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# Rehabilitation of Reaching and Grasping Function in Severe Hemiplegic Patients Using Functional Electrical Stimulation Therapy

T. Adam Thrasher, PhD, Vera Zivanovic, MD, William McIlroy, PhD, and Milos R. Popovic, PhD

**Objective.** The aim of this study was to establish the efficacy of a therapeutic intervention based on functional electrical stimulation (FES) therapy to improve reaching and grasping function after severe hemiplegia due to stroke. **Methods.** A total of 21 subjects with acute stroke were randomized into 2 groups, FES plus conventional occupational and physiotherapy (FES group) or only conventional therapy (control group) 5 days a week for 12 to 16 weeks. A third group of 7 subjects with chronic hemiplegia (at least 5 months poststroke) received only FES therapy (chronic group) and pre-post training changes were compared. FES was applied to proximal and then distal muscle groups during specific motor tasks. At baseline and at the end of treatment, grasping function was assessed using the Rehabilitation Engineering Laboratory Hand Function Test, along with more standard measures of rehabilitation outcome. **Results.** The FES group improved significantly more than the control group in terms of object manipulation, palmar grip torque, pinch grip pulling force, Barthel Index, Upper Extremity Fugl-Meyer scores, and Upper Extremity Chedoke-McMaster Stages of Motor Recovery. The chronic stroke subjects demonstrated improvements in most categories, but the changes were not statistically significant. **Conclusions.** FES therapy with upper extremity training may be an efficacious intervention in the rehabilitation of reaching and grasping function during acute stroke rehabilitation.

**Key Words:** Hemiplegia—Rehabilitation—Grasping—Reaching—Functional electrical stimulation—Upper extremity

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Although many stroke patients are able to recover some walking function during initial rehabilitation, the majority of stroke patients are unable to use their upper extremity in their activities of daily living (ADL) after months of standard occupational therapy and physiotherapy. It has been estimated that 55% of stroke survivors have a nonfunctional upper extremity following initial therapy and 30% of stroke survivors have had some partial recovery of upper extremity function in terms of range of motion and strength, but are still unable to perform ADLs with the affected upper extremity, which negatively affects their independence and increases the burden of care.

Treatment options for stroke survivors with severe paralysis of the upper extremity are limited. Constraint-induced movement therapy has been shown to be effective in recovering upper limb function in randomized trials of acute and subacute upper extremity paresis when the subject is able to extend the fingers and wrist, that is, mild paresis.<sup>1,2</sup> However, as discussed by Dobkin<sup>3</sup> and Wolf et al,<sup>4</sup> the EXCITE trial did not use a control group that received an equal amount of more conventional therapy. A community-based group exercise program has been shown to improve upper extremity function in people with chronic hemiplegia due to stroke, which suggests that socially motivated use of the affected upper extremity is also effective.<sup>5</sup> These treatments can be beneficial for individuals who have already some voluntary movement in their shoulder, elbow and hand, that is, mild paresis, but not for patients who have no voluntary movement, that is, severe paralysis. Other new therapies are taking advantage of technology such as robot-assisted therapy,<sup>6</sup> biofeedback therapy,<sup>1</sup> and virtual reality training,<sup>7</sup> which have produced positive results in terms of clinical scales, such as Fugl-Meyer score, motor status scores, and kinematic performance of basic upper extremity movements in the chronic hemiplegia population. Therapies similar to those mentioned above showed improvement in individuals with mild paresis and were not found to be effective in individuals who have severe paralysis.

One of the most promising alternate interventions to help stroke patients recover upper limb function is functional electrical stimulation (FES).<sup>8</sup> Functional electrical stimulation is a technology that activates paretic muscles using short duration electrical pulses applied through the skin. Since the 1960s, the primary focus of FES development was to produce assistive devices that could be worn or implanted and used in ADLs.<sup>9</sup> More recently, evidence has emerged that FES can be applied as part of a clinical intervention for training. It has been reported that people who use FES to activate paretic muscles on a regular basis sometimes improve their voluntary control of those muscles, that is *without* FES.<sup>10,11</sup> We call this FES therapy.<sup>12</sup>

A small number of FES devices have been tested as interventions for acute and chronic stroke.<sup>13,14</sup> The NESS Handmaster is a multichannel neuroprosthesis worn by the patient.<sup>15</sup> Training with the device led to gains in small randomized trials as an intervention for grasping impairment in both chronic hemiparesis<sup>16</sup> and subacute hemiparesis due to stroke.<sup>17,18</sup> In these studies, the device was used for 12 weeks, and positive results were seen as an increase in volitional hand tests for the FES group in contrast to the control group that performed task-oriented training without FES. Other studies have implemented FES therapy using general multipurpose dual-channel stimulators.<sup>19,20</sup> These devices are less expensive than the Handmaster but require special training and greater care to operate properly. They have been employed in home-based programs for people with chronic hemiparesis and have demonstrated modest improvements in terms of upper extremity function and spasticity following 6 weeks<sup>21</sup> and 18 weeks of use.<sup>19,22</sup> These devices have also been used in clinical settings, under the supervision of a trained FES practitioner, and yielded improvements in grasping function in subjects with chronic paresis in as little as 10 sessions.<sup>23</sup>

One of the main challenges in applying FES therapy is to achieve effective, synergistic muscle activity that results in functional movement, and the generation of useful forces. For this, the appropriate sequence of electrical pulses must be provided. Upper limb neuroprostheses are able to facilitate 2 common grasping styles: the palmar grasp and the lateral grasp.<sup>9</sup> The palmar grasp is used to hold large, heavy objects such as cans and bottles, and is achieved by flexion of the 4 fingers against the palm of the hand. The lateral grasp is used to hold small, thin objects such as keys and paper between the thumb and the fully flexed index finger. Reaching is assisted by stimulating the anterior and posterior deltoid muscles, biceps, and triceps. Proper sequencing of contractions of these muscles facilitates a large variety of reaching and retrieving movements of the upper limb.

Repeated execution of various reaching and grasping tasks against natural resistance (ordinary weighted objects) constitutes a FES therapy intervention. The purpose of this study was to implement such an FES therapy program in a clinical setting and evaluate it for efficacy during the acute and chronic phases of rehabilitation. What makes this study unique as compared to similar studies performed in the past is that it was applied to severe hemiplegic patients and was used to retrain both reaching and grasping functions.

## METHODS

This study consisted of 2 parts. First, a randomized control trial of FES therapy versus conventional therapy was conducted on a sample of the acute hemiplegia population. Second, FES therapy was applied as a pilot study to a small group of people with chronic hemiplegia due to stroke, and improvements in function and independence were assessed. The same outcome measures were recorded.

### Participants

Hemiplegic patients (N = 21) who had been hospitalized due to a recent stroke were recruited in the first part of this study. Patients who were admitted to the stroke rehabilitation program at Toronto Rehabilitation Institute, and who met all of the inclusion and exclusion criteria, were invited to participate. Eligible participants were required to have a score of 1 or 2 for combined arm and hand on the Chedoke–McMaster Stages of Motor Recovery (CMSMR),<sup>24</sup> which is defined as spastic or flaccid paralysis of the arm and hand, with little or no voluntary movement. The time between stroke and the start of treatment was 2 to 7 weeks. We excluded individuals who had edema in their affected upper limb, or a skin rash, allergy or wound at the locations where stimulation electrodes would be placed. Also excluded were individuals who experienced loss of proprioception, which was assessed using the Thumb Localization Test.<sup>25</sup>

In the second part of the study, a convenience sample of 7 people with chronic hemiplegia due to stroke was recruited from the outpatient population at the Toronto Rehabilitation Institute. These subjects had some spasticity and little or no voluntary movement of the arm and hand, which was defined as a score of 2 or 3 on CMSMR. The same exclusion criteria were applied as for the participants in the first part of the study. All participants signed informed consent documents in accordance with the local Research Ethics Board.

**Table 1.** Summary of Outcome Measures

Name of Test	Maximum Value	Units	Type of Value
Rehabilitation Engineering Laboratory Hand Function Test			
Objects	56		Ordinal
Blocks	18		Ordinal
Grip torque	5	N m	Continuous
Pinch force	50	N	Continuous
Eccentric load	60	cm	Continuous
Functional Independence Measure	126		Ordinal
Barthel Index	100		Ordinal
Fugl–Meyer Assessment <sup>a</sup>	66		Ordinal
Chedoke-McMaster Stages of Motor Recovery <sup>b</sup>	14		Ordinal

<sup>a</sup>Sum of scores for shoulder/elbow, wrist, hand, and coordination speed.

<sup>b</sup>Sum of scores for arm and hand.

## Outcome Measures

Each participant underwent a series of assessments immediately before and after treatment. These tests are summarized in Table 1. All assessments were performed by a researcher who was blinded to the intervention. General function of the affected hand was assessed using the Rehabilitation Engineering Laboratory Hand Function Test (RELHFT).<sup>9</sup> This test yielded 5 outcome variables relating to the ability of the affected hand to perform the following tasks in timely fashion: (1) manipulate common household objects, (2) pick up and release blocks of varying weight and surface friction, (3) produce axial torque on a cylinder with a palmar grasp, (4) produce a pinch force on a credit card using a lateral grasp to prevent it from slipping while the card is pulled, and (5) hold a cylindrical bar horizontally in a pronated palmar grasp with the center of mass of the bar at a varying distance from the hand.

Participants were also assessed using the Functional Independence Measure (FIM)<sup>26</sup> and the Barthel Index (BI).<sup>27</sup> These tests were performed with the affected upper extremity. In addition, the CMSMR was used to assess the functional state of the affected upper extremity.<sup>24</sup> The 2 components of CMSMR relating to the arm and hand were added together and analyzed as a single outcome measure. Finally, the Fugl–Meyer Assessment (FMA)<sup>28</sup> was used to assess the affected upper limb's motor function by summing the 4 motor components of the FMA test relating to the upper limb function (shoulder/elbow, wrist, hand, and coordination speed).

## Randomization

The acute hemiplegia patients who participated in the first part of the study were randomized into 2 groups after all of the baseline assessments were recorded. The first group ( $n = 10$ ) received FES therapy and is designated

“FES group.” The second group ( $n = 11$ ) received conventional occupational therapy and physiotherapy without FES therapy and is designated the “control group.” Randomization was carried out using sealed envelopes, half of which allocated subjects to the FES group. The “shuffling” of the envelopes was accomplished using a random number generator. The “chronic group” was not randomized; all received FES therapy.

## Training Programs

Participants in both the control and FES groups entered into the acute stroke portion of the study received a regimen of conventional physiotherapy and occupational therapy pertaining to shoulder, elbow, wrist, and hand function. The control group received therapy 5 days per week for 12–16 weeks; each therapy session lasted 45 minutes. Participants in the FES group also received conventional physiotherapy and occupational therapy 5 days per week for 12 to 16 weeks, but the duration of the conventional therapy was shorter and combined with FES therapy for 45 minutes per session. The chronic group received FES therapy for 45 minutes daily 3 days per week for 12 to 16 weeks. The chronic group did not receive additional physiotherapy and occupational therapy. Treatment was scheduled for 16 weeks in all cases; however, several subjects were unable to attend the final weeks of treatment due to a variety of issues involving transportation, family, and so on.

## Conventional Therapy

Conventional therapy consisted of the following: (1) muscle facilitation exercises emphasizing the neurodevelopmental treatment approach; (2) task-specific, repetitive functional training; strengthening and motor control training using resistance to the patients' volitional movements;

(3) electrical stimulation applied primarily for isolated muscle strengthening (not for functional training); (4) activities of daily living including self-care where the upper limb was used to assist if appropriate; and (5) caregiver training.<sup>29</sup>

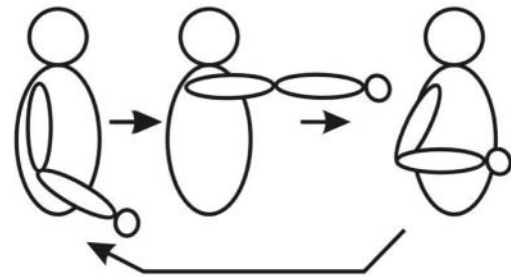
### Functional Electrical Stimulation Therapy

Functional electrical stimulation therapy was applied using a Compex Motion stimulator (Compex SA, Ecublens, Switzerland), which is a programmable device designed to provide electrical stimulation sequences for any FES-related application.<sup>30</sup> Four pairs of self-adhesive surface electrodes were attached to the skin and secured with tape each session, requiring about 8 minutes to don and 5 minutes to doff. The stimulator was programmed to respond to a single pushbutton command. It provided stimulation sequences to elicit a series of functional movements and muscle contractions. The stimulation sequences were modulated by altering the pulse-width in the range of 0 to 300 microseconds. A constant stimulation frequency of 40 Hz was used. The current amplitude of each channel was set to produce a near maximal contraction. Amplitudes of 10 to 50 mA were used based on a pretest at the beginning of every session.

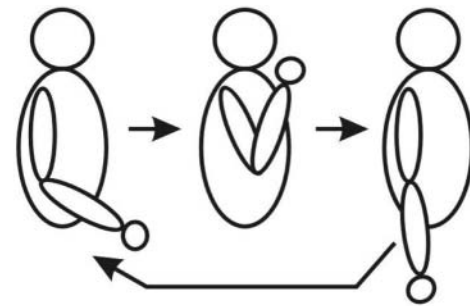
Treatment was delivered in 2 phases. The muscles recruited and resulting movements are summarized as follows:

#### Phase 1

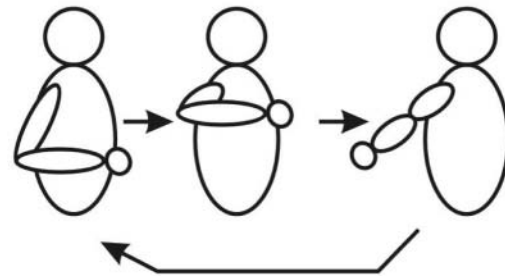
1. Forward reaching motion: A participant was instructed to reach with the affected upper extremity forward in a particular direction and to try to execute this task voluntarily (Figure 1a). When the participant reached the limit of voluntary range of motion, a preprogrammed electrical stimulation sequence was delivered to the anterior deltoid, triceps brachii, posterior deltoid, and biceps brachii muscles to produce the instructed motion. The stimulation lasted only 1 to 3 seconds until the hand reached the desired end position in space and the upper extremity assumed the desired posture. Then the stimulation was turned off and the participant was instructed to retract the upper extremity and place it next to the body with elbow at 90° of flexion (Figure 1a). Similarly, the participant was instructed to perform the task voluntarily and the stimulation was only used to assist the movement that the patient was unable to perform.
2. Nose reaching motion: The participant was instructed to reach for the nose or chin or contralateral shoulder with the paretic upper extremity and attempt to execute this task voluntarily (Figure 1b). Once this was achieved, the participant was instructed to fully extend the upper extremity down and beside the body. Similar



a) Phase 1 - Task 1: Forward reaching movement



b) Phase 1 - Task 2: Nose reaching movement



c) Phase 1 - Task 3: Adduction followed by elbow extension

Figure 1. Illustration of movement tasks performed during phase 1 of treatment.

to above, electrical stimulation was used only to help execute components of the task that the participant was unable to perform voluntarily. Muscles that were stimulated were: the anterior deltoid, triceps brachii, posterior deltoid, and biceps brachii.

3. Shoulder adduction followed by elbow extension: The participant was instructed to adduct the shoulder while the elbow was at 90° of flexion (Figure 1c). Once the upper extremity was adducted, the participant was asked to extend the elbow. Once the elbow was fully extended, the participant was instructed to relax the upper extremity. Stimulation was used only to help execute components of the task the participant was unable to perform voluntarily. Muscles that were stimulated were: the anterior deltoid, posterior deltoid, and triceps brachii.

During phase 1, tasks 1 to 3 were carried out in arbitrary order. Each task took at least 5 minutes to perform and the participant performed the same task multiple times during that time period. During one treatment session all 3 tasks were performed at least once. Phase 1 of the treatment typically was completed by the end of week 6 or 7, when the improvement in voluntary shoulder and elbow function was considered sufficient, that is, the participant was able to place the affected hand within 50% to 60% of the reach work space when seated. All participants with acute hemiplegia had very limited movement in the upper extremity when they entered the program. Successful completion of phase 1 would mean that the participant was able to volitionally reach forward and was ready to engage in the grasping training part of the FES therapy.

*Phase 2.* This phase consisted of a set of exercises aimed at restoring grasp and release function. This was achieved by applying the neuroprosthesis for grasping to the forearm as described in our previous studies with individuals with spinal cord injury.<sup>9,21,23-27</sup> The following muscles were stimulated to generate hand opening and hand closing while controlling the wrist angle between the neutral position and a few degrees of extension: flexor carpi radialis and flexor carpi ulnaris (wrist flexion); extensor carpi radialis longus and brevis, and extensor carpi ulnaris (wrist extension); flexor digitorum superficialis and flexor digitorum profundus (finger flexion), thenar (thumb flexion); extensor digitorum and lumbricals I-IV (finger extension). During phase 2 of the treatment, the participant was instructed to grasp and release various objects such as a pen, a teacup, mobile phone, and so on. Components of the task that the participant was unable to perform voluntarily were assisted using FES. While the participant was training to grasp and release objects, it was common to redo some or all of the reaching activities described in phase 1. The purpose of these treatments was to further expand the range of motion during reaching, to further strengthen the shoulder and elbow muscles, and most frequently to break the pattern of pathologic synergies commonly observed in individuals after stroke. Figures 1 and 2 depict how reaching and grasping trainings were performed.

In the early stages of the FES therapy, all the movements were performed with the help of FES. In later treatments, FES was used less and only to help particular movements, for example hand opening or wrist extension, which were the most difficult to train in this patient population. Movements were performed against gravity and sometimes against light manual resistance. The number of repetitions depended on the participant's strength and endurance capacity. In general, a single task would be performed 20 to 30 times within a

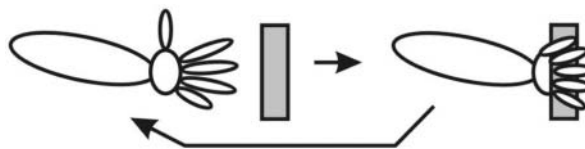


Figure 2. Grasping and releasing tasks that involve reaching and performed during phase 2 of treatment.

session. During the course of treatment, the participants' shoulder, elbow, wrist, and hand control improved, and adjustments were made to the stimulation protocols accordingly. That is, the stimulator was "fine-tuned" to meet each individual's specific needs at least weekly, and the adjustments were made by a trained FES therapy facilitator.

In our paradigm, the timing of stimulation is controlled by the therapist, who delivers it only after the participant has unsuccessfully tried to perform the task briefly without success. During task execution, the therapist manually guided the paretic upper extremity to ensure that all movements were carried out in close approximation to a normal movement. That is, the FES-assisted movements did not oppose natural joint movements.

## Statistical Analysis

In the randomized controlled part of this study (acute hemiplegia), the baseline scores were subtracted from the posttreatment scores to calculate changes over the course of treatment. Differences between the control group and the FES group with respect to the 9 outcome measures were determined using a signed Wilcoxon rank-sum test with a significance level of  $P < .05$ . In the second part of this study (chronic hemiplegia), the outcome measures before treatment were tested against the outcome measures following treatment. Again, a signed Wilcoxon rank-sum test with a significance level of  $P < .05$  was used. This nonparametric statistical test was selected to test the hypotheses because the data were mostly derived from ordinal scales and were not normally distributed.

## RESULTS

### Participants

A total of 21 subjects (8 women, 13 men) participated in the first part of this study, and 7 subjects (3 women, 4 men) participated in the second part. Table 2

Table 2. Subject Demographics and Treatment Times

Subject Class	Group	n	Age (Years) <sup>a</sup>	Time Between Stroke and Start of Treatment <sup>a</sup>	Duration of Treatment (Weeks) <sup>a</sup>
Acute hemiplegia	Functional electrical stimulation	10	57 ± 14.7	29.8 ± 11.8 days	13.5 ± 2.5
	Control	11	58 ± 19.7	28.5 ± 9.0 days	13.1 ± 2.4
Chronic hemiplegia	Chronic	7	56 ± 15.8	2.7 ± 1.8 years	12.9 ± 2.9

<sup>a</sup>Values given in the form of mean ± standard deviation.

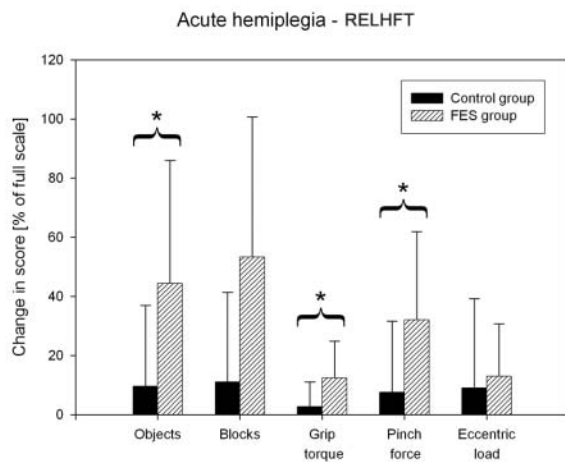


Figure 3. Changes in grasping function as measured by the Rehabilitation Engineering Laboratory Hand Function Test (RELHFT) for acute hemiplegic subjects. Asterisks (\*) indicate significant differences between the treatment and the control groups ( $P < .05$ ). Mean value shown with error bars representing 1 standard deviation.

describes the composition of the groups as well as the mean time post-stroke and the mean treatment duration for each group.

### Treatment Effects

Both the FES group and control group experienced improved scores in all outcome measures over the course of treatment. This is expressed in Figures 3 and 4 as a positive change in score. The FES group improved significantly more than the control group in terms of object manipulation, palmar grip torque, and pinch grip pulling force ( $P < .05$ ), as shown in Figure 3. There were no significant differences in blocks score and eccentric load. The acute FES group also improved more than the control group in terms of the BI, FMA, and CMSMR ( $P < .05$ ), as shown in Figure 4. No significant difference occurred for the FIM.

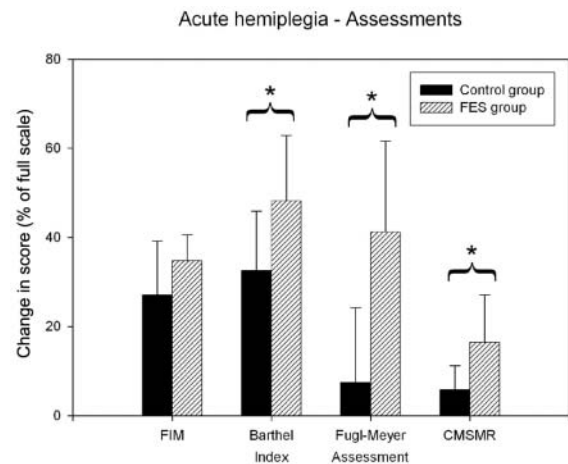
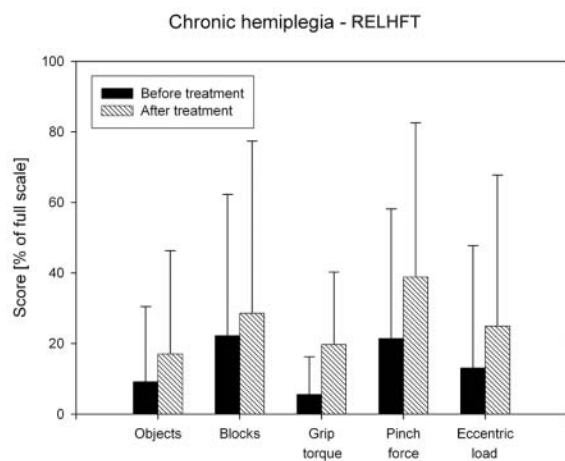


Figure 4. Changes in independence in terms of activities of daily living and assessments of motor recovery for acute hemiplegic subjects. Asterisks (\*) indicate significant differences between the treatment and the control groups ( $P < .05$ ). Mean value shown with error bars representing 1 standard deviation. FES, functional electrical stimulation; FIM, Functional Independence Measure; CMSM, Chedoke–McMaster Stages of Motor Recovery.

The chronic group tended to score slightly higher after FES therapy as compared with baseline for most measures, but the differences were not statistically significant. Figure 5 shows the results of the hand function tests for the chronic hemiplegia group. Figure 6 shows the results of the measures of functional independence and level of disability.

### DISCUSSION

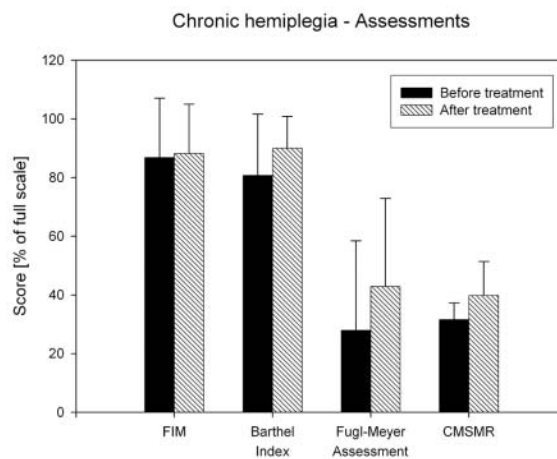
This small trial examined the efficacy of FES therapy as a clinical intervention in the treatment of severe unilateral upper extremity paralysis resulting from recent stroke. We found significant improvements in the FES group in outcome measures that represent hand function and



**Figure 5.** Grasping function as measured by the Rehabilitation Engineering Laboratory Hand Function Test (RELHFT) before and after treatment for chronic hemiplegic subjects (at least 2 years poststroke). Trends can be seen, but the results are not statistically significant ( $n = 7$ ). Mean value shown with error bars representing 1 standard deviation.

level of disability, including greater improvements in grip torque and pinch grip force as well as the ability to manipulate basic objects compared to the control group. This implies increased control of the thumb and finger movements. The acute subjects who received FES therapy also demonstrated greater improvements in terms of the BI but not FIM. Both indices are common clinical measures of general level of disability with respect to ADLs; however, they grade and weigh activities differently. The activities covered by the BI are more dependent on hand function<sup>19</sup> and are specifically designed to assess stroke patients, unlike the FIM, which is a more general test of independence. The FES group also improved significantly more than the Control group in terms of the upper limb components of the CMSMR and FMA scales.<sup>16,20</sup> Improvements in terms of these scales represent clinically significant reductions in level of disability.

Improvements were not statistically significant in the convenience sample of chronic stroke patients who participated in the study, although trends of improvement were observed. In this small number of subjects, statistical power was low and the treatment period may not have been sufficient to produce measurable gains. Other studies of FES therapy in chronic upper extremity hemiparesis have yielded measurable improvements in 1 to 10 subjects after 6 to 18 weeks of their particular type of intervention.<sup>16,19-21</sup> Our hypothesis that FES therapy can be efficacious in treating upper extremity function in chronic hemiplegia due to stroke cannot be confirmed within the limitations of this study.



**Figure 6.** Independence in terms of activities of daily living and assessments of motor recovery measured before and after treatment for chronic hemiplegic subjects (at least 2 years poststroke). Trends can be seen, but the results are not statistically significant ( $n = 7$ ). Mean value shown with error bars representing 1 standard deviation. FIM, Functional Independence Measure; CMSMR, Chedoke-McMaster Stages of Motor Recovery.

Our FES therapy program differs from other published studies on the rehabilitation of reaching and grasping in hemiplegia due to stroke in the following ways. First, the subjects who participated in this study were unable to move the paralyzed upper extremity at all or were able to perform very limited movements with the upper extremity, and as such were not candidates for FES programs proposed by Popovic et al,<sup>12</sup> Francisco et al,<sup>13</sup> or Cauraugh and Kim.<sup>14</sup>

## Implications

The results of this study suggest that FES therapy could be implemented in a rehabilitation setting to significantly improve the clinical outcomes of acute stroke patients as compared with results achieved from conventional therapy. It is not clear whether the improvements observed in this study are due to direct neurological effects of FES therapy or the facilitation of better therapeutic exercises through muscle stimulation.

## Limitations

Although this study provides evidence for the efficacy of FES therapy, it does not address the potential for effectiveness of FES therapy. Further trials with larger numbers of perhaps more diverse subjects from at least

a few other sites will be necessary to determine whether our strategy and results during subacute rehabilitation are reproducible in other settings and to determine whether factors such as cost, therapist training, ease of use of the technology, therapist and patient acceptance, and intensity of training can have utility for community practice.

## CONCLUSIONS

An intensive 12-week to 16-week regimen of FES therapy, which combined proximal muscle stimulation during reaching tasks and distal stimulation during grasp and pinch tasks, improved hand function and minimize upper extremity impairments in severe stroke patients more than conventional occupational therapy and physiotherapy alone in hemiplegic subjects during subacute stroke rehabilitation. Benefits of this program for patients with severe chronic hemiplegia were not found in our pilot study.

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