

Effect of Intensive Functional Electrical Stimulation Therapy on Upper-Limb Motor Recovery after Stroke: Case Study of a Patient with Chronic Stroke

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ABSTRACT

Purpose: Motivated by a prior successful randomized controlled trial showing that functional electrical stimulation (FES) therapy can restore voluntary arm and hand function in people with severe stroke, this study was designed to examine neuromuscular changes in the upper limb following intensive FES therapy, consisting of task-specific upper-limb movements with a combination of preprogrammed FES and manual assisted motion. **Methods:** The patient was a 22-year-old woman who had suffered a haemorrhagic stroke 2 years earlier. FES therapy was administered for 1 hour twice daily for 12 weeks, for a total of 108 treatment sessions. **Results:** While maximal voluntary contraction level of the upper-limb muscles did not show significant improvement, the ability to initiate and stop the muscle contraction voluntarily was regained in several upper-limb muscles (approx. 5%–15% of the maximum voluntary contraction of the same muscle in the less-affected arm). A reduction in arm spasticity was also observed, as indicated by the reduction of H-reflex in the wrist flexor muscle (82.1% to 45.0% in H_{max}/M_{max}) and decreased Modified Ashworth Scale scores (from 3 to 2 for the hand and 4 to 3 for the arm). Coordination between shoulder and elbow joints during the circle-drawing test improved considerably over the course of FES therapy: the patient was unable to draw a circle at all at baseline but was able to do so proficiently at discharge. **Conclusion:** Improvements in upper-limb function observed in people with severe stroke following intensive FES therapy can be attributed to (a) regained ability to voluntarily contract muscles of the affected arm, (b) reduced spasticity and improved muscle tone in the same muscles, and (c) increased range of motion of all joints.

Key Words: functional electrical stimulation; rehabilitation; neuronal plasticity; stroke; muscle spasticity; upper limb.

RÉSUMÉ

Objectif : Cette étude, motivée par un essai clinique randomisé qui démontrait que la thérapie par stimulation électrique fonctionnelle (FES) pouvait redonner la fonction volontaire du bras et de la main chez les patients qui avaient subi un AVC grave, a été conçue pour examiner les changements neuromusculaires aux membres supérieurs à la suite d'une thérapie intensive par FES comprenant une série de mouvements spécifiques du bras ainsi qu'une combinaison de séances de FES préprogrammées et de mouvements assistés. **Méthode :** La patiente, une femme de 22 ans qui avait subi un AVC hémorragique 2 ans plus tôt, a été traitée grâce à une thérapie par FES, à raison de 2 séances quotidiennes d'une heure chacune, pendant 12 semaines pour un total de 108 séances de traitement. **Résultats :** Bien que la contraction volontaire maximale des muscles de la portion supérieure du bras n'ait pas montré d'amélioration notable, la capacité d'amorcer et d'arrêter la contraction musculaire a augmenté pour un certain nombre de muscles des membres supérieurs (soit d'environ 5 à 15 % de la contraction musculaire maximale des mêmes muscles dans le bras moins affecté). Une réduction de la spasticité du bras a aussi été observée, notamment par la réduction du réflexe H dans le muscle fléchisseur du poignet (de 82,1 % à 45,0 % du H_{max}/M_{max}) et par une baisse des pointages obtenus à l'échelle d'Ashworth modifiée (de 3 à 2 pour la main, et de 4 à 3 pour le bras). La coordination entre les articulations de l'épaule et du coude au cours d'un test qui consistait à dessiner des cercles s'est améliorée considérablement pendant la thérapie par FES : la patiente n'était pas en mesure de tracer un cercle au départ, mais elle a pu le faire couramment après avoir reçu son congé. **Conclusion :** Des améliorations à la fonction des membres supérieurs observées chez les personnes ayant subi un AVC grave à la suite d'une thérapie intensive par FES peuvent être attribuées à (a) une capacité retrouvée à contracter volontairement les muscles du bras touché; (b) une spasticité réduite et une amélioration du tonus des mêmes muscles et (c) une amplitude de mouvement plus grande pour toutes les articulations.

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Neuromuscular electrical stimulation (NMES) is a useful therapeutic method to improve motor function.^{1–9} Previous studies examining the use of NMES have demonstrated improvements in joint range of motion (ROM),^{1–4} force production of digits,⁵ and magnitude of electromyographic (EMG) muscle activity,⁶ as well as reduction of muscle tone.^{7–9} While these studies have used NMES for single-joint exercise, some more recent research has focused on the effect of electrical stimulation on multi-joint upper-arm movement.^{4,5,10–13} Functional electrical stimulation (FES) therapy integrates electrical stimulation to peripheral sensory and motor nerves with repetitive functional movement of the paretic arm in people with hemiplegia or quadriplegia.^{13–16} In FES therapy, preprogrammed electrical stimulation and manual assisted joint motion by a therapist are used to help the patient improve voluntary arm and hand function. The combination of FES and manual assist allows the person to feel the desired muscle contractions as well as the associated arm motion. Simultaneously, sensory signals may be generated by the excitation of afferent pathways in the stimulated peripheral nerves. In theory, such neural activity promotes motor re-learning.¹⁷ Recent studies using FES therapy have reported significantly better recovery of upper-limb function, specifically, in people with subacute stroke.^{11–13,15,18} In particular, a randomized controlled trial (RCT) published by Thrasher and colleagues¹⁵ showed an improvement of 24.5 points on the Upper Extremity Fugl–Meyer Assessment (maximum score = 66 points; a difference of 10 points represents clinically relevant change). However, the neural mechanism underlying the improvement in sensorimotor function is still not fully understood, and it remains uncertain whether this therapy is effective for people with chronic stroke.^{13,19,20}

The purpose of our study, therefore, was to examine neuromuscular changes occurring in the upper limb (UL) of people with severe stroke over the course of intensive FES therapy. To eliminate any potential contributions of spontaneous recovery that may occur following stroke, we recruited a patient with chronic severe stroke whose stroke occurred 24 months before the study. The FES therapy consisted of a variety of task-specific multi-joint movements with the combination of manual assisted passive motion and preprogrammed electrical stimulation. To capture the FES therapy-induced improvements in UL function, we performed the following assessments:

1. Clinical assessments:
 - Chedoke–McMaster Stages of Motor Recovery (CMSMR)
 - Motricity Index
 - Maximum voluntary contraction (MVC)
 - Modified Ashworth Scale (MAS)

2. Electrophysiological assessment:
 - H-reflex and maximal motor response M_{max}
3. Measurement of upper-arm joint kinematics:
 - Dynamic ROM test
 - Drawing test

Below, we use the results of these tests to discuss the mechanisms behind the improvements we observed following intensive FES therapy.

METHODS

Case description and selection

The study participant was a 22-year-old woman who had experienced a haemorrhagic stroke in the right frontal parietal area, secondary to an arteriovenous malformation (AVM) bleed, 2 years (>24 months) before the study. According to practice guidelines endorsed by the American Heart Association and the American Stroke Association, she can be regarded as a chronic stroke patient (the guidelines define “chronic stroke” as >6 months post stroke).²¹ When the patient began in-patient rehabilitation, her motor recovery status, scored by CMSMR, was as follows: arm = 1, hand = 2, leg = 2, and foot = 2. After 4 months of rehabilitation, her CMSMR scores were arm = 2, hand = 2, leg = 4, and foot = 2. While her left leg showed good recovery, her left arm was not functional and had high muscle tone.

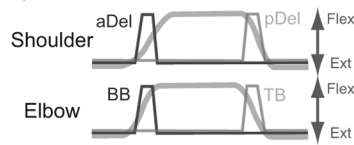
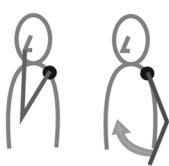
At the beginning of the FES therapy, the patient was walking independently in activities of daily living, with the help of a cane and ankle-foot orthosis, but rarely used her paretic arm for functional activities. Movement of her upper limb was characterized by a flexor synergy pattern. She had increased resistance to passive stretching in the distal flexor musculature. Using the two-point discrimination test, we confirmed that her tactile sensation was not severely impaired: she was able to discriminate two-point touch with her palm when points were about 3.5 cm apart. Before participating in the study, the patient was informed about the intervention and its potential risks and signed an informed consent form that was approved by the Review Board of the Toronto Rehabilitation Institute.

Functional electrical stimulation

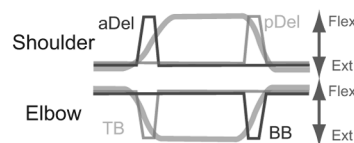
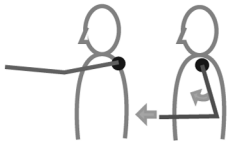
To deliver the FES therapy, we used the Compex Motion electric stimulator (DJO International, Guildford, UK), a fully programmable FES system with standard self-adhesive surface stimulation electrodes that can be used to develop sophisticated custom-made neuroprostheses.²¹ The following muscles were stimulated with surface stimulation electrodes (electrode locations are shown in Figure 1): anterior (aDel) and posterior deltoid (pDel), biceps (BB) and triceps brachialis (TB), extensor carpi radialis, extensor carpi ulnaris, flexor carpi radialis, and flexor carpi ulnaris. Muscles and nerves were stimu-

A

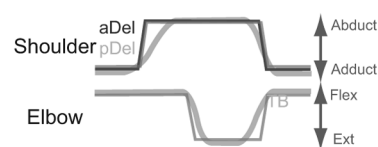
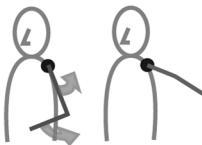
① Touch nose (or shoulder)



② Swing forward



③ Left side up



B

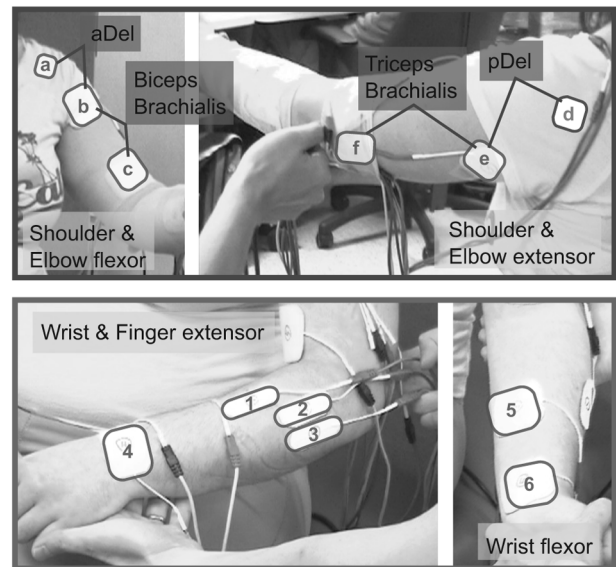


Figure 1 (a) schematic picture of functional motion tasks (left) and schematic examples of shoulder- and elbow-joint angle changes and stimulus pattern for each muscle (right); thick and thin lines indicate joint motion and stimulus pattern (timing of ON/OFF). (b) Location of electrodes.

lated using symmetrical biphasic current pulses, with a pulse duration of 250 microseconds and ramp-up and ramp-down times of 2 seconds. As in our previous studies, a constant stimulation frequency of 40 Hz was used.^{13,14} The therapist used a hand switch to trigger the stimulation in accordance with the patient's arm motion (see Figure 1a).

FES therapy protocol

The protocol used in this study has been described elsewhere.^{13–15} Briefly, the therapy consisted of preprogrammed coordinate muscular stimulation and manual assisted (externally generated) passive motion to establish physiologically correct movement. During each movement, the patient was asked to imagine the movements and to try to carry them out herself. The FES was delivered to shoulder and elbow extensor and flexor muscles while the patient (assisted by the therapist) performed six types of motions: (1) touch the nose, then extend the arm; (2) touch the contralateral shoulder, then extend the arm; (3) extend the arm forward in front of the body, then flex the arm; (4) abduct the shoulder with

flexed biceps, then extend the elbow, then extend the fingers; (5) grasp and release large objects; and (6) grasp and release small objects. The stimulus pattern and target muscles are summarized in Table 1 and described in detail elsewhere.^{13–15} FES therapy sessions took place twice daily for 1 hour per session. In people with stroke, neuromuscular recovery typically starts proximally, followed by recovery of the distal neuromuscular compartments.¹⁵ The FES therapy therefore began by training shoulder and upper-arm muscles.

During the treatment, a therapist controlled/triggered the arm movements using a push button. During the movements, the physiotherapist guided the patient's arm and assisted her with the neuroprosthesis in performing the desired tasks. This assistance ensured that all movements were carried out in a physiologically correct way (i.e., neuroprosthesis-induced movements did not oppose natural joint movements and respected the anatomy of bone and soft-tissue composition). In the early stages of treatment, arm and hand tasks were performed by a combination of muscular stimulation and assistance from the therapist. As UL function improved improved,

Table 1 Combination of Shoulder- and Elbow-Joint Motions in Each Task

Task	Shoulder motion	Electrodes	Elbow motion	Electrodes
Touch nose	Flexion	a–b	Flexion	b–c
Touch shoulder	Flexion and interior rotation	a–b	Flexion	b–c
Swing forward	Extension	d–e	Extension	e–f
Left side up	Abduction	a–b and d–e	Extension	e–f

assistance was reduced to the necessary minimum. Typically, the stimulation protocols were adjusted weekly or every 2 weeks. The participant was asked to repeat the same arm task 10 times for each motion during a single treatment session.

Outcome measures

Clinical assessments

CMSMR was used to evaluate motor paralysis of the arm and hand; Motricity Index tests²² for the UL were also used to assess arm and hand function. The degree of spasticity in the affected UL was evaluated using the five-grade Modified Ashworth Scale (MAS).

H-reflex and M_{\max} assessments

To assess the excitability of the spinal motoneuron pool in the flexor carpi radialis (FCR) muscle, the Hoffman reflex (H-reflex) was elicited via stimulation of the left median nerve. A pair of anode and cathode electrodes was placed on the medial position of the cubital joint. A rectangular pulse (1 ms) was generated by a constant voltage stimulator (DPS-007; Dia Medical System Co., Japan), which was triggered once every 5 seconds. The magnitude of the motor (M) response and the H-reflex were measured as the peak-to-peak amplitude of each response. The maximum values of the H-reflex (H_{\max}) and the motor response (M_{\max}) were quantified. To evaluate the excitability of the spinal motoneuron pool, we calculated the H_{\max}/M_{\max} ratio.

Maximal voluntary contraction (MVC) test

Using a bipolar differential amplifier (Bortec AMT-8; Bortec Biomedical, Calgary, AB), we measured the EMG signals in the following paralyzed upper-arm muscles: aDel, pDel, BB, TB, FCR, extensor digitorum longus (EDL), and first distal interosseous (FDI). A pair of surface electrodes (BiPole; Bortec Biomedical, Calgary, AB) was placed along the muscle fibres over the belly of each muscle, with an inter-electrode (centre-to-centre) distance of 10 mm. The recorded EMG signals were amplified 500 times and digitized at a sampling rate of 1,000 Hz, over a period of 500 milliseconds before and 500 milliseconds after the onset of the movement.

Active ROM test

The patient was asked to move her arm (1) forward, (2) backward, (3) upward, (4) to the right side, and (5) to the left side as much as she could. During these movements, we used a three-dimensional tracking device (FASTRAK; Polhemus, Colchester, VT) to record the positions of the shoulder joint, elbow joint, wrist joint, and second joint of the index finger. The relative orientations and positions of each sensor were collected, at a sampling rate of 40 Hz, and stored on a PC.

Circle-drawing test

This test assessed the patient's ability to coordinate shoulder- and elbow-joint movements. Drawing a circle

requires coordinating shoulder and elbow movements; for people with stroke, and specifically those who have spasm in their elbow joint, it is not easy to draw a wide and a properly shaped circle. As in the dynamic ROM test, we recorded the position of the shoulder, elbow, and wrist joints and the second joint of the index finger while the patient drew circles on a table. During the assessment, her movements were self-paced, and the task continued for 30 seconds.

Originally we planned to assess the patient using only clinical scales, H-reflex, and MVC measurements. During the first 6 weeks of training, however, she showed remarkable improvement in her shoulder and elbow motion, which prompted us to add dynamic ROM and circle-drawing tests to further evaluate functional motion of the UL.

RESULTS

Clinical assessments

The patient successfully completed all training sessions and assessments. Following 12 weeks of the FES therapy, she was able to pick up a thin object and to touch her nose, which she could not do before the FES therapy sessions. Table 2 summarizes the changes in clinical assessment scores over the course of therapy. The CMSMR and Motricity Index showed no changes during the FES therapy period; MAS scores for the hand and wrist showed a reduction in spasticity over the course of training (wrist: 3 to 2; hand: 4 to 3).

H-reflex and M_{\max}

H-reflex, which reflects spinal motoneuron excitability, also showed remarkable reduction with training (see Figure 2). The size of the H-reflex was quite large at the beginning of therapy (82.1% M_{\max}); as time passed, it decreased considerably, to 53.65% in week 6 and 45.04% in week 12.

Table 2 Time-Course Changes of CMSMR, Motricity Index, and MAS

	Baseline	Week					
		2	4	6	8	10	12
CMSMR							
Arm	2	2	2	2	2	2	2
Hand	2	2	2	2	2	2	2
Motricity Index							
Arm pinch grip	0	0	0	0	0	0	0
Elbow flexion	14	14	14	14	14	14	14
Shoulder abduction	0	0	0	0	0	0	0
MAS							
Arm	3	3	3	3	3	2	2
Hand	4	4	4	4	4	4	3

CMSMR = Chedoke–McMaster Stages of Motor Recovery; MAS = Modified Ashworth Scale.

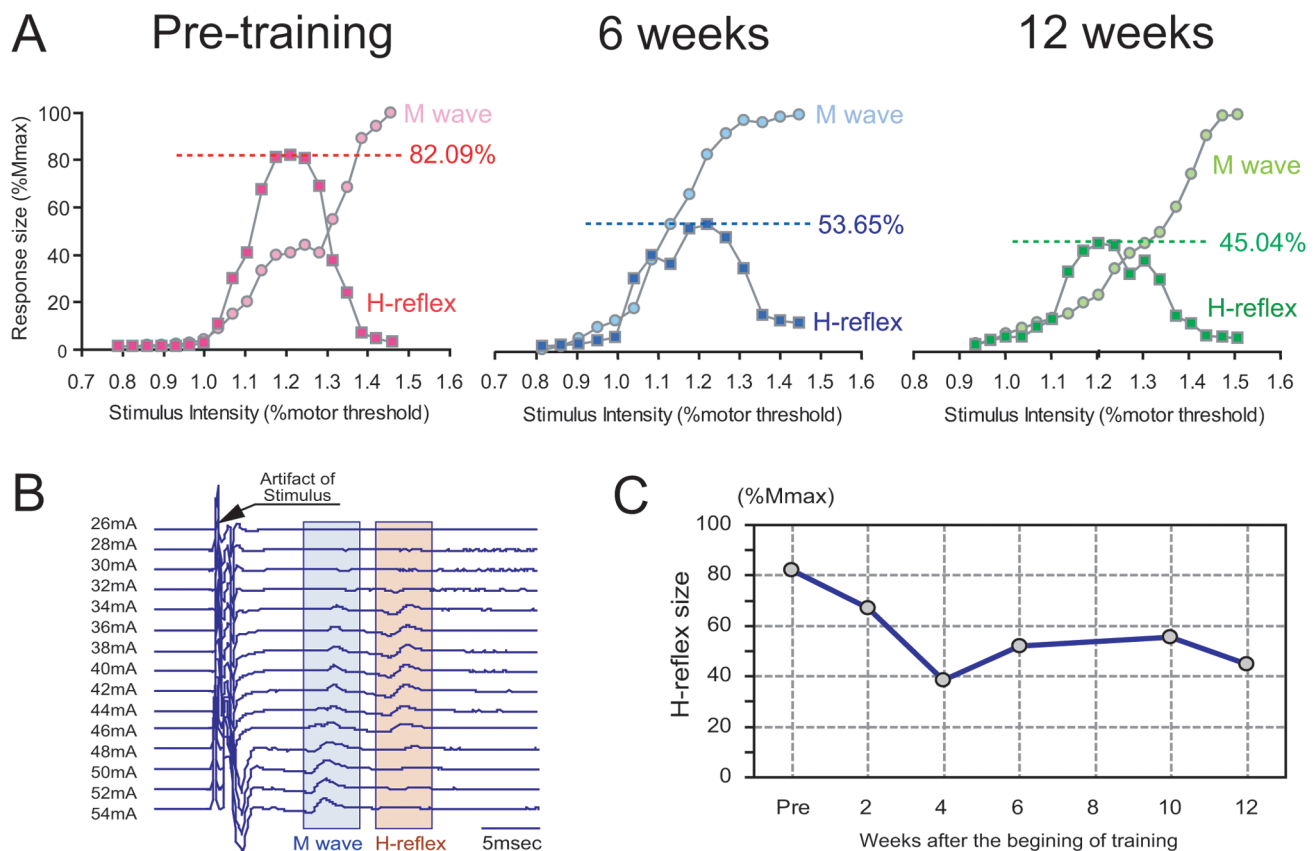


Figure 2 (a) recruitment curves of the H-reflex and M wave; (b) changes in M wave and H-reflex response to stimulus intensity; (c) change in H-reflex and M response over the course of training.

Maximal voluntary contraction

Figure 3 shows the changes in MVC in the upper-arm muscles, obtained every 2 weeks. The MVC level of the affected arm was remarkably smaller than that of the unaffected arm. While some muscles showed no alteration in the MVC level, both FDI and TB muscles showed meaningful changes over the course of training, from no EMG activity at baseline to visible EMG activities as a result of the FES therapy. It is also worth noting that for many of the muscles that exhibited EMG activity from day 1, the patient had no voluntary control; following 5 or 6 weeks of FES therapy, however, she began to exhibit voluntary control over several stimulated muscles and was able to voluntarily activate and relax them. This was a dramatic change from her original condition, in that muscle tone decreased and the patient was now able to voluntarily activate the muscles of interest, but the maximum EMG activity of these muscles did not change substantially.

Active ROM test

Table 3 shows shoulder and elbow dynamic ROM. For the shoulder and elbow joints, ROM tended to be larger at week 12 than those measured at week 6.

Circle-drawing test

Figure 4 shows shoulder, elbow, wrist, and index-finger trajectory during performance of the circle-drawing test. The absolute position of individual joints is represented in Figure 4a; position of elbow, wrist, and index finger relative to the shoulder-joint coordinate (i.e., assuming that the reference coordinate frame is in the shoulder joint) are shown in Figure 4b. It is clear that as the FES therapy progressed, the patient went from not being able to draw a circle on day 1 to being able to do so during week 6 and, finally, being able to draw an even larger circle during week 12.

DISCUSSION

The purpose of our study was to assess the effect of 12 weeks of intensive FES therapy on a person with chronic stroke. Although motor-capacity scores (i.e., CMSMR and MVC tests) showed no changes, MAS scores and the amplitude of the H-reflex were reduced as a result of the FES therapy. In addition, the kinematic results showed a profound improvement in the participant's ability to perform arm movements and to coordinate the shoulder and elbow joints. Furthermore, she acquired the ability to voluntarily contract and relax the muscles in

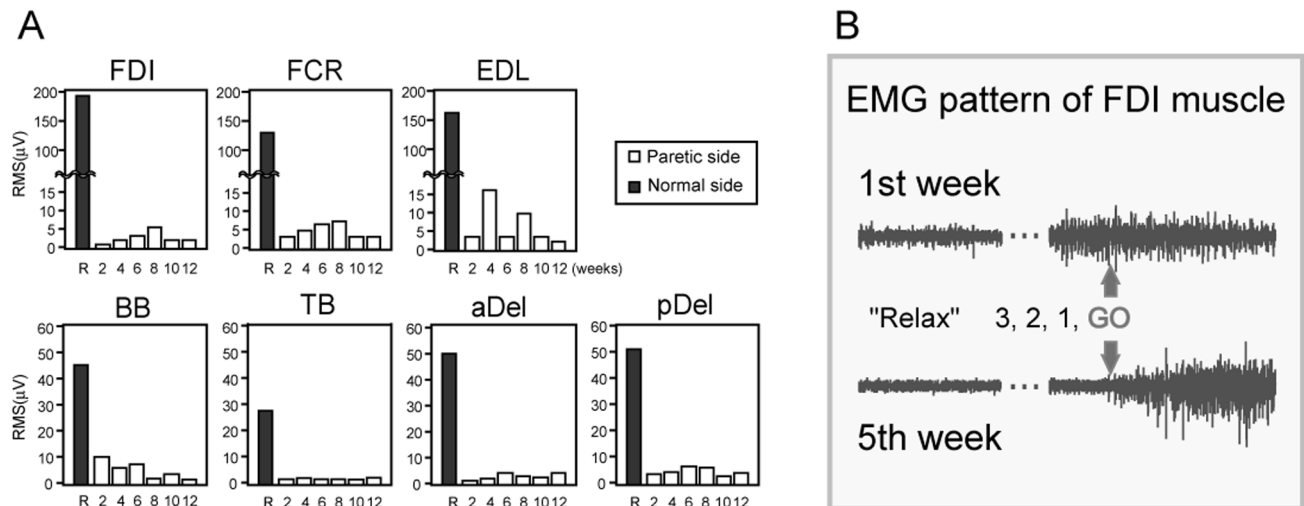


Figure 3 (a) Change over time in maximal voluntary contraction level of first distal interosseous muscles (FDI), flexor capi radialis (FCR), extensor digitorum (EDL), biceps brachialis (BB), triceps brachialis (TB), anterior (aDel) and posterior deltoid (pDel) muscles; black (print) / blue (online) bar = data from right (less affected side) arm. (b) EMG pattern in FCR muscle at initiation of voluntary muscle contraction.

her arm, although the strength of the muscle contraction did not improve substantially. Together, these changes effectively improved voluntary UL function so that our study participant, who was previously unable to use her stroke-affected arm, could voluntarily reach objects and grasp and manipulate smaller and light objects.

Traditionally, NMES has been used to increase the strength of voluntary muscle contractions in people with stroke. But recent applications of electrical stimulation are shifting the focus from muscle strengthening toward retraining the central nervous system and improving control of voluntary movements. In our study, FES therapy was used to retrain a person with severe chronic stroke to voluntarily perform coordinated multi-joint movements with her paretic arm, which previously was completely paralyzed. Since the stimulus intensity we used was approximately $2\times$ the motor threshold, one could not expect that the FES therapy would increase muscle strength. This assumption was confirmed by the results shown in Figure 3; that is, there were no consistent changes in MVC in the UL muscles. Therefore, the improvement observed should be attributed not to im-

proved muscle strength but, rather, to retraining and plasticity of the central nervous system.

Although motor score and MVC level showed no changes over the course of FES therapy, some muscles (i.e., TB and FDI) showed improved EMG activity as a result of FES therapy. Our results suggest that the contraction level induced by electrical stimulation was sufficient to reactivate the “deactivated” motor command to these muscles, since although these muscles showed no visible EMG activity at the beginning of the therapy, following the therapy the patient was able to voluntarily contract and relax them.

At the beginning of the FES therapy, the patient’s UL had high muscle tone. The muscle tone of the wrist and elbow flexors decreased remarkably as a result of the FES therapy, as is clearly reflected in the results of the MAS (Table 2) and H-reflex (Figure 3). This result agrees with previous findings describing the effects of electrical stimulation in terms of reducing abnormally high muscle tone.^{7–9,12} The resting position and condition of the patient’s arm and hand in her daily life were drastically changed over the course of training. At discharge from

Table 3 Dynamic Range of Shoulder- and Elbow-Joint Motion

Direction	Joint range of motion, degrees									
	Flexion		Abduction		Internal rotation		External rotation		Elbow extension	
	wk 6	wk 12	wk 6	wk 12	wk 6	wk 12	wk 6	wk 12	wk 6	wk 12
Forward	19.82	28.77	31.25	31.77	–	–	–	–	74.9	75.36
Upward	34.81	44.25	55.22	62.63	–	–	–	–	100.78	112.67
Left side	–	–	32.51	40.47	–	–	22.74	31.84	–	–
Right side	52.19	47.35	–	–	83.47	108.7	–	–	–	–

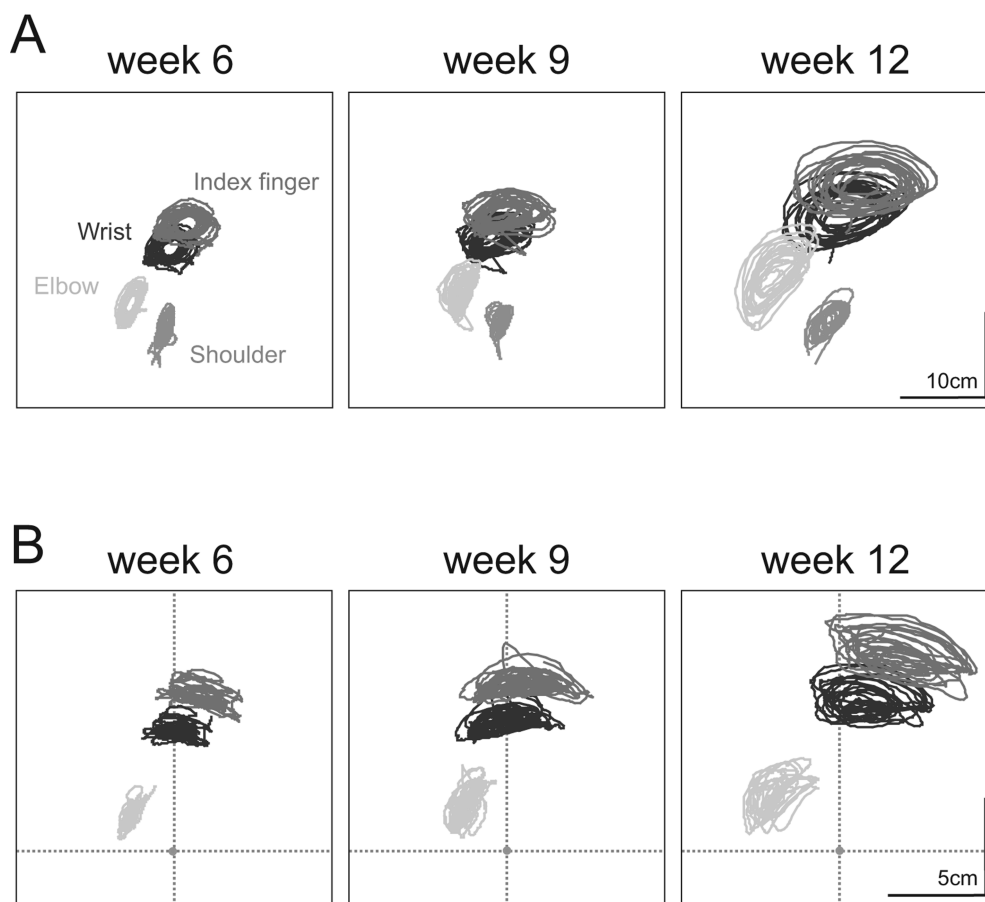


Figure 4 Trajectory of the shoulder, elbow, wrist, and index finger as the patient performed the circle-drawing test: (a) absolute positions of individual joints; (b) positions normalized with respect to the shoulder joint.

therapy, she could relax her arm and hand voluntarily and have them hang naturally at her side when not using the arm; when she needed to reach and grasp an object, her hand remained relaxed as her arm reached for the object, becoming active only when needed to grasp or release the object. This behaviour was strikingly different from the severe UL flexor synergy pattern observed when the study began.

Our study used a preprogrammed stimulus pattern that was able to generate four UL movements/functions, similar to our previous RCT.¹⁵ The temporal muscle-activation patterns induced by the FES were similar to those of an intact neuromuscular system performing the same task (i.e., the muscle activations were designed to clone actual natural movements). During the movements, therefore, the patient could feel when she was supposed to activate muscle contractions and how to sequence them to produce the desired movements. The fact that we observed marked changes in the H-reflex, and that several muscles that she was previously unable to voluntarily contract were under her voluntary control by the end of therapy, suggests that the functional improve-

ments induced by FES therapy were due at least in part to changes occurring in the central nervous system. In other words, we believe that the intensive and repetitive yet diverse FES therapy promoted cortical reorganization.^{13,15,23} We speculate, therefore, that the following mechanism is responsible for the changes observed in this and our previous studies:^{13–15} if a person with hemiplegia who struggles to execute a task is assisted with FES to carry out that same task, he or she is effectively voluntarily generating the motor command (desire to move the arm, i.e., efferent motor command) while the FES is providing the afferent feedback (afferent sensory input) to indicate that the command was executed successfully. We hypothesize that by providing both motor command and sensory input to the central nervous system repetitively, for prolonged periods, this type of treatment facilitates functional reorganization and retraining of intact parts of the central nervous system and allows them to take over the functions of the damaged part. As voluntary function improves, the volitional-related sensory feedback from the stimulated muscles and arm^{13,15,24} further contributes to this retraining process.

CONCLUSION

The present study confirms the findings we previously obtained in an RCT,¹⁵ as well as those of others,¹² that FES therapy can be used to improve voluntary UL function in people with chronic severe stroke. It also reinforces our prior finding that intensive FES therapy is effective even in cases of severe chronic UL impairment. This study is unique in having investigated on a weekly basis how the H-reflex and the EMGs of various muscles changed over time as a result of FES therapy. Our key finding is that muscles that were paralyzed before the study became active and were under the patient's voluntary control by the completion of therapy. The H-reflex also decreased almost 50% over the course of therapy, which suggests a significant reduction in muscle tone and/or spasticity as a result of this therapy. In future research, an RCT will be needed to ascertain the effect of FES therapy on the motor recovery of people with chronic severe stroke.

KEY MESSAGES

What is already known on this topic

Functional electrical stimulation (FES) therapy consists of preprogrammed electrical stimulation and manual support of joint motion by a therapist, which together enable the patient to achieve functional arm motion. Recent randomized controlled trials of patients with severe subacute stroke, using identical FES therapy, reported significantly better recovery of UL function in the FES therapy group than in the control group, which received intensive conventional occupational therapy and physiotherapy to improve UL function following stroke. However, some important questions remain with respect to the FES therapy; for example, What is the neural mechanism underlying an improvement of the sensorimotor function? Will this therapy be equally effective for people with chronic stroke?

What this study adds

In this study, a person with chronic severe stroke received FES therapy for 60 minutes 2×/day for 12 weeks and extensive neuromuscular assessments each week. As this level of therapy and the intensity and frequency of assessment is very demanding for the participant, only a single, carefully selected patient could participate in the study. Although our findings are derived from only one individual, they clearly show the efficacy of the FES therapy and provide insight into potential mechanisms of recovery of voluntary UL function observed in earlier randomized controlled trials with people with severe stroke.

REFERENCES

1. Faghri PD, Rodgers MM, Glaser RM, et al. The effects of functional electrical stimulation on shoulder subluxation, arm function recovery, and shoulder pain in hemiplegic stroke patients. *Arch Phys Med Rehabil*. 1994;75(1):73–9. Medline:8291967
2. Pandyan AD, Granat MH, Powell J, et al. Effects of electrical stimulation on the wrist of hemiplegic subjects. *Physiotherapy*. 1996;82(3):184–8. [http://dx.doi.org/10.1016/S0031-9406\(05\)66920-9](http://dx.doi.org/10.1016/S0031-9406(05)66920-9)
3. Pandyan AD, Granat MH, Stott DJ. Effects of electrical stimulation on flexion contractures in the hemiplegic wrist. *Clin Rehabil*. 1997;11(2):123–30. <http://dx.doi.org/10.1177/026921559701100205>. Medline:9199864
4. Chae J, Bethoux F, Bohinc T, et al. Neuromuscular stimulation for upper extremity motor and functional recovery in acute hemiplegia. *Stroke*. 1998;29(5):975–9. <http://dx.doi.org/10.1161/01.STR.29.5.975>. Medline:9596245
5. Powell J, Pandyan AD, Granat M, et al. Electrical stimulation of wrist extensors in poststroke hemiplegia. *Stroke*. 1999;30(7):1384–9. <http://dx.doi.org/10.1161/01.STR.30.7.1384>. Medline:10390311
6. Dimitrijević MM, Stokić DS, Wawro AW, et al. Modification of motor control of wrist extension by mesh-glove electrical afferent stimulation in stroke patients. *Arch Phys Med Rehabil*. 1996;77(3):252–8. [http://dx.doi.org/10.1016/S0003-9993\(96\)90107-0](http://dx.doi.org/10.1016/S0003-9993(96)90107-0). Medline:8600867
7. Levin MF, Hui-Chan CW. Relief of hemiparetic spasticity by TENS is associated with improvement in reflex and voluntary motor functions. *Electroencephalogr Clin Neurophysiol*. 1992;85(2):131–42. [http://dx.doi.org/10.1016/0168-5597\(92\)90079-Q](http://dx.doi.org/10.1016/0168-5597(92)90079-Q). Medline:1373366
8. Alfieri V. Electrical treatment of spasticity. Reflex tonic activity in hemiplegic patients and selected specific electrostimulation. *Scand J Rehabil Med*. 1982;14(4):177–82. Medline:6983718
9. King TI II. The effect of neuromuscular electrical stimulation in reducing tone. *Am J Occup Ther*. 1996;50(1):62–4. <http://dx.doi.org/10.5014/ajot.50.1.62>. Medline:8644838
10. Cauraugh J, Light K, Kim S, et al. Chronic motor dysfunction after stroke: recovering wrist and finger extension by electromyography-triggered neuromuscular stimulation. *Stroke*. 2000;31(6):1360–4. <http://dx.doi.org/10.1161/01.STR.31.6.1360>. Medline:10835457
11. Popovic MB, Popovic DB, Sinkjaer T, et al. Clinical evaluation of Functional Electrical Therapy in acute hemiplegic subjects. *J Rehabil Res Dev*. 2003;40(5):443–53. <http://dx.doi.org/10.1682/JRRD.2003.09.0443>. Medline:15080229
12. Popovic MB, Popovic DB, Schwirtlich L, et al. Functional Electrical Therapy (FET): Clinical Trial in Chronic Hemiplegic Subjects. *Neuromodulation*. 2004;7(2):133–40. <http://dx.doi.org/10.1111/j.1094-7159.2004.04017.x>. Medline:22151194
13. Popovic MR, Thrasher TA, Zivanovic V, et al. Neuroprosthesis for restoring reaching and grasping functions in severe hemiplegic patients. *Neuromodulation*. 2005;8(1):58–74. <http://dx.doi.org/10.1111/j.1094-7159.2005.05221.x>
14. Popovic MR, Thrasher TA, Adams ME, et al. Functional electrical therapy: retraining grasping in spinal cord injury. *Spinal Cord*. 2006;44(3):143–51. <http://dx.doi.org/10.1038/sj.sc.3101822>. Medline:16130018
15. Thrasher TA, Zivanovic V, McIlroy W, et al. Rehabilitation of reaching and grasping function in severe hemiplegic patients using functional electrical stimulation therapy. *Neurorehabil Neural Repair*. 2008;22(6):706–14. <http://dx.doi.org/10.1177/1545968308317436>. Medline:18971385
16. Popovic MR, Kapadia N, Zivanovic V, et al. Functional electrical stimulation therapy of voluntary grasping versus only conventional rehabilitation for patients with subacute incomplete tetraplegia: a randomized clinical trial. *Neurorehabil Neural Repair*. 2011;25(5):433–42. <http://dx.doi.org/10.1177/1545968310392924>. Medline:21304020
17. Nudo RJ, Milliken GW. Reorganization of movement representations in primary motor cortex following focal ischemic infarcts in adult squirrel monkeys. *J Neurophysiol*. 1996;75(5):2144–9. Medline:8734610
18. Ring H, Rosenthal N. Controlled study of neuroprosthetic functional electrical stimulation in sub-acute post-stroke rehabilitation. *J Rehabil Med*. 2005;37(1):32–6. <http://dx.doi.org/10.1080/16501970410035387>. Medline:15788330

19. Chae J, Yu DT. Neuromuscular electrical stimulation for motor restoration in hemiparesis. *Top Stroke Rehabil.* 2002;8(4):24–39. <http://dx.doi.org/10.1310/REXB-AKV9-2XBE-U5QA>. Medline:14523728
20. de Kroon JR, van der Lee JH, IJzerman MJ, et al. Therapeutic electrical stimulation to improve motor control and functional abilities of the upper extremity after stroke: a systematic review. *Clin Rehabil.* 2002;16(4):350–60. <http://dx.doi.org/10.1191/0269215502cr504oa>. Medline:12061468
21. Duncan PW, Zorowitz R, Bates B, et al. Management of adult stroke rehabilitation care: a clinical practice guideline. *Stroke.* 2005;36(9):e100–43. <http://dx.doi.org/10.1161/01.STR.0000180861.54180.FF>. Medline:16120836
22. Collin C, Wade D. Assessing motor impairment after stroke: a pilot reliability study. *J Neurol Neurosurg Psychiatry.* 1990;53(7):576–9. <http://dx.doi.org/10.1136/jnnp.53.7.576>. Medline:2391521
23. Bül N, Roderick J, Mohamed O, et al. Effectiveness of sensory and motor rehabilitation of the upper limb following the principles of neuroplasticity: patients stable poststroke. *Neurorehabil Neural Repair.* 2003;17(3):176–91. <http://dx.doi.org/10.1177/0888439003257137>. Medline:14503438
24. Raghavan P, Krakauer JW, Gordon AM. Impaired anticipatory control of fingertip forces in patients with a pure motor or sensorimotor lacunar syndrome. *Brain.* 2006;129(6):1415–25. <http://dx.doi.org/10.1093/brain/awl070>. Medline:16597653