Neuromuscular Electrical Stimulation–Assisted Grasp Training and Restoration of Function in the Tetraplegic Hand: A Case Series

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OBJECTIVE. This study investigated the immediate effects of repetitive neuromuscular electrical stimulation (NMES)–assisted grasp-and-release activities on the hand of patients with tetraplegia.

METHOD. Three participants with C-5–C-6 tetraplegia underwent grasp training with sequential application of NMES to wrist extensors, finger flexors, and finger extensors to assist participants in grasping and then releasing balls. Before the intervention, participants were assessed with the Jebsen–Taylor Hand Function Test and the Box and Block Test. They were evaluated with the same measures after the first and eighth sessions of intervention. Participants participated in eight 30-min sessions over 14 days.

RESULTS. Within-participant improvements in performance were observed in all outcome measures. Sub-tests of the Jebsen–Taylor Hand Function Test requiring grasping function showed the greatest improvements. Participants reported reduction of spasticity and more effective grasp.

CONCLUSION. NMES-assisted grasp paired with repetitive task practice resulted in improved performance on functional tests and subjectively improved hand function in the participants.

An estimated 12,000 new cases of spinal cord injury (SCI) occur every year. About 55.8% result in tetraplegia, or complete or partial loss of arm and hand function (National Spinal Cord Injury Statistical Center, 2011). This loss of function severely limits participation in activities of daily living (ADLs). Many people with tetraplegia select recovery of arm and hand function as a priority during rehabilitation over sexual function, bowel and bladder function, trunk stability, and recovery of walking movements (Anderson, 2004; Snoeck, Ijzerman, Hermens, Maxwell, & Biering-Sorensten, 2004).

Recent evidence indicates that motor patterns may continuously change across the lifespan with task practice or when challenged under motor learning conditions (Classen, Liepert, Wise, Hallett, & Cohen, 1998). The motor cortex has been observed to reorganize after stroke and SCI (Curt et al., 2002; Hoffman & Field-Fote, 2007). Stroke research shows that the central nervous system adapts to changes in the internal and external environments throughout life (Hallett, 2001; Heddings, Friel, Plautz, & Nudo, 2000).

Changes that occur through cortical reorganization after SCI are not dissimilar to those that occur following stroke. Transcranial magnetic stimulation has been used to show that cortical reorganization occurs following SCI. Specifically, in the area of the hand, the cortical representation is shifted posteriorly in people with SCI compared with those without SCI (Davey et al., 1999; Hoffman & Field-Fote, 2007). Two interventions that have proved to be successful in improving both cortical control of movement and functional outcomes in chronic stroke are the use of repetitive task training and neuromuscular electrical stimulation (NMES; Classen et al., 1998; Santos, Zahner, McKiernan, Mahnken, & Quaney, 2006).

NMES may be delivered transcutaneously through surface electrodes over...
motorneuronal innervation sites. In healthy people, NMES induces both motor and somatosensory cortical reorganization that outlasts a short simulation period (McDonnell, Hillier, Miles, Thompson, & Ridding, 2007; Popovic et al., 2006). In people who have experienced stroke, NMES prompted further recovery of motor control long after the traditional recovery period.

People with chronic stroke and minimal to moderate hand dysfunction improved performance speeds of functional tasks following just a single NMES session applied to the wrist extensors and flexors (Santos et al., 2006).

Applying NMES to the forearm to simulate grasp could act as an aid in relearning grasping patterns to increase independence with functional activities. This procedure may be beneficial to people with severe hand dysfunction resulting from cervical SCI. Although the cardiovascular and musculoskeletal benefits of NMES in patients with SCI are well documented (Bhamhani, Tuchak, Burnham, Jeon, & Maikala, 2000; Field-Fote, Lindley, & Sherman, 2005; Johnston et al., 2005; Kakebeeke et al., 2008), little evidence exists to suggest true improvement in function like those seen in patients with stroke.

Repetitive task training is the practice of performing discrete tasks in the context of a therapeutic environment with the goal of reducing the underlying impairments. In stroke rehabilitation, repetitive exercise has been shown to increase corticospinal excitability and improve function in the affected upper extremity (McDonnell et al., 2007).

We examined repetitive NMES-assisted gross grasp training in the postinjury dominant hand of 3 participants with chronic tetraplegia resulting from traumatic SCI. We wanted to determine whether intense training, involving combined repetitive task practice and NMES, would result in an increase in strength and efficiency when performing a functional task. Additionally, we looked to assess the participants’ perception of and satisfaction with the intervention.

### Method

#### Research Design

This article describes a prospective case series with a short-duration intervention. We administered quantitative measures at baseline and after the first and last training sessions and analyzed the data using nonparametric statistics, as described later in this article. Qualitative assessment was completed after the final training session only. All assessment and interventions were clinic based and took place at the International Center for Spinal Cord Injury in Baltimore, Maryland. This project received exempt status from the institutional review board of the Johns Hopkins Medical Institutes, and all participants signed informed consent forms.

#### Participants

Three participants (1 woman, 2 men; age 18.7 ± 2.1 yr) with cervical SCI participated in the intervention (Table 1). All participants were living in the community and receiving therapy services at the International Center for Spinal Cord Injury at the time of the study. During the intervention, they continued to receive physical and occupational therapy consistent with their individual plans of care, but they received no other hand therapy. All participants demonstrated marked paralysis in at least one hand, as indicated by abberant or absent voluntary grasp patterns. Participants reported being able to complete less than 50% of their ADLs without assistance. To receive the intervention, participants were required to demonstrate voluntary shoulder flexion or abduction to 90° against gravity, elbow flexion and extension sufficient to reach anterior to midline, and full passive range of motion at all joints of the wrist and fingers. Participants were excluded from the intervention if they had a cardiac pacemaker, uncontrolled seizures, active cancer with metastasis, or evidence of pregnancy. The postinjury dominant hand was trained in each participant.

#### Outcome Measures

We tested participants’ upper-extremity motor performance function and speed before starting the intervention (baseline), immediately after the first training session (post-1), and 24 hr after the eighth training session (post-8).

The Jebsen–Taylor Hand Function Test (JTHFT; Jebsen, Taylor, Trieschmann, Trotter, & Howard, 1969) was used to assess the efficacy of grip and pinch patterns. The JTHFT is a standardized 7-item test designed to evaluate various hand functions, including writing, simulated page turning, picking up small common objects, stacking checkers, simulated feeding, lifting large and light objects, and lifting large and heavy objects. Time of performance is recorded for each task. The JTHFT has been used in many studies examining the effect of stimulation on upper-extremity function in stroke and SCI (Beekhuizen & Field-Fote, 2005; Conforto, Cohen, dos Santos, Scaff, & Marie, 2007; Kimberley et al., 2004). It is a well-established test with good test–retest reliability that ranges from .67 to .99, depending on the subtest and hand dominance (Jebsen et al., 1969). Concurrent validity with other tests of hand function is also good—for example, .86 to .88 with the 9-Hole Peg Test (Bovend’Eerdt, Dawes, Johansen-Berg, & Wade, 2004). For our purposes, the writing subtest was excluded because of the severe hand dysfunction of the participants. We evaluated total subtest times for change. Additionally, we separately analyzed subtests requiring gross

#### Table 1. Participant Characteristics

<table>
<thead>
<tr>
<th>Participant</th>
<th>Gender</th>
<th>Age</th>
<th>Mo Since Injury</th>
<th>Hand Trained</th>
<th>Neurological Level</th>
<th>AIS Classification</th>
<th>MASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Female</td>
<td>21</td>
<td>21</td>
<td>Left</td>
<td>C5</td>
<td>A</td>
<td>2/5</td>
</tr>
<tr>
<td>2</td>
<td>Male</td>
<td>17</td>
<td>6</td>
<td>Left</td>
<td>C5</td>
<td>C</td>
<td>3/5</td>
</tr>
<tr>
<td>3</td>
<td>Male</td>
<td>18</td>
<td>12</td>
<td>Right</td>
<td>C4</td>
<td>A</td>
<td>1/5</td>
</tr>
</tbody>
</table>

*Note. AIS = American Spinal Injury Association Impairment Scale; MASS = Modified Ashworth Spasticity Score of the long finger flexors.*
grasp (simulated feeding, lifting large and light objects, and lifting large and heavy objects) and those requiring alternative patterns of prehension (simulated page turning, picking up small common objects, and stacking checkers). Alternative patterns of prehension include tip and lateral pinches and tripod grasp.

We administered the Box and Block Test (BBT; Mathiowetz, Volland, Kashman, & Weber, 1985) to assess grasping speed. The BBT is an assessment of gross hand function that requires the participant to move 1-in. wooden blocks, one at a time, across a divider in the middle of a box. Blocks are moved with one hand from the ipsilateral side to the contralateral side. The number of blocks moved in 60 s is recorded. Normative data were established by Mathiowetz and colleagues in 1985 using 628 adults with and without disabilities. Test–retest reliability ranges from .94 to .98, depending on handedness and time intervals (Cromwell, 1976). Further validation studies have examined special populations (Desrosiers, Bravo, Hébert, Dutil, & Mercier, 1994; Palamara, West, Saroja, Wikstrom, & Malkia, 2005; Svensson & Häger-Ross, 2006) and have also yielded good test–retest reliability. No specific validation studies have been conducted in SCI. Administration of the BBT always followed the JTHFT on the testing days.

Finally, we conducted semistructured interviews with each participant to obtain information on his or her thoughts and feelings related to the NMES-assisted grasp training. We analyzed this information using a phenomenological approach (Creswell, 1998) to help define the experience of NMES-assisted grasp training. We used the following questions as a basis for the interview:

1. What does it mean to have limited hand function?
2. What changes did you experience going through therapy?
3. What kind of impact did the therapy have?

We selected these questions to guide the participants in describing the lived experience of having tetraplegia and participating in a therapy program. Follow-up questions were asked for clarification purposes only.

**Intervention**

We used a portable electrical stimulator (Empi 300 PV; Empi, Saint Paul, MN) to activate the flexors and extensors of the forearm of the selected upper extremity. Self-adhesive, reusable gel electrodes (2-in. diameter; Axelgaard, Fallbrook, CA) were attached at the motorneuronal innervation site of the targeted muscles. A symmetrical, biphasic waveform with a fixed pulse width of 300 µs was used to generate a tetanic contraction of the selected muscles. Frequency (30–50 Hz) and amplitude (20–40 mA) were adjusted to participant tolerance. The NMES was delivered by a single occupational therapist (Kristin Johnston) following a written protocol. The specific parameters used and the participants’ responses to NMES were documented at the conclusion of the session. No adverse reactions occurred over the course of the intervention.

NMES was sequentially applied to the wrist extensors, finger extensors, and finger flexors to assist the participants in grasping and then releasing balls 2–4 in. in diameter into a container (Figure 1). The qualities of the balls (weight, texture, and density) were varied to prevent accommodation to task. Electrodes were placed over the motorneuronal innervation site of the extensor carpi radialis, extensor carpi ulnaris, extensor digitorum communis, flexor digitorum profundus, and flexor digitorum superficialis. A two-channel stimulator with trigger was used. Stimulation was provided to the extensor group first. When the trigger was depressed, stimulation was provided to the flexors to produce a composite grasp. Releasing the trigger returned stimulation to the extensors, causing release of the grasp. Stimulation was provided for 30 min per training session. On average, participants transferred 220 balls per 30-min treatment session. The intervention was performed 8 times during a 2-week period.

**Data Collection**

Motor performance tests were performed by the primary occupational therapist (Kristin Johnston), who carried out the intervention. Johnston was responsible for administration of both the intervention and assessments, so blinding was not possible; however, interrater reliability was not a concern. Each of the three participant interviews was conducted by two therapists (Kristin Johnston and Rebecca Martin) jointly. Both therapists were present for the interviews, although only one (Rebecca Martin) asked the questions. Having two therapists present enabled multiple reviews of the interview content to more accurately capture the major themes. Both therapists had received training in qualitative research.
Data Analysis

**Motor Performance Tests**

Data measurement was performed before starting the intervention (baseline), after the first training session (post-1), and after the final training session (post-8). At each time point, the treating therapist collected data manually according to the standardized instructions. We analyzed the JTHFT subtest scores in total and separated into subtests requiring gross grasp (simulated feeding, lifting large and light objects, and lifting large and heavy objects) and those requiring alternate patterns of prehension (simulated page turning, stacking checkers, picking up small common objects). A Friedman repeated-measures analysis of variance on ranks was used to compare changes across time points in all subtests of the JTHFT, grasping subtests of the JTHFT, prehension subtests of the JTHFT, and the BBT. This test was selected because the data would not meet parametric assumptions because of the limited sample size. Chi-square ($\chi^2$) and $p$ values were generated for each comparison (Portney & Watkins, 2000). Post hoc testing included one-tailed paired $t$ tests to determine the interval during which significant change occurred. Scores across time points were compared as follows: baseline to post-1, post-1 to post-8, and baseline to post-8. A Bonferroni correction was used to account for multiple comparisons, setting $\alpha$ at .017. Use of a Bonferroni correction protects against Type I error (Portney & Watkins, 2000). SigmaStat for Windows (Version 3.11; Systat Software, Inc., Chicago) and Microsoft Excel were used for all statistical analyses.

![Figure 2. Statistically significant improvements were observed in all subtests, $\chi^2(2, N = 3) = 6.00, p = .028$, and grasping subtests, $\chi^2(2, N = 3) = 6.00, p = .028$, of the Jebsen–Taylor Hand Function Test across time points. Changes in the prehension subtests were not significant, $\chi^2(2, N = 3) = 2.667, p = .361$. Post-1 = immediately after the first training session; Post-8 = 24 hr after the eighth training session.](image)

**Table 2. Mean Scores for Motor Performance Tests**

<table>
<thead>
<tr>
<th>Motor Test</th>
<th>Baseline</th>
<th>Post-1</th>
<th>Post-8</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JTHFT, all subtests, s</td>
<td>74.22</td>
<td>49.10</td>
<td>34.39</td>
<td>.015*</td>
</tr>
<tr>
<td>Grasp subtests, s</td>
<td>107.78</td>
<td>63.99</td>
<td>35.22</td>
<td>.028</td>
</tr>
<tr>
<td>Prehension subtests, s</td>
<td>40.66</td>
<td>34.21</td>
<td>30.52</td>
<td>.038</td>
</tr>
<tr>
<td>Box and Block Test, no. of blocks</td>
<td>18.00</td>
<td>20.67</td>
<td>24.67</td>
<td>.216</td>
</tr>
</tbody>
</table>

Note. Post-1 = immediately following the first training session; Post-8 = 24 hr after the eighth training session.

*Denotes statistically significant change with $\alpha = .017$.

**Results**

**NMES Effects on Motor Performance**

Repeated-measures analysis revealed statistically significant effects over time on all subtests of the JTHFT, $\chi^2(2, N = 3) = 6.00, p = .028$. The differences in the mean values at each time point are greater than would be expected by chance (Figure 2). A one-tailed paired $t$ test with Bonferroni’s correction indicated a statistically significant change at each time point in all subtests of the JTHFT (Table 2), indicating that the NMES-assisted training had a positive effect on performance time across all subtests.

A significant effect was also observed for the grasping subtests of the JTHFT, $\chi^2(2, N = 3) = 6.00, p = .028$. The
differences in the mean values among the treatment groups are greater than would be expected by chance. A one-tailed paired t test with Bonferroni’s correction indicated a significant change between post-1 and post-8 and between baseline and post-8; however, the change after the first session only was not significant (see Table 2).

Repeated-measures analysis across time points for the prehension subtests of the JTHFT showed no significant changes, $X^2(2, N = 3) = 2.667, p = .361$. Finally, repeated-measures analysis of the BBT scores across time points showed no significant effect, $X^2(2, N = 3) = 4.667, p = .194$. Post hoc t tests between time points for the prehension subtests were not significant at any point, and t tests of the BBT were significant from baseline to post-8 but not at any other point (see Table 2).

Participants’ Perspectives on Training

The purpose of the qualitative data analysis was to extract the significance of retraining gross grasp for the 3 participants. Two thematic categories emerged from the interviews. The first, “experiencing loss of control,” emerged as a result of their paralysis and had both physical and psychological components. Three subthemes emerged from this category: dependence, adaptation, and coping. The second theme specifically addressed the therapeutic process and is described as “experiencing changing hand function.” The three subthemes that surfaced from this category were changes in the quality of movement, relearning movement, and increase in freedom.

Loss of Control. All participants in this case report were in the later years of adolescence when their injuries occurred. This stage in life is a transition period where responsibility shifts from parental and caregiver control to the adolescent becoming more independent and self-reliant. For all 3 participants, reliance had shifted back to parents and caregivers, leaving them with a sense of dependence on others and a loss of control. All participants reported being no longer able to do daily tasks such as feeding themselves, lifting heavy objects, and driving. Participant 2 described having limited hand function as follows: “To me, it means that I need help opening stuff. . . . Doing everyday things that I did before, like grip or pinch or anything that I did before I got injured, I need help now.”

The participants also spoke of a sub-theme of adaptation that seemed to coincide with the concept of coping. They spoke of a feeling of loss associated with dependence but then transitioned to speak of how they adapted to complete functional tasks, which led to coping. When Participant 1 spoke of using adaptive equipment to feed herself, she said, “I feel like I’ve learned, I’ve adapted—I’ve learned to use my hands the best I can.” Participant 2 reported, “But you kind of get adapted to it; it’s you. It’s not really going to change, at least within the next couple of hours. You just get used to it. You find ways to open stuff or do things.”

Experiencing Changing Hand Function. Conversation during the interviews also addressed the changes in hand function participants experienced during NMES-assisted grasp training. The subthemes of changes in the quality of movement and relearning movement emerged from this topic. Participant 1 reported, “I mainly learned what the best way to do things was, not necessarily . . . anything in strength. The changes weren’t really in the strength of my hands, but more so in the function of them.”

All participants also reported an increase in freedom following participation in the NMES-assisted grasp retraining. Participant 3 recalled that he was able to bring a soda can to his mouth using one hand. For him, the freedom from the worry of looking different and the risk of spilling his drink was significant. The other participants reported significant independence and freedom in meaningful tasks such as holding glasses, independently using cellular phones, opening packages, and sending text messages.

Discussion

This study demonstrates that a short period of NMES-assisted grasp training targeting the wrist extensors and finger flexors and extensors significantly improved hand function in these 3 participants with tetraplegia. The effects were observed immediately after the first session of training and 24 hr after the final training session, indicating a modest carryover effect. Moreover, closer inspection of the data demonstrates that NMES-assisted grasp training preferentially improved grasp function over other patterns of prehension. Although all subtests of the JTHFT demonstrated some improvement across time points, the grasping subtests (simulated feeding, lifting large and light objects, and lifting large and heavy objects) accounted for the greatest change in each participant. Participants reported that these changes carried over to their everyday function. Their reports were commensurate with the quantitative findings indicating that performance in tasks requiring grasp improved more than tasks requiring alternate patterns of prehension. Although participants reported changes in the tone of their hands, such changes were not seen in the clinical exam. Only 1 participant had elevated tone to begin with, and his Modified Ashworth Spasticity score (Bohannon & Smith, 1987) remained unchanged after the intervention.

Together, the qualitative and quantitative evidence indicates that the participants experienced improvements in overall function without experiencing appreciable changes in component-level skills. Given that historically it has been thought to be difficult to remediate hand dysfunction in chronic tetraplegia, we find these effects from a short bout of NMES-assisted training to be promising.

The SCI literature frequently addresses the physiological and functional outcomes that occur following rehabilitation but only occasionally addresses the psychosocial changes that occur. During the interviews, the participants in this study described the process of adapting to their changing function rather than the specifics of retraining grasp. Beginning initially with the themes of loss of control, they described the experience of changing hand function when asked about the experience of participating in the program to remediate hand function. This experience of living with limited hand function began with feelings of dependence; participants reported difficulty in performing meaningful tasks and frustration at their need for assistance.
At the completion of the study, participants reported that participating in NMES-assisted grasp training led to changes in the quality of movement, relearned movement, and increased freedom, leading in turn to adaptation and coping. Participants experienced these changes both in their physiological well-being (e.g., decreased tone, increased efficiency) and in their psychological well-being (e.g., greater feelings of independence and control).

Limitations and Future Research

The small sample size of this study limits the application and generalizability of the results. In future projects, more extensive baseline testing would help establish chronicity and sort out the effects of learning. In our study, we could not tease out the specific individual contribution of repetitive task training versus NMES effects because the study was conducted during regular occupational therapy sessions. Separating these interventions and comparing them with traditional occupational therapy interventions may yield clearer results. Additionally, a longer bout of treatment with more testing points to better assess change would benefit the validity of the results. Conducting multiple interviews and expanding the ways in which data are obtained before, during, and after participation in the program would increase the veracity of the qualitative results.

Implications for Occupational Therapy Practice

This study demonstrated that NMES-assisted grasp improved severe hand dysfunction associated with chronic tetraplegia in 3 participants.

- Within-participant improvements were observed, as measured by the JTHFT and BBT, across each time point.
- Improvements were observed after the first session of training, indicating an immediate effect occurring within 30 min of the treatment session, and 24 hr after the final training session, indicating a carryover effect.
- Participants reported subjective improvements in tone and quality of movement.
- Moreover, participants experienced changes in the quality of movement, relearning movement, and an increase in independence through participation in NMES-assisted grasp training.

Conclusion

These results indicate that NMES-assisted grasp training is a reasonable, practical occupational therapy intervention for patients with SCI. The quantitative findings suggest real and sustained improvements in the participants’ ability to grasp objects. This impairment-level change yielded improvements in the quality of function and ability to complete desired daily skills, as was indicated in participants’ subjective report. The qualitative findings add to a body of work that indicates that restoring hand function in this population is an important pursuit. ▲

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References


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