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Improving Hand Function in Stroke Survivors: A Pilot Study of Contralaterally Controlled Functional Electrical Stimulation in Chronic Hemiplegia

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Abstract

Objective—To assess the feasibility of a new stroke rehabilitation therapy for the hemiparetic hand.

Design—Case series. Pre- and post-intervention assessment with 1 and 3 month follow-ups.

Setting—Clinical research laboratory of a large public hospital.

Participants—Three subjects with chronic (> 6 mo post-CVA) upper extremity hemiplegia.

Intervention—Subjects used an electrical stimulator to cause the paretic hand extensor muscles to contract and thereby open the hand. The subjects controlled the intensity of the stimulation, and thus the degree of hand opening, by volitionally opening the unimpaired contralateral hand, which was detected by an instrumented glove. For 6 weeks the subjects used the stimulator to perform active repetitive hand opening exercises 2 hours daily at home and functional tasks 1½ hours twice a week in the laboratory.

Outcome Measures—Maximum voluntary finger extension, maximum voluntary isometric finger extension moment, finger movement control, and Box and Block score at pre- and post-treatment, and at 1 month and 3 months post-treatment.

Results—Maximum voluntary finger extension increased from baseline to end-of-treatment and from end-of-treatment to 1 month follow-up in two subjects. Maximum voluntary isometric finger extension moment, finger movement control, and Box and Block score increased from baseline to end-of-treatment and from end-of-treatment to 1 month follow-up in all 3 subjects. The improvements generally declined at 3 months.

Conclusions—The results suggest a positive effect on motor impairment, meriting further investigation of the intervention.

Keywords

stroke; hemiplegia; rehabilitation; electrical stimulation; medical device

Impaired hand function is one of the most frequently persisting consequences of stroke.¹ Paralysis of the hand or upper limb occurs acutely in up to 87% of all stroke survivors.^{2,3} Some recovery of motor control after a stroke is typical, occurring most rapidly during the first 3 months and usually plateauing by 6 months.^{4,5} Yet, 40% to 80% of all stroke

survivors have incomplete functional recovery of the upper extremity at 3 to 6 months post-stroke.^{2,3,6}

Advanced rehabilitation techniques may improve hand function in stroke survivors even after 6 months. Studies in both animals^{7,8} and humans^{9,10} suggest that active, repetitive, task-specific movement of the impaired limb is important in facilitating motor recovery after stroke. Constraint-induced movement therapy,^{11,12} robot-assisted movement,^{13–15} and EMG-triggered neuromuscular electrical stimulation (NMES) of paretic muscles^{16–20} are among several relatively new rehabilitation strategies that attempt to improve motor recovery by encouraging repetitive, active (self-initiated), functional movement of the impaired upper limb. Additional therapies shown to reduce motor impairment include bilateral symmetric exercise of the paretic and nonparetic upper limbs^{21–23} and motor imagery techniques,^{24–27} including the use of a mirror^{28,29} or virtual reality environments^{30–32} to create the perception of restored motor control. However, many of these emerging therapies require some residual movement of the impaired arm or hand and therefore are not applicable to severely disabled stroke survivors. Also, some of these techniques require long intensive therapy sessions or expensive equipment, which make them difficult to implement in the present healthcare environment.

This pilot study investigated Contralaterally Controlled Functional Electrical Stimulation (CCFES), a new therapy for improving recovery of hand function. CCFES integrates several rehabilitation techniques that are associated with improved motor recovery: 1) active, repetitive, goal-oriented movement, 2) neuromuscular electrical stimulation, and 3) bimanual symmetric exercise. CCFES therapy uses a stimulator that electrically activates paretic finger and thumb extensor muscles to open the hand. The stroke survivor controls the stimulation intensity and consequent degree of paretic hand opening by modulating the degree of opening of the contralateral unimpaired hand, which is detected by sensors attached to a glove worn on the unimpaired hand. While using the stimulation system, the stroke survivor has the ability to open and modulate the opening of their paretic hand. This article reports on the first 3 chronic stroke survivors to undergo a 6-week intervention of CCFES therapy, which consists of active repetitive stimulated hand opening exercises plus CCFES-assisted functional task practice with the paretic hand.

METHODS

Subjects

Stroke survivors with chronic upper extremity hemiplegia were recruited from an outpatient stroke clinic. The criteria for inclusion were (1) at least 6 months post-stroke, (2) manual muscle grade of 3 or less for finger extensors, (3) adequate active movement of shoulder and elbow on paretic side that allows the subject to volitionally position the hand in the workspace without pain, (4) functional hand opening without pain produced by stimulation through surface electrodes, and (5) ability to demonstrate correct use of the stimulator. Subjects were excluded if they had intramuscular botulinum toxin injections in any upper extremity muscle within 3 months prior to enrollment or at any time during the study, were apraxic, had uncompensated hemi-neglect, or uncompensated hemianopsia. The study protocol was approved by the hospital's Institutional Review Board, and written informed consent was obtained from each subject.

Instrumentation

The CCFES System (fig 1) consists of a stimulator, a command glove, and surface electrodes. The stimulator delivers up to 3 independent monopolar channels of biphasic current, and modulates the stimulation intensity (pulse duration) from each channel in

response to an analog input from the command glove. Sound and light cues from the stimulator prompt the subject to attempt to open and rest both hands for preprogrammed durations and duty cycles. The command glove has a sensor assembly attached on the dorsal side, which can be removed and attached to different sized gloves as needed. The sensor assembly consists of three 4½" x ¼" bend sensors^a enclosed in cloth sheaths that attach with Velcro to the glove over the index, middle, and ring fingers. When the fingers open and close proportional impedance changes in the sensors modulate the analog voltage input to the stimulator. Square 2"x2" and round 1¼" self-adhering pre-gelled electrodes^{b,c} are used to deliver stimulation to the extrinsic and intrinsic finger and thumb extensor muscles.

Setting up the CCFES System for each subject required determining the electrode positions and stimulation intensities that produced functional hand opening. For each subject, a 2"x2" electrode was placed over the dorsum of the wrist as the anode. To produce finger extension, the extensor digitorum communis (EDC) was targeted with a 2"x2" electrode placed on the dorsal mid-forearm. If the forearm electrode did not also produce thumb extension, a 1¼" electrode was placed either distal to the EDC electrode to recruit the extensor pollicis longus (EPL) or at the base of the thumb to recruit abductor pollicis brevis (AbPB). If extension of the proximal interphalangeal joints of the fingers was incomplete with EDC stimulation, a 1¼" electrode was placed on the dorsum of the hand to activate the dorsal interosseous (DI) muscles. The extensor indicis proprius (EIP) in the forearm was also targeted to enhance extension of the index finger if necessary.

The minimum and maximum stimulus intensities were determined for each stimulating electrode. The minimum intensity was defined as the pulse duration associated with the first perceived sensation or muscle twitch. The maximum intensity was defined as the pulse duration that produced maximum finger or thumb opening without discomfort. The input signal from the command glove was programmed to modulate the stimulation intensity of each channel from minimum to maximum as the gloved hand moved from a closed resting posture to fully open. The sound and light cues for hand opening were programmed to turn on and off with a duty cycle comfortable to the subject.

To assist the subjects or their caregivers in properly positioning the electrodes themselves at home, in the laboratory the electrodes were traced on the skin with a pen, pictures of the electrodes on the arm and hand were taken and given to the subjects, and the electrodes were color-coded to help ensure their connection to the correct stimulus channels. A user's manual detailing how to put on and use the CCFES System at home was carefully reviewed with each subject before they were sent home with it.

Intervention

The 6-week intervention consisted of using the CCFES System at home daily and in the laboratory twice a week. At home, the subjects were asked to use the stimulator to perform two 1-hour sessions of active, repetitive hand opening exercises every day. An exercise session consisted of three 15-minute sets separated by 5 minutes of rest. During a set, light and sound cues from the stimulator prompted the subject to open then relax both hands at the duty cycle programmed for them. The subjects were instructed to perform these exercises while sitting in a comfortable chair with minimal distractions and to separate the 2 hour-long sessions by at least 2 hours to avoid muscle fatigue. At the end of each exercise session, the subjects were instructed to fill out a diary, which had spaces for them to indicate the date, start time, and end time of each exercise session. The diaries were turned in

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^bAxelgaard Manufacturing Co, 1667 South Mission Road, Fallbrook, CA 92028

^cEmpi, 599 Cardigan Road, St. Paul, MN 55126

weekly. On days that the subject came to the laboratory, they were asked to perform only one exercise session at home at least 2 hours after their session in the laboratory.

At the beginning of each laboratory session, the study therapist or principal investigator answered any questions the subjects had regarding their home exercises, ensured that the subjects were placing their electrodes as prescribed, checked and collected usage diaries (weekly), and replenished electrodes (weekly). The laboratory session consisted of practicing a finger movement control task for 15 minutes, followed by practicing using the stimulated paretic hand to perform several functional tasks for approximately 75 minutes. Both the finger movement control task and the functional tasks were practiced with the CCFES System on; that is, the uninvolved hand modulated stimulation of the paretic hand during these tasks. For the finger movement control task, an electrogoniometer was attached to the paretic index or middle finger and connected to a computer. The computer displayed a track scrolling across the screen and a dot. The dot's vertical position corresponded to the total degree of extension of the finger recorded by the electrogoniometer. The subject's task was to keep the dot on the track by modulating the opening of the stimulated paretic finger. The track was scaled to the range of opening that the subject could achieve with the CCFES System that day. This task was designed to require the subject to concentrate on controlling the degree of hand opening, to develop motor skill, and to provide a strong perception that their motor intention is producing the desired modulated motor output.

Functional task practice was performed under the instruction and guidance of an occupational therapist. The session was divided into five 15-minute segments, each segment working on a different task with the paretic hand assisted by CCFES. The CCFES System was worn in a fanny pack around the waist and stockinette sleeves were slipped over both arms to prevent the cables from catching on objects during the task practice. All tasks emphasized hand opening, and ranged from easy to difficult. The more difficult tasks required the ability to slowly or carefully open the hand and coordinate hand function with proximal upper limb movement. Example tasks include repeatedly squeezing and releasing a foam ball, stacking blocks with controlled release, picking up and releasing cups of various diameters without overturning them, and using scissors. The tasks selected depended on the subject's ability and progress and varied from session to session.

Assessments

Upper extremity motor function was assessed at enrollment, end-of-treatment, and at 1 and 3 months thereafter. The outcome assessments included (1) active range of finger extension, (2) finger movement control, (3) isometric finger extension moment, (4) and the Box and Block Test.

Active range of finger extension was measured with an electrogoniometer placed on the index finger. The electrogoniometer recorded the metacarpophalangeal (MP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) joint angles simultaneously. Subjects were seated with their wrist and forearm restrained in a neutral posture and attempted to open the hand maximally in response to an audio tone of 3 or 5-sec duration. One minute of rest separated 6 maximum voluntary extension trials.

Finger movement control was measured using a finger movement tracking test similar to the tracking task used during the laboratory sessions. The electrogoniometer on the index finger displayed the total degree of finger extension as a dot while two parallel traces scrolled across the screen creating a target track. The vertical position of the dot corresponded to the total degree of finger extension ($MP^\circ + PIP^\circ + DIP^\circ$). The subject was instructed to keep the dot on the track by opening or closing their hand. The amplitude of the track ranged from -170° to 0° for Subjects 1 and 2, where 0° corresponds to full extension at the MP, PIP, and

DIP joints and -170° corresponds to slight flexion from a normal resting finger posture. For Subject 3, the resting posture of the index finger was approximately -230° , outside the track range of the first two subjects, so for this subject the track range was made -230° to -180° . Six 30-sec trials were run using three different tracks, each track presented twice. One minute of rest separated the 6 trials. The subjects were allowed to practice up to two 30-sec trials before beginning the test.

The isometric extension moment of the index MP joint was measured using an instrumented beam against which the subject extended the finger³³ in response to an audio tone of 3 or 5-sec duration. The beam was positioned so that the MP joint was fixed at 30° of flexion during the isometric moment measurements. One minute of rest separated 6 maximum voluntary isometric moment trials.

The Box and Block Test is a measure of gross manual dexterity,^{34,35} and requires the subject to pick up one block at a time, move it over a partition, and release it in a target area as many times as possible in 1 minute. Reliability and validity of the Box and Block test have been reported.³⁴ The subjects performed one 60-sec trial first with the unimpaired hand, and then with the impaired hand. Fifteen seconds of practice with each hand preceded the trials.

Analysis

For each trial of active range of finger extension, the mean MP, PIP, and DIP joint angles during the last second of the audio tone were calculated and summed to provide a total degree of maximum finger extension achieved. The mean total degree of maximum finger extension was calculated for the 6 trials. Similarly, for each trial of isometric finger extension moment, the average moment during the last second of the audio tone was calculated and the mean across 6 trials determined. ANOVA was used to compare across assessment sessions finger extension and isometric moment means for each subject. If ANOVA indicated that the means were not equal across assessment sessions ($P < .05$), then pairwise comparisons of the means were made using the Tukey procedure to determine the assessment sessions at which statistically significant differences from baseline occurred.

Finger movement control was evaluated by calculating the error per tracking trial and summing the errors over all 6 trials. The error per trial was the cumulative distance between the dot and the track. To allow valid comparison across subjects, the total error for each assessment session was normalized by the maximum total error for that subject. Statistical analysis was not possible on the finger movement control measure or Box and Block score because single measurements were obtained for each assessment session.

RESULTS

Three subjects were enrolled in this pilot study. The subjects' demographic and stroke-related characteristics are shown in table 1. For Subject 1, electrodes were positioned to stimulate the EDC, EPL/EIP, and DI muscles. For Subject 2, the EDC, EIP, and EPL were stimulated. For Subject 3, EDC, DI, and EPL/EIP were stimulated and produced extension of the thumb and index and long fingers but with inconsistent opening of the index PIP joint because of flexor tone that increased during attempts to use the hand. The sound and light cues used for the home exercise were programmed to turn on and off with the following duty cycle: 12/24 sec on/off for Subjects 1 and 2, and 8/15 sec on/off for Subject 3.

All 3 subjects were able to put on the electrodes and glove independently, although Subject 2 usually had a caregiver help him at home. For all 3 subjects it quickly became easy to operate the system and appropriately respond to the sound and light cues. Each subject

expressed enthusiasm for using the CCFES System, and according to the subjects' diaries compliance was 93%, 89%, and 100% for Subjects 1, 2, and 3, respectively.

The mean active range of finger extension (fig 2) for Subject 1 increased by 29° from baseline to end-of-treatment ($P = .001$), and increased another 10° at 1 month ($P < .001$). Subject 2 was able to achieve full finger extension at baseline (with slight hyperextension at the MP and PIP joints), so there was no gain to be achieved with respect to range of finger extension range. Subject 3 had a modest increase in mean finger extension of 8° at end-of-treatment ($P = .497$), which increased to 33° ($P = .002$) at 1 month. The gains in finger extension made by Subjects 1 and 3 had diminished by the 3 month follow-up.

Finger movement tracking error decreased from baseline to end-of-treatment by 61%, 13%, and 29% for Subjects 1, 2, and 3, respectively (fig 3). Further decreases in error were realized by all three subjects at 1 month. At 3 months, Subject 3 maintained her 1 month performance level, but Subjects 1 and 2 had greater tracking errors than at 1 month, yet not as great as at baseline. Subject 1 demonstrated progressive improvement from baseline to 1 month follow-up, with a subsequent regression at 3 months (fig 4).

The mean isometric finger extension moment for all 3 subjects increased from baseline to end-of-treatment, and further increased from end-of-treatment to 1 month follow-up (fig 5). For Subject 1, the mean isometric moment increased from 21 N-cm at baseline to 28 N-cm at 1 month, but this increase was not statistically significant ($P = .558$). For Subject 2, the mean isometric moment increased from 7 N-cm at baseline to 18 N-cm at 1 month ($P = .002$). The mean isometric moment produced by Subject 3 increased from 3 N-cm to 17 N-cm at 1 month ($P = .002$). For all 3 subjects finger extension strength returned toward baseline levels at 3 months.

Box and Block scores for all 3 subjects increased from baseline to end-of-treatment, and further increased at 1 month (fig 6). At 3 months, Subject 1 improved his score again, Subject 2 maintained his 1 month score, and Subject 3 had a sharp drop back to baseline level. Subject 3 complained of shoulder and arm pain during her 3 month follow-up.

DISCUSSION

Although the neurophysiological basis for motor recovery after stroke is not completely understood, research has shown that neuronal cortical connections and cortical representation areas, which were once thought to be static, are in fact modifiable by sensory input, experience, and learning.³⁶⁻⁴³ After a brain lesion, undamaged areas of the cortex may assume the function of damaged areas.⁴⁴⁻⁴⁶ Basic and clinical studies have demonstrated that motor neuroplasticity is facilitated by goal-oriented active repetitive movement training.^{7,47-49} This activity-dependent modification of synaptic connections and reorganization of adult cortical areas may be explained by long-term potentiation (LTP) of excitatory postsynaptic potentials.^{36,50} LTP provides a molecular explanation of Hebb's postulate that synapses are strengthened when pre- and post-synaptic neurons are repeatedly and synchronously active.⁵¹ At higher levels of neuronal organization, Hebbian plasticity relates to the presence of temporally correlated neural activity.⁵⁰ Therefore, rehabilitation therapies that generate synchronous activation of neurons along motor and sensory pathways might facilitate synaptic remodeling along those pathways, possibly leading to neural reorganization and improved motor recovery.

NMES may uniquely provide an artificial way of ensuring synchronized presynaptic and postsynaptic activity at the spinal level if the electrical stimulation is combined with simultaneous voluntary effort activating the residual upper motor neurons.⁵² CCFES capitalizes on this principle. Unlike cyclic (passive) NMES⁵³ which requires no active effort

by the participant, or EMG-triggered NMES¹⁷ which requires the participant to generate a supra-threshold muscle twitch to set off a preprogrammed intensity and duration of stimulation, CCFES maximizes the degree of coupling between motor intention (central, or pre-synaptic activity) and stimulated motor response (peripheral, or post-synaptic activity) by making the stimulation intensity proportional to the amplitude of the control signal (opening of the contralateral hand). Thus, the user not only controls the onset of the stimulation (as in EMG-triggered stimulation), but also controls the duration *and* intensity of stimulation and resultant hand opening.

In addition to these potential neuromechanistic advantages, CCFES incorporates several rehabilitation techniques associated with improved motor recovery: 1) *Repetitive movement* is incorporated by having the individual perform repetitive hand opening exercises daily and repetitive task practice in the laboratory. 2) *Active movement* is built into the therapy by having the hand stimulated to open only in response to deliberate opening of the contralateral hand. 3) *Task-specific or goal-oriented movement* is incorporated through therapist-supervised sessions in which participants are coached to use their paretic stimulated hand in functional tasks graded by difficulty. 4) *Bilateral symmetric movement* of the paretic and nonparetic upper limbs is implicit in the CCFES paradigm, as participants are instructed to attempt to volitionally assist the stimulation with their paretic hand to provide bilateral cortical drive. 5) *The perception of restored motor control* of the paretic hand is incorporated by synchronizing motor intention to motor response and proprioceptive and cutaneous feedback, potentially giving the participant the perception that he or she has regained control over their paretic hand.

The results of this pilot study suggest there is an association between CCFES therapy and positive changes in active finger extension, finger extension moment, finger movement control, and Box and Block score. Clearly, with a sample size of 3 and no control group no conclusion can be drawn regarding the strength of association or the probability of causation. Nevertheless, the data suggest that there may be a positive effect of the intervention, and therefore further investigation is merited.

The outcomes generally improved from baseline to end-of-treatment, improved further at 1 month, and regressed at 3 months. This trajectory supports the notion that the improvement is associated with the intervention and is not within the normal variability of the outcome measure or the subject. The decline at 3 months suggests that the improvements were not sustained. If the gains achieved during CCFES therapy are not large enough, it is likely that the individual will go back to performing tasks unilaterally with the unimpaired hand and regress again to the 'learned non-use' state, thereby losing the gains that were made. Perhaps larger and longer-lasting gains could be produced by optimizing the treatment dosage and duration. Future research is needed to validate or refute these initial trajectory observations and to determine the dose-response relationship.

The 1 month gains in total degree of maximum finger extension achieved by Subjects 1 and 3 were statistically significant, but modest, and whether those gains translate to improvements in whole hand function is uncertain. The maximum voluntary extension of one finger (the index) was used as a proxy for degree of achievable hand opening. This seemed reasonable given that the EDC, the primary target muscle of the intervention, extends all four fingers. Although changes in thumb extension were not measured, they in combination with index finger extension may better represent true hand opening. To reduce the chances of the subjects becoming fatigued during measurements of several digits, we decided to use measurements of one finger only to represent hand opening range and strength, and to rely on the Box and Block test as a more global measure of hand function.

Although the magnitudes of maximum isometric finger extension moment were much less than normal (~ 60 N-cm) for all 3 subjects during the entire study, some statistically significant gains were made. These gains in strength were expected because it is well known that NMES of paralyzed muscles increases their force-generating capacity and fatigue resistance.⁵⁴ These increases in extensor strength may be important for counteracting flexor tone, which was notably a problem in Subject 3 and to some extent in Subject 1. The modest strength increases parallel the increases in active extension range and may account for those gains in Subjects 1 and 3.

We interpret the improvements in finger movement tracking to correspond in part to improvement in motor control of the fingers. Such improvements may have come about by practicing the tracking task during the laboratory sessions, although the tracks presented during those sessions were different from the tracks presented during the assessments. The largest improvements in tracking occurred between baseline and end-of-treatment, coinciding with the 6-week intervention phase. The improvements between end-of-treatment and 1 month follow-up, however, could not be attributed to practice because no tracking practice sessions occurred during that interval. Perhaps there was a carry-over effect of the intervention that lasted through the 1 month follow-up. By 3 months, Subject 1 had lost the extension range he had gained (fig 2) which accounted for the decrease in tracking performance (figs 3 & 4). Thus, the finger movement tracking performance is not entirely dependent upon motor control, but also on active finger extension range.

The participants' subjective response to the intervention was positive. All 3 subjects reported that they had benefited from using the CCFES System. Subjects 1 and 3 expressed a desire to continue using it beyond the prescribed 6 weeks (though that was not allowed). Subject 1 said the intervention was "a total positive experience" and reported that it gave him greater hand strength resulting in greater use of his hand with greater confidence. Subject 3 stated at the end-of-treatment assessment, "I feel more in control of hand opening; I can 'will it' open more now than before." These responses together with the compliance data demonstrate that chronic stroke survivors can well tolerate CCFES therapy and can use the CCFES System at home as prescribed for two hours per day.

CONCLUSIONS

This pilot study demonstrated the feasibility of using CCFES to facilitate motor relearning in chronic hemiplegia. The results indicate a possible positive effect of the intervention. Future randomized controlled studies will seek to investigate the efficacy of CCFES therapy for chronic and acute stroke survivors and to compare CCFES with other NMES paradigms.

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Fig 1. CCFES System, consisting of electrodes, a stimulator, and a command glove. By opening the unimpaired hand wearing the command glove, the stroke survivor controls the intensity of electrical stimulation delivered to the paralyzed finger and thumb extensor muscles of the paretic hand.

Fig 2.

Sum of joint angles (MP° + PIP° + DIP°) of index finger during maximum voluntary finger extension (mean $\pm$ standard deviation). EOT = end-of-treatment assessment. Stars (*) indicate statistical significance ($P < .05$) relative to baseline.

Fig 3. Finger movement tracking error. Sum of errors over six tracking trials normalized to the maximum error, which was recorded at baseline for each subject.

Fig 4.

A single tracking trial for Subject 1 from each assessment session. Vertical axis is the sum of joint angles ($MP^\circ + PIP^\circ + DIP^\circ$) of index finger.

Fig 5. Isometric finger extension moment during maximum voluntary index finger extension (mean + standard deviation). Stars (*) indicate statistical significance ($P < .05$) relative to baseline.

Fig 6.
Box and Block score. Number of blocks transferred in 60 seconds.

Table 1

Baseline Characteristics of Three Stroke Survivors Receiving Contralaterally Controlled Functional Electrical Stimulation Therapy

Subject	1	2	3
Age (years)	50	65	44
Sex	M	M	F
Hemiplegic Side	L	L	R
Time since CVA (years)	1.3	3.8	7.8
Type of CVA	Ischemic, lacunar, subcortical	Ischemic, lacunar, subcortical	Ischemic, thrombotic, cortical
Baseline Fugl-Meyer score (max = 66)	43	28	32
Baseline observation of hand opening	Short duration, incomplete, weak	Full, weak, incomplete after flexion	Opens at MP joints, PIPs flexed, thumb adducted