COG of the cortical map, indicating that the COG is stable in clinical populations with chronic injury in the absence of intervention.\(^4\) The magnitude of the anterior shift in COG in the patient in this case report was greater than the variability of shift in individuals with impaired upper-extremity movement.

One limitation to this case report is the lack of normalization to the M-wave; we normalized to the maximum MEP of the map. Therefore, changes in cortical motor excitability could have occurred anywhere along the motor pathway including at the spinal level or peripheral nerve level. By measuring spinal excitability (through F-waves) and peripheral nerve excitability (through M-waves), a more precise location of the change in excitability could be determined.

**Conclusion**

This is the first report of an induced change in the cortical representation of an upper-extremity muscle associated with training in an individual with chronic SCI. These changes may represent more normal levels of excitability and areas of cortical activation. Furthermore, these changes appear to be associated with improved functional abilities. This case report suggests that an intense therapy intervention combining bimanual task-oriented training with somatosensory stimulation may improve functional use of the upper extremities in individuals with chronic SCI. Future investigations are warranted to study the implications of these findings in a larger group of subjects with comparison to a control group. In addition, normalization of neurophysiological measures to the M-wave will be an important factor in determining whether these changes are occurring at a central or peripheral level.

Both authors contributed to the research design and writing. Ms. Hoffman provided project management, data collection, and data analysis and was the primary author of the manuscript. Dr. Field-Fote was the director of the study’s conceptualization and provided supervision, subjects, institutional liaisons, equipment, facilities, and fund procurement. This work was performed at The Miami Project to Cure Paralysis, University of Miami Miller School of Medicine. The authors thank Christine Thomas for her expert consultation, Mohd Khan for his assistance with training, and Lea Lenahan for her assistance with testing, and Lea Lenahan for her contribution with training. The authors also gratefully acknowledge funding support by The Miami Project to Cure Paralysis and by the Peacock Foundation.

This case report is based on a presentation at the III STEP Symposium on Translating Evidence Into Practice: Linking Movement Science and Intervention; July 15–21, 2005; Salt Lake City, Utah.

*This article was received November 18, 2005, and was accepted September 18, 2006.*


**References**


