High-Versus Low-Frequency Stimulation Effects on Fine Motor Control in Chronic Hemiplegia: A Pilot Study

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High- Versus Low-Frequency Stimulation Effects on Fine Motor Control in Chronic Hemiplegia: A Pilot Study

Barbara M. Doucet, OTR, PhD, and Lisa Griffin, PhD

Background: The optimal parameters of neuromuscular electrical stimulation (NMES) for recovery of hand function after stroke are not known. This clinical pilot study examined whether higher or lower frequencies are more effective for improving fine motor control of the hand in a chronic poststroke population. Methods: A 1-month, 4 times per week, in-home regimen of either a high-frequency (40 Hz) or low-frequency (20 Hz) NMES program was applied to the hemiplegic thenar muscles of 16 persons with chronic stroke. Participants were identified a priori as having a low level of function (LF) or a high level of function (HF). Outcome measures of strength, dexterity, and endurance were measured before and after participation in the regimen. Results: LF subjects showed no significant changes with either the high- or the low-frequency NMES regimen. HF subjects showed significant changes in strength, dexterity, and endurance. Within this group, higher frequencies of stimulation yielded strength gains and increased motor activation; lower frequencies affected dexterity and endurance. Conclusions: The results suggest that higher frequencies of stimulation could be more effective in improving strength and motor activation properties and that lower frequencies may affect coordination and endurance changes. Results also indicate that persons with a higher functional level of recovery may respond more favorably to NMES regimens, but further study with larger patient groups is warranted. Key words: dexterity, hand, hemiplegia, neuromuscular electrical stimulation, rehabilitation, stroke

Hemiplegia is one of the most debilitating conditions after stroke, and the loss of motor function of the upper extremity is a significant burden that can impair or prevent independent living. One study reported that 6 months after a stroke, half of all stroke survivors reported persistent hemiplegia and almost a third were institutionalized. Until recently, much of the research dedicated to upper extremity rehabilitation after stroke has focused on persons in the acute phase of recovery (1-6 months after onset) who tend to demonstrate quicker motor gains and a more rapid resolution of symptoms. Rehabilitation therapies are usually implemented immediately after the stroke, but the average inpatient rehabilitation stay is typically only 23.5 days. To date, less scientific inquiry has been directed toward interventions specifically for persons living with stroke who are more than 6 months since onset (chronic stroke) and have enduring motor deficits. By the sixth month, most therapies have ended, and further intervention is usually not offered or available. Current evidence regarding neuroplasticity of the cortex indicates that poststroke motor recovery can continue to occur months and even years after the onset of disability. Few rehabilitation efforts have been identified as being effective for this segment of the population with chronic stroke, yet these are the individuals who are most in need of innovative strategies that restore movement.

Current traditional treatment options for persons who demonstrate severe hand dysfunction associated with chronic stroke have shown limited effectiveness and have been largely inadequate. Constraint-induced movement therapy (CIMT) has proven quite effective for increasing movement in the affected upper extremity, but several persons with stroke cannot meet strict eligibility requirements, as evidenced in early CIMT trials. Neurodevelopmental treatment (Bobath method), while popular with practicing therapists, has little empirical evidence to support its advantage...
over other interventions. Even less evidence exists on superior patient outcomes when other traditional methods, such as Brunnstrom treatment or proprioceptive neuromuscular facilitation, are used. Recently, neuroprosthetics and robotics have been developed that activate grasp and release or reaching abilities in the hemiplegic extremity, but these remain largely cost-prohibitive for the consumer.

Neuromuscular electrical stimulation (NMES) is a modality used by therapists to enhance motor recovery after stroke. NMES has been effective in a variety of applications used in both acute and chronic phases of poststroke recovery, including improvement in arm and hand movement for function, reduction of spasticity, minimization of poststroke shoulder pain, and re-education of muscle for specific movement patterns. Benefits in sensory awareness after NMES have been reported as well. Because NMES can induce a high rate of muscular fatigue, constant low-frequency stimulation is often used to produce a smooth contraction at low force levels. Typical frequencies used in clinical applications for motor recovery after stroke range from 20 to 50 Hz. Lower frequencies of stimulation have been shown to impart a long-lasting depression of force output known as low-frequency fatigue, first described by Edwards et al. These researchers observed that fatigued muscle stimulated with lower frequencies (10-30 Hz) could exhibit a depression in force output lasting 24 hours or longer but that the same effect was not seen at higher frequencies. Investigators are currently calling for more research into the optimal parameters of NMES that will maximize force output while minimizing fatigue, thereby allowing successful performance of rehabilitation regimens.

The contribution of stimulation frequency in rehabilitation regimens has been previously studied. When NMES was delivered to the knee extensors of 7 healthy participants and the influence of frequency, pulse width, and amplitude on fatigue was studied, investigators found that fatigue was affected most when frequency was modulated; varying other parameters had no appreciable effect on reducing fatigue. We previously examined a group of chronic poststroke individuals during stimulation of the hemiparetic thenar muscle group with a 3-minute fatiguing protocol and found that stimulation programs that incorporated higher frequencies (40 Hz) and varying pulse patterns were more effective in maximizing force output than 20 Hz constant-pattern stimulation programs. On the basis of these outcomes, we hypothesize that the use of higher frequencies of stimulation may be more effective in maximizing force output and improving fine motor skills after stroke. Additionally, keeping stimulation frequencies high (eg at approximately 40 Hz) would serve to maximize force production yet offset fatigue effects seen in 60 Hz and higher frequency applications.

The purpose of our pilot study was to compare the effects of using a high-frequency NMES protocol (40 Hz) versus a low-frequency NMES protocol (20 Hz) to improve fine motor control in the affected hands of a chronic stroke population. We chose to focus intervention on the thenar muscle group, because these muscles contribute significantly to functional grip and release skills, pinch movements, and prehensile digit patterns. Outcome measures included changes in muscle strength, dexterity, and endurance of the affected hand after implementation of the 1-month in-home program. This information will be useful in identifying effective clinical intervention strategies and determining the optimal frequencies of NMES that facilitate improved fine motor control in the chronic poststroke population.

Methods

Participants

Sixteen persons with chronic stroke were recruited from the Austin, Texas, area through a local newspaper advertisement. Individuals were selected if the following criteria were met:

- Stroke onset of at least 6 months before the start of study involvement;
- Full discharge from any inpatient, outpatient, or home health therapies and not receiving any co-interventions to confound the effects of NMES during the period of study;
- No significant cognitive impairment as documented by a physician;
• Upper limb paresis with at least 20° of wrist extension, 20° wrist flexion, 30° metacarpophalangeal (MCP) extension, and active grasp/release intact in the affected extremity (necessary to perform pre- and posttesting batteries and to position the extremity in the testing apparatus); and
• Able to comprehend objectives of study and follow study-related directions.

Participants were required to have been discharged from other therapies to avoid confounding the results of the study. All research procedures were approved by the University of Texas Institutional Review Board (UT IRB) in accordance with the Declaration of Helsinki; all subjects signed informed consent forms per protocol by the UT IRB.

Procedure

Participants were a priori designated as high functioning (HF) or low functioning (LF) as determined by their score on the upper extremity subsection of the Fugl-Meyer Motor Assessment (FMA). Because of the extreme variability of functional levels and functional performance present in chronic stroke survivors, researchers often separate participants with stroke into high and low functional groups in study designs. This is typically done a priori using scores from motor performance tests such as the FMA or other standard motor assessments.37-39 The FMA is a reliable and valid assessment of movement and function used extensively in research and clinical applications.40 The total possible score on this measure is 66. Participants scoring 60 or above were classified as HF; those scoring below 60 were classified as LF.

In the LF group, scores on the FMA averaged 45.62 ± 11.09; in the HF group, the average was 62.62 ± 1.76. Within each recovery level group, participants were randomly assigned to receive either the low-frequency stimulation regimen (20 Hz) or the high-frequency stimulation regimen (40 Hz); therefore, 4 subjects received the low-frequency regimen and 4 subjects received the high-frequency regimen within each group. Table 1 shows subject demographics, FMA scores, and stimulation frequency regimens administered to the 2 groups.

Participants also provided documentation of medical clearance from their personal physicians.

Table 1. Participant demographics and characteristics

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Gender</th>
<th>TPS, months</th>
<th>Dominant UE</th>
<th>Affected UE</th>
<th>FMA</th>
<th>Stimulation regimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>73</td>
<td>M</td>
<td>41</td>
<td>R</td>
<td>R</td>
<td>32</td>
<td>Low freq</td>
</tr>
<tr>
<td>2</td>
<td>74</td>
<td>M</td>
<td>247</td>
<td>L</td>
<td>L</td>
<td>43</td>
<td>Low freq</td>
</tr>
<tr>
<td>3</td>
<td>73</td>
<td>M</td>
<td>33</td>
<td>R</td>
<td>R</td>
<td>45</td>
<td>Low freq</td>
</tr>
<tr>
<td>4</td>
<td>76</td>
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<td>52</td>
<td>L</td>
<td>R</td>
<td>58</td>
<td>Low freq</td>
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<tr>
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<td>R</td>
<td>R</td>
<td>34</td>
<td>High freq</td>
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<tr>
<td>6</td>
<td>64</td>
<td>M</td>
<td>54</td>
<td>R</td>
<td>R</td>
<td>37</td>
<td>High freq</td>
</tr>
<tr>
<td>7</td>
<td>65</td>
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<td>93</td>
<td>L</td>
<td>R</td>
<td>58</td>
<td>High freq</td>
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<tr>
<td>8</td>
<td>70</td>
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<td>L</td>
<td>R</td>
<td>58</td>
<td>High freq</td>
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<tr>
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<td>L</td>
<td>R</td>
<td>59</td>
<td>Low freq</td>
</tr>
<tr>
<td>10</td>
<td>58</td>
<td>M</td>
<td>108</td>
<td>R</td>
<td>R</td>
<td>64</td>
<td>Low freq</td>
</tr>
<tr>
<td>11</td>
<td>79</td>
<td>M</td>
<td>11</td>
<td>R</td>
<td>R</td>
<td>64</td>
<td>Low freq</td>
</tr>
<tr>
<td>12</td>
<td>65</td>
<td>M</td>
<td>20</td>
<td>R</td>
<td>L</td>
<td>64</td>
<td>Low freq</td>
</tr>
<tr>
<td>13</td>
<td>47</td>
<td>F</td>
<td>7</td>
<td>R</td>
<td>R</td>
<td>60</td>
<td>High freq</td>
</tr>
<tr>
<td>14</td>
<td>67</td>
<td>M</td>
<td>91</td>
<td>R</td>
<td>R</td>
<td>62</td>
<td>High freq</td>
</tr>
<tr>
<td>15</td>
<td>60</td>
<td>F</td>
<td>27</td>
<td>R</td>
<td>R</td>
<td>63</td>
<td>High freq</td>
</tr>
<tr>
<td>16</td>
<td>47</td>
<td>F</td>
<td>14</td>
<td>R</td>
<td>R</td>
<td>64</td>
<td>High freq</td>
</tr>
</tbody>
</table>

Note: F = female; freq = frequency; FMA = Fugl-Meyer Motor Assessment; L = left; M = male; R = right; TPS = time post stroke; UE = upper extremity.

*High frequency = 40 Hz; low frequency = 20 Hz.
verifying that they had no current medical condition that would preclude them from participation (e.g., presence of a pacemaker or lesions at the site of stimulation application). All participants provided informed consent and then attended an initial orientation/assessment session where they completed a short hand-use questionnaire to determine typical hand use.

**Rehabilitation training program**

All participants received supervised in-home training 4 times a week for 4 weeks. The duration of treatment was chosen based on the typical length of an outpatient or inpatient therapy program. The 8 participants in the low-frequency regimen received NMES at 20 Hz to the thenar muscle group for 40 minutes via a portable electrical stimulation unit (300PV, Empi, Inc., St. Paul, MN). The frequency was ramped up from 0 Hz to 20 Hz over a 1-second period, was held at 20 Hz for 10 seconds, and was then ramped down to 0 Hz over a 1-second period. A rest period of 10 seconds followed. This pattern was repeated for the duration of the program. The 8 participants in the high-frequency regimen received NMES at 40 Hz to the thenar muscle group for 20 minutes via the same portable electrical stimulation unit. For these participants, the frequency was ramped up from 0 Hz to 40 Hz over a 1-second period, was held at 40 Hz for 5 seconds, and was then ramped down to 0 Hz over a 1-second period. A rest period of 5 seconds followed.

The high-frequency regimen matched the low-frequency regimen such that the total number of pulses delivered per session was the same for both groups. That is, for the low-frequency regimen, 200 pulses were delivered every 20 seconds for 40 minutes (10 seconds “on” and 10 seconds of rest). This yielded a total of 24,000 pulses. For the high-frequency regimen, 200 pulses were delivered every 10 seconds for 20 minutes (5 seconds “on” and 5 seconds of rest), also yielding a total of 24,000 pulses delivered.

For all participants, the current was adjusted to an appropriate intensity level at each session to elicit a tetanized contraction of 30% of each subject’s maximal voluntary contraction (MVC). As strength changes occurred over the treatment period, intensity of stimulation was increased to maintain a 30% MVC for each training session, thereby controlling the effects of muscle workload.

**Instruments**

Fine motor skill was measured using outcomes of manual dexterity, grip and pinch strength, and motor endurance. Pre- and postintervention measures included the Minnesota Manual Dexterity Test (MMDT; American Guidance Service, 1969). The MMDT measures the ability to grasp multiple 3-cm disks from indentations on the main test board and place the disks accordingly in an identical test board positioned directly below the upper test board (placing test). The test is performed while the subject is standing, with the boards on a tabletop, and is timed.

Grip and pinch strength dynamometry (Jamar hydraulic hand dynamometer [Patterson Medical, Bolingbrook, IL]) were used to measure lateral, palmar, and tip pinch force, as well as grip strength. Thumb adductor strength and motor endurance were measured using a customized upper extremity apparatus with transducers positioned to record force output; electromyography (EMG) during muscle contractions was also recorded to measure motor activation. Participants sat in a high-back armless chair with their affected arm placed in a prefabricated metal splint (Progress elbow hinge splint, NC25658; North Coast Medical) that stabilized the elbow in 100° of flexion, the forearm in pronation, and the thumb abducted and extended against the force transducer. The custom-designed force-recording device (Mechanical Engineering Shop, University of Texas at Austin) consisted of a vertical surface that measured forces of thumb adduction \((x)\) and a horizontal surface that measured forces of thumb extension \((y)\). The contact area spanned from the thumb tip to midway between the interphalangeal (IP) and MCP joint. Using this device, the participants performed 3 maximal voluntary isometric contractions (MVCs) of thumb adduction for thumb strength measures and a voluntary isometric contraction of 30% MVC of thumb adduction, which was held until endurance limit
as a measure of motor endurance. The resultant force, \( R = \sqrt{x^2 + y^2} \) was calculated, displayed on the computer monitor, and recorded by using commercially available software (Spike 2, Version 5.14; Cambridge Electronic Design, Cambridge, UK). The force output signal was amplified by 100 (Bridge 8 Amplifier System, Model 74030; World Precision Instruments, Sarasota, FL) sampled at 1,000 Hz and low-pass–filtered at 1 kHz.

During the isometric contractions, the electromyographic signal was recorded through 2 adhesive pregelled Ag/AgCl–bipolar surface electrodes 5-mm in diameter (Danlee Medical Products, Inc., Syracuse, NY). The active electrode was placed over the thenar eminence slightly medial to the MCP joint of the thumb and the reference electrode was approximately 1 cm medial to the active electrode, both targeting the thenar muscles. The electromyographic signal obtained from the thenar muscles during contractions was amplified by 100 (isolated bioamplifier with bandpass filter, Model V75-04; Coulbourn Instruments, Whitehall, PA), high-pass–filtered above 8 Hz, sampled at 2,000 Hz, and digitally converted (Micro 1401 mkII 500kHz 16-bit Analog-Digital Converter with ADC 12 Expansion; Cambridge Electronic Design).

All data were recorded on computer and analyzed offline using Spike 2 for Windows (version 5) software package (Cambridge Electronic Design). All experimental procedures were repeated after the 4-week training program for postintervention measures.

Statistical analysis

A 2-way mixed method analysis of variance (ANOVA) test with factors of frequency (high-frequency stimulation regimen or low-frequency stimulation regimen) and time (repeated measure; pre- or postintervention) was performed for each recovery condition. Outcome measures were strength (grip; lateral, palmar, and tip pinch; thumb adductor strength), dexterity (MMDT scores), motor endurance, and root mean square (RMS) of thumb adductor MVC. Holm-Sidak tests were used for post hoc pairwise comparisons. An alpha level of 0.05 was used for all statistical tests, and significance was determined at \( P \leq 0.05 \). Data are presented as means ± standard deviation.

Results

Strength

For grip strength changes in the LF group, there was no significant difference from baseline when high or low frequencies were used; however, for the HF group, the higher frequency regimen resulted in significantly greater gains in grip strength than the low-frequency regimen (average grip strength change for low-frequency regimen, 100.75 ± 10.05 lb pre and 102.75 ± 13.72 lb post; high-frequency regimen, 54.50 ± 11.62 lb pre and 67.00 ± 17.57 lb post).

Prehensile strength measures included lateral, palmar, and tip pinches obtained with dynamometry and thumb adductor MVC strength obtained with the equipment setup described previously. Although there were no significant changes before and after intervention for either the LF or HF group when the palmar and tip pinches were considered, a notable difference was found in lateral pinch changes in the HF group. Those participants who received the high-frequency regimen in this group demonstrated a statistically significant change after intervention when compared with those receiving the low-frequency regimen (average lateral pinch, low frequency, 20.00 ± 4.76 lb pre and 19.25 ± 3.77 lb post; average lateral pinch, high frequency, 14.25 ± 2.87 lb pre and 17.00 ± 2.45 lb post). No significant changes in thumb adductor MVC strength were observed in either the LF group or the HF group.

Dexterity

Dexterity scores as measured by scores on the timed MMDT (placing subtest) showed a change from pre intervention to post intervention for the HR group only; those who received the low-frequency regimen showed a significantly greater reduction in time to perform the test after intervention than those who received the high-frequency regimen (low frequency, 4.07 ± 0.46
The purpose of this pilot study was to compare the changes in fine motor control in the affected hands of a chronic stroke population when a high-frequency NMES protocol was implemented versus a low-frequency protocol. On the basis of previous findings in our laboratory, we hypothesized that the use of higher frequencies of stimulation would be more effective in maximizing force output and improving fine motor skills after stroke. Participants in the HF group showed significant improvement in many of the postintervention measures; however, participants in the LF group did not show meaningful differences on outcome measures. Within the HF group, the data suggest that high-frequency electrical stimulation regimens may facilitate changes in strength and motor activation and that lower frequency stimulation may enhance gains in dexterity and endurance.

Sensorimotor recovery is typically rapid in persons with acute stroke, but is less predictable in the chronic stroke, lower functioning population such as those in our LF group; few effective interventions exist for these individuals. Stroke sequelae, such as severe sensory impairment and spatial neglect, are related to longer lengths of hospital stay and usually coexist with lower overall functional levels. Deficient sensation may also limit the effectiveness of NMES in persons with chronic stroke; in a recent study of 140 stroke survivors more than 1 year post infarct, severe sensory impairment and spasticity were determined to be the primary factors for persisting lack of dexterity in the upper extremity.

Our research confirms previous findings of other investigators demonstrating that strength can be facilitated through the use of stimulation with higher frequencies. Shin et al used EMG-triggered stimulation on 14 chronic poststroke patients at 35 Hz over 10 weeks; persons in the stimulation group performed notably better than those in the control group on tasks of strength and dexterity, and improvement in muscle activation properties was noticeable through EMG measures after the intervention. Additionally, increased activation areas and cortical representation were apparent through functional MRI in the experimental group.

### Discussion

The purpose of this pilot study was to compare the changes in fine motor control in the affected hands of a chronic stroke population when a high-frequency NMES protocol was implemented versus a low-frequency protocol. On the basis of previous findings in our laboratory, we hypothesized that the use of higher frequencies of stimulation would be more effective in maximizing force output and improving fine motor skills after stroke. Participants in the HF group showed significant improvement in many of the postintervention measures; however, participants in the LF group did not show meaningful differences on outcome measures. Within the HF group, the data suggest that high-frequency electrical stimulation regimens may facilitate changes in strength and motor activation and that lower frequency stimulation may enhance gains in dexterity and endurance.

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### Table 2. Optimal frequencies within the high-functioning (HF) group for specific outcome measures studied

<table>
<thead>
<tr>
<th>Measure</th>
<th>Frequency</th>
<th>Significance (P value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grip</td>
<td>High (40 Hz)</td>
<td>.001*</td>
</tr>
<tr>
<td>Lateral pinch</td>
<td>High (40 Hz)</td>
<td>.04*</td>
</tr>
<tr>
<td>Palmar pinch</td>
<td>High (40 Hz)</td>
<td>.36</td>
</tr>
<tr>
<td>Tip pinch</td>
<td>High (40 Hz)</td>
<td>.08</td>
</tr>
<tr>
<td>MMDT</td>
<td>Low (20 Hz)</td>
<td>.02*</td>
</tr>
<tr>
<td>Endurance</td>
<td>Low (20 Hz)</td>
<td>.02*</td>
</tr>
<tr>
<td>MVC</td>
<td>High (40 Hz)</td>
<td>.75</td>
</tr>
<tr>
<td>RMS</td>
<td>High (40 Hz)</td>
<td>.02*</td>
</tr>
</tbody>
</table>

Note: The low-functioning (LF) group showed no significant changes when pre- and postintervention measures were compared. MMDT = Minnesota Manual Dexterity Test; MVC = maximal voluntary isometric contraction of thumb adduction; RMS = root mean square of electromyography during maximal voluntary isometric contraction of thumb adduction; *Significant at $\alpha \leq 0.05$. 

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Endurance

The HR group again showed changes in thumb adduction motor endurance, whereas the LF group did not. Endurance time in participants receiving the low-frequency regimen was significantly greater after the regimen than in those receiving the high-frequency regimen (low frequency, $452.50 \pm 204.47$ s pre and $619.50 \pm 349.24$ s post; high frequency, $281.37 \pm 116.89$ s pre and $236.50 \pm 40.12$ s post).

Motor activation

The RMS of electromyographic amplitude is an indicator of muscle power or energy. For MVC thumb adduction, there were significant changes from pretesting to posttesting in the HF group, but not in the LF group. The high-frequency regimen within the HF group resulted in a greater increase in RMS of the electromyographic amplitude than the low-frequency regimen. Changes from pre- to posttesting were as follows: low frequency, $0.23 \pm 0.02$ mV pre, $0.19 \pm 0.03$ mV post; high frequency, $0.18 \pm 0.02$ mV pre, $0.21 \pm 0.03$ mV post. See Table 2 for a summary of outcome measures.
found that higher frequencies of stimulation (80-100 Hz) used on the ankle plantarflexors could activate motor neurons in the spinal pool through a volley of impulses, resulting in higher centrally generated torque output. Therefore, higher frequencies of stimulation applied peripherally may have the ability to affect central structures, potentially reinforcing motor learning.

Participants in the HF group receiving low-frequency stimulation improved their rate of manipulation on the MMDT. Other researchers showed that a low-frequency stimulation program (1.7 Hz) delivered to the elbow and wrist extensors of 26 persons with stroke for 5 days a week for 60 min/day for 3 months improved upper extremity motor function when compared with a control group; 23% of the treatment group showed increases specifically in hand and wrist function.47 Similarly, a program of 20 Hz NMES was delivered to the adductor pollicis muscle of 30 poststroke individuals 3 times daily for 8 weeks; these participants experienced gains in their ability to grasp and manipulate items.33

Participants in the HF group receiving low-frequency stimulation improved motor endurance of the thenar muscle group more so than participants receiving high-frequency stimulation. A long-term stimulation program in which a pulse rate of 30 Hz was used resulted in greater endurance in the quadriceps of individuals with paraplegia; however, when an even lower rate (16 Hz) was used, the amount of neuromuscular fatigue was significantly reduced.48 Long-term low-frequency stimulation has been suggested to modify the contractile property of muscle in animal models49 as well as in human subjects50 from fast-twitch to slow-twitch. The mechanisms behind this transition have been identified as direct alteration of muscle proteins and isoforms within the filaments and decreases in protein levels within the T tubules of the sarcoplasmic reticulum; this is said to occur as a result of the uniform and slowed stimulation of motor unit activity continually produced during the low-frequency regimen.31

Heightened sensory perception could also influence motor performance on the dexterity tests. Fingertip force coordination and gradation are skills modulated by sensory and haptic awareness, processes that have been repeatedly found to improve after training with NMES.26,52 The reduction in time to perform the MMDT observed in our participants after training could have resulted from improved brain organization, enhanced sensory awareness, and/or changes in grip processes.

Individuals in the high-frequency group showed a decrease in motor endurance in pre- to postintervention measures. The reason for this decrement in performance is unclear, although variability in motor unit firing rates and accompanying force variability have frequently been observed in older adults.53,54 Kurillo, Bajd, and Tercelj55 also found older adults to have significantly greater variability in controlling a lateral pinch grip when compared with younger adults; however, a recent study now indicates that strength training of the wrist and hand may improve finger and pinch forces and decrease this variability.56

**Conclusions**

The results of this pilot study suggest that specific electrical stimulation frequencies selected for use in rehabilitation regimens may have a direct impact on skills gained. Although clinical frequencies typically used for rehabilitation intervention are in the 20 to 50 Hz range,30 our outcomes indicate that higher frequencies of stimulation may prove to be more effective for improving hand strength in higher functioning chronic poststroke individuals. Additionally, the results also suggest that lower frequency stimulation programs may have a greater impact on hand dexterity and endurance; however, additional work with larger patient groups and more comprehensive investigations are needed to statistically confirm this trend.

Limitations of our pilot study include the small number of participants; additional work with this population should expand these findings and incorporate larger numbers. Subjects were classified as HF or LF according to FMA scores; therefore, age and time since stroke varied greatly and could have confounded the results. Because of the extreme variability in the motor presentation of poststroke individuals, baseline pretesting scores on some measures showed differences between groups. Further testing with larger patient
groups and a wider variety of recovery levels and stimulation frequencies is recommended to reduce these confounders, improve test power, and capitalize on these initial findings. Gains achieved were not tested at follow-up to determine whether the effects were lasting. This additional information would strengthen subsequent studies on this topic.

Our pilot investigation explored the possible benefits of high-frequency NMES to enhance specific motor function in the hand when used with a chronic stroke population; this information will be extremely useful for designing effective therapeutic interventions for this population and enhancing client outcomes.

REFERENCES


