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Functional Electrical Stimulation Therapy Improves Grasping in Chronic Cervical Spinal Cord Injury: Two Case Studies

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Abstract— **OBJECTIVE AND IMPORTANCE: To present case studies of two individuals with chronic cervical spinal cord injury (SCI) who participated in functional electrical stimulation (FES) therapy with the objective to restore voluntary grasp function. CLINICAL PRESENTATION: Both individuals (right hand dominant males, age 24 and 31) had a sustained a cervical SCI (C6 and C4-5, respectively) at least 8 years prior to participation in this study. INTERVENTION: Both individuals participated in an individualized FES therapy program for 6 weeks. FES therapy was administered through a regimen of three, one-hour sessions, per week for three months. A single arm of each participant (n = 2) was treated. FES therapy is an integrative intervention strategy combining muscle strengthening, functional movement training and stretching. The participant's hand movement abilities were assessed pre and post FES therapy using the Manual Muscle Test (MMT), a modified Sollerman Hand Function Test (mSHFT), and the Reach, Grasp, Transport and Release Task (RGTR). DISCUSSION: As the injuries of participants in the current study were chronic and thus neurologically stable, no spontaneous improvements/recovery in hand function was expected. However, FES as part of an integrated therapeutic approach affected restoration and improvement of hand function in both participants. CONCLUSION: The concurrent improvement in strength, integrated motor function and object contact following FES therapy, demonstrated that there is potential for affecting change in hand function of individuals with chronic SCI.**

Index Terms **— chronic spinal cord injury, functional electrical stimulation therapy, hand function, restoration of voluntary function.**

I. INTRODUCTION

SPINAL cord injury (SCI) results in the impairment of motor and/or sensory function below and at the level of injury. The extent of an individual's impairment varies according to the level, location and severity of the injury. Seventy-three percent of all SCI patients show some degree of neural recovery with associated gains in activities of daily living (ADL) [1]. Most neurological return occurs within the first year after the SCI [2]. Recovery occurs most rapidly in the first six months, and continues at a slower pace for up to two years [2].

In Canada and the United States of America, there are about 11,000 new SCIs per year and approximately 240,000 individuals who are living with a chronic SCI [3]. Individuals with cervical SCI (approximately 50 % of the SCI population) consider recovery in their upper extremities most important [4,5]. The ability of an individual to effectively use the hand is critical to his or her independence [6]. Although biological mechanisms for upper extremity recovery following cervical SCI are poorly understood [7], it has been stated that disproportionate functional benefits can be gained from minor neuromuscular gains [8]. Furthermore, small improvements in the ability to perform daily activities can have large impact on quality of life for individuals recovering from SCI [9]. Additionally, there have been reports of late recovery occurring in individuals with SCI [10,11].

Current rehabilitation procedures aim to minimize the negative effects of immobilization, to prevent complications, and to teach individuals independence in ADL [12]. The muscular systems below the level of SCI receive limited attention during rehabilitation. Rehabilitation of sensorimotor function is achieved through adaptation (e.g., application of an orthosis) and compensation (e.g., training new muscle synergies) [13]. Strategies that aim to improve upper extremity motor abilities of individuals with SCI and that use electrical stimulation include: conventional therapy, biofeedback, electrical stimulation and functional electrical stimulation (FES). These strategies are often combined and customized to the participant's functional abilities and goals and modified as motor recovery occurs.

FES uses trains of small electrical impulses to generate muscle contractions to achieve meaningful movements (i.e., palmar grasp) and FES has been used in the clinical care of individuals with SCI chiefly as a means to facilitate movement of the upper and lower extremities [14]. In recent years, there have been several reports of the recovery of voluntary movement in both the upper [14-17] and lower extremities [10,11,30] of individuals with SCI after repeated use of FES. The building evidence of restoration of movement ability at or below the level of injury, regardless of time since injury, encouraged the investigation of FES as a component of therapeutic intervention.

FES therapy is an integrative intervention strategy combining muscle strengthening, functional movement training, and stretching used both to facilitate muscle strengthening and functional training. Due to the customized

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progressive nature of FES therapy, the ratio of time, as well as the duration of the session, may vary to ensure that participants receive the amount of therapy that may maximize their potential recovery without causing undue fatigue. The construct of FES therapy encompasses multiple aspects of established rehabilitation strategies (Figure 1).

Specifically, the FES therapy presented in this paper focuses on attempting to assist individuals with chronic cervical SCI to improve their hand function. Hand function is the integrated capacity of an individual to sense, generate force, move, and sustain movement and force against loads. Restoration of hand function is important to individuals with cervical SCI as it provides more independence through the ability to perform ADL; thus, increasing the quality of life [6].

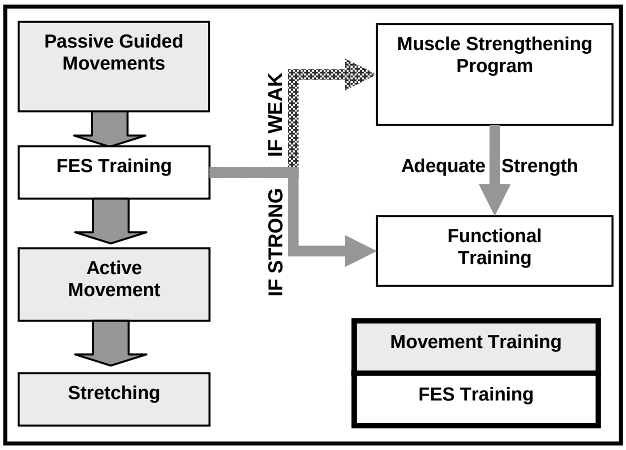

Figure 1: FES therapy construct

II. METHODS

A. Participants

Two case studies are presented in this paper. Both individuals (right hand dominant males) had a cervical SCI. Participant 1 (P1) was 24 years old, and his injury occurred in the C6 region (AIS B) nine years prior to this study (American Spinal Injury Association (ASIA) Impairment Scale (AIS)[18]). Participant 2 (P2) was 31 years old, and his injury occurred in the C4-C5 region (AIS C) eight years prior to this study (see Table 1).

Table 1: Participant's Clinical Information

	Participant 1	Participant 2
Age	24 years	31 years
Duration of Injury	9 years	8 years
AIS Classification	C6 AIS B	C4-C5 AIS C
SCIM Score	68/100	42/100

B. Assessments and Outcome Measures

Each participant's neurological level of injury and level of independence were assessed using AIS [18] and the Spinal Cord Independence Measure (SCIM) [19], respectively. Participants were required to have functional biceps and deltoid muscle activation (i.e., AIS individual muscle motor score of three or more), which ensured the placement of their hand in the working space and enabled participation in the functional training paradigm. The individual's hand movement abilities were assessed using the Manual Muscle Test (MMT) [20], a modified Sollerman Hand Function Test (mSHFT) [21], and the Reach, Grasp, Transport and Release Task (RGTR) [22].

A single arm of each participant (n = 2) was treated. The decision on which arm to treat was determined by the research team after an extensive participant interview to determine motivation to participate, and neurological and electromyographic evaluation. The arm to be treated had to have a positive muscular response to electrical stimulation.

To determine if the observed changes were significant the literature was reviewed to determine significance levels for change scores for MMT and mSHFT that are considered indicative of an actual functional change in hand function. According to the published reliability data of MMT [20], and mSHFT [29] tests, the levels of change in score that were considered significant for both tests were set to **greater than 2** for MMT, and **greater than 2** for each item of the mSHIFT.

The three groupings of muscles were examined by MMT were as follows: the muscles controlling the movement of the wrist, thumb and fingers. Due to the varying degrees in complexity and variability with testing the different groupings of muscles, each muscle group was evaluated separately. The scoring system used was as follows: 0=no palpable contraction; 1=palpable contraction; 2=complete range of motion (ROM) with gravity eliminated; 3=complete ROM against gravity; 4=complete ROM against gravity and against some resistance; and 5=normal, complete ROM against gravity and against full resistance. Further in regard to the muscles that control the actions of the fingers (which had the largest number of muscles tested, as shown in Table 2) were also grouped by muscle that received direct stimulation or were trained with the FES therapy paradigm. A probability estimate was then calculated for those muscles in both the treated and untreated limb, where the frequency of the muscles with a change in score greater than two was counted, enabling the treatment effect to be examined.

The tasks in the mSHFT were placed into one of five groups according to the movement involved in performing the task. The groups are as follows: 1) *tenodesis grasps:* pick up a crumpled piece of paper (Task1) and pick up thick marker (Task 2); 2) *active finger flexion and co-activation of thumb and finger flexor strength:* turn a key in a Yale lock 90 degrees (Task 3); 3) *pinch grasps:* pick up a 1 ”X1” block (Tasks 4), write a word on paper using unmodified pen (Task 5) and pick up a 5 ”X5” block (Task 6); 4) *active finger extension and wrist rotation:* unscrew lid of jars (Task 7); and 5) *active finger flexion and strength:* turn screw with screwdriver (Task 8) and lift iron over edge of mSHFT box (Task 9). The scoring of these tasks was as follows: 0=unable to complete the task; 1=partially complete task without prescribed grip; 2=partially completes task with prescribed grip; 3=completes the task without the prescribed grip; 4=completes the task with the prescribed grip but with unrefined movement; 5=completes task with the prescribed grip in a normal fashion

Table 2: Muscles Assessed (MMT), *denotes change expected

	FINGERS *	THUMB *	WRIST *
1	Flexor Digitorum Superficialis (FDS)*	Flexor Pollicis Brevis (FPB)*	Wrist Flexors (WF)*
2	Flexor Digitorum Profundus (FDP)*	Flexor Pollicis Longus (FPL)	Wrist Extensors (WE)*
3	Extensor Digitorum (ED)*	Abductor Pollicis Brevis (AbPB)*	
4	Extensor Minimus (EM)*	Abductor Pollicis Longus (AbPL)	
5	Extensor Indicis (EI)*	Extensor Pollicis Brevis (EPB)	
6	IP Extensors – Lumbricals (LUM)*	Extensor Pollicis Longus (EPL)	
7	Adductors – Palmar Interossi (PI)	Opponens Pollicis (OP)	
8	Abductors – Dorsal Interossi (DI)		
9	Abductor Digiti Minimi (AbDM)		
10	Opponens Digiti Minimi (ODM)		

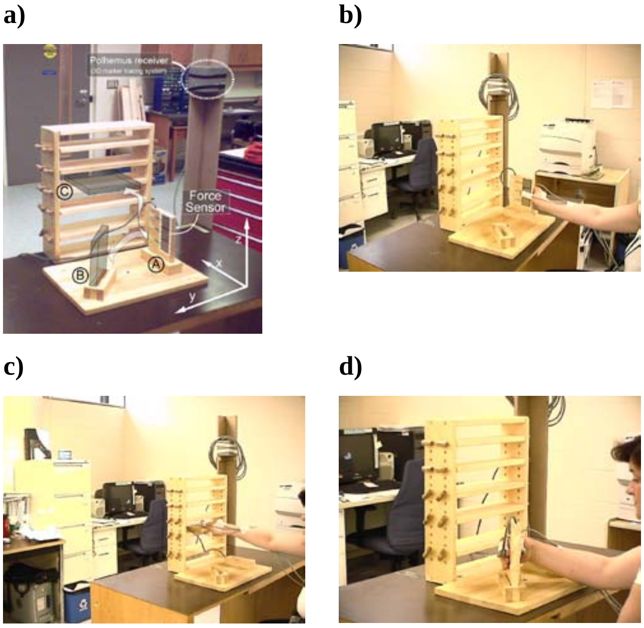

Figure 2: The Reach, Grasp, Transport and Release Task (RGTR): a) This photograph captures the main components of the RGTR system, which are: 1) instrumented wooden block with FSRs, 2) Fastrak (Polhemus Inc., USA) sensor for measuring finger kinematics and four 6 degrees of freedom sensors which were placed on the index finger, thumb, back of the palm and upper arm (not show on this figure but shown on the remaining three), 3) shelf (C), and 4) two locations where the instrumented wooden block can be placed (A) and (B). b-d) These figures show how the objects is manipulated during RGTR test in a sequence b-c-d.

The Reach, Grasp, Transport and Release Task (RGTR) [22] consists of grasping a small wooden block (approximately the size of a VHS tape) in one of two positions (see Figure 2 – (A) and (B) positions). Each trial consisted of: a) 5 movements where the wooden object was grasped in position (A), placed on the highest shelf possible and back to the position (A); and b) 5 movements where the wooden object was grasped in position (B), placed on the highest shelf possible and back to the position (B). The initial placement and the order of placement in positions (A) and (B) was random. Forces Sensitive Resistors (FSRs) were used to measure the force production of the thumb, index and middle digits during the RGTR. A custom designed data analysis program was used to score the participants' ability to maintain successful contact with the object. Successful contact with the object was determined by examining the force profiles produced when the participants performed the task properly. This requires the ability to co-activate the finger and thumb flexors while the wrist is in either an extended or neutral position for the duration of the grasp and transport portion of the RGTR task.

The RGRT data, which captured arm and hand kinematics during reaching and grasping as well as the grip force, was divided into kinematic and FSR data. For the purposes of this paper only the FSR data is reported. The FSR data comprises of outputs from two FSR sensors which were used to measure the grip force. The FSR data were filtered with a 4th order Butterworth filter with no phase lag and a cutoff frequency of 10 Hz [23,24]. The onset of grasp was determined when two opposing FSR signals exceeded 1 V, and the completion of grasp was determined when either of the FSR signals fell below 1 V. Variability was defined as the + 1 standard deviation (SD) of the FSR signal during the grasp. The first 10 FSR data points (0.2 s) and the last 10 FSR data points of each grasp were excluded from the SD calculation, as they represent the transient rise and fall time when the grasp was not in steady-state. Grasps of duration less than 1.0 s were considered too brief to achieve steady-state and were excluded from the analysis. Additionally, the grasps that were successful (as determined by the above criteria) were tallied and submitted to a Student's t-test with a significance level set at $p<0.05$ for comparison pre-post analysis.

In an effort to determine if the RGTR task would be reliable to measure change in an individual's grasp, the RGTR task was performed and analyzed first by able-bodied subjects. It was determined that within the able-bodied age matched controls there were no differences in the FSR variability or task success regardless of the hand used in the task or with time. Additionally, it was determined, that able-bodied individuals produce a significantly more variable force ($p < 0.0001$) than individuals with a cervical SCI. Therefore, this method of analysis was used for the individuals with SCI, to determine if FES treatment would alter FSR variability for each participant.

Repeated measures ANOVA was performed on the variability of both FSR signals. Two factors were considered: hand (treated vs. untreated) and time of measurement (before vs. after treatment). Statistical significance level was set at $p<0.05$.

After receiving approval from the University of Toronto and Toronto Rehabilitation Institute Ethics Boards, both individuals attended 18 one-hour FES therapy sessions over approximately three months.

C. FES Therapy

The following is an example how FES therapy was employed in this study. Each participant in the study was asked to execute a one-handed task (eg. reaching and grasping a cup). The participant would first try to execute the task unassisted. The components/sequences of the task that the participant was unable to perform were assisted by the FES system. Hence, the functional training began by designing a stimulation protocol that could assist or generate a palmar and/or the lateral grasp on demand. In other words, the stimulation sequence (protocol) was developed for each participant individually using a Compex Motion stimulator (Compex SA, Switzerland)[31] that allowed the participant, who otherwise could not grasp, to do so with the FES system. No splinting was used during the application of FES therapy. The electrodes were placed with great care to produce only the desired movements. Therefore, it was not necessary to block wrist flexion or extension. The command for activating the stimulation sequence was issued with a push button. By pressing a button, the participant controlled hand opening and closing. Stimulation parameters and the list of muscles that were stimulated during the study for each participant are presented in Tables 3 and 4.

Once the individualized FES protocol for grasping was developed the participant was trained with the system to perform grasping and releasing of everyday objects (i.e., a soft drink can, pencil, credit-card, etc.). The participant was asked to perform a variety of hand tasks multiple times during a 45-minute long treatment session. During the intervention, the therapist adjusted the placement of electrodes and guided the hand movements. The therapist ensured that all movements were functional, efficient and used normal movement patterns.

Table 3: Participant 1 - FES Therapy Details

Duration	May 6, 2004 – Aug 20, 2004	
Hand Treated	Right	
FES Therapy	Strengthen	Wrist flexors
		Wrist extensors
		Digit 3-5 flexors
	Acquire	Digit 1-3 flexors
		Digit 1-5 extensors
FES Parameters	General	Balanced biphasic pulse, width of 300 μs and a frequency of 40 Hz, self paced blocked on/off cycle
	Motor Stimulation (pulse amplitude mA)	*ED (15.7 ± 2.3)
		*Median Nerve (MN) Thumb (11.1 ± 1.2)
		*FDS (16.5 ± 2.4)
		*MN: Finger and Thumb (12.2 ± 1.1)

III. RESULTS

A. Participant 1

The AIS examination assessed Participant 1 as having a C6 sensory incomplete (AIS B) SCI. His SCIM score was 68/100. Neither of these assessment scores changed following the three months of FES therapy.

Table 4: Participant 2 - FES Therapy Details

Duration	May 6, 2004 – Aug 23, 2004	
Hand Treated	Left	
FES Therapy	Strengthen	Wrist extensors
	Acquire	Wrist flexors
		Digit 1-5 flexors
		Digit 1-5 extensors
FES Parameters	General	Balanced biphasic pulse, width of 300 μs and a frequency of 40 Hz, self paced blocked on/off cycle
	Motor Stimulation (pulse amplitude mA)	*ED (25.7 ± 1.8)
		*MN: Thumb (11.8 ± 0.6)
		*FDS (15.5 ± 1.1)
		*FDP (20.2 ± 0.6)

Tables 3 and 4: Delineate between muscle groups where existing movement was strengthened and where acquisition of movement was attempted. In addition the mean stimulation amplitude for the muscle and/or nerve is given. *ED: Extensor digitorum, MN: Median nerve, FDS: Flexor digitorum superficialis, FDP: Flexor digitorum profundus.

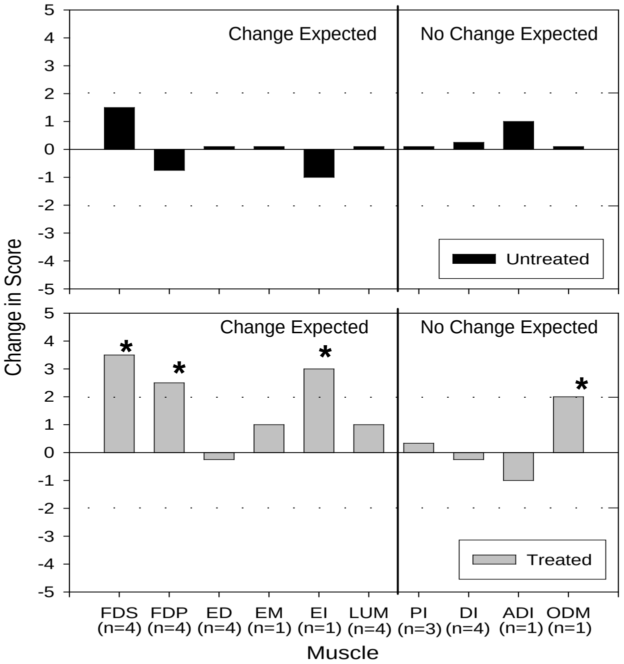

Figure 3: Average MMT Change Scores by Muscle for the Fingers (Participant 1): Untreated hand has no increases in MMT scores. * Denotes a change in score greater or equal to two for the treated wrist. FDS: flexor digitorum profundus, FDP: flexor digitorum profundus, ED: extensor digitorum, EM: extensor minimus EI: extensor indicis, LUM: lumbricals, PI: palmar interossi, DI: dorsal interossi, ADM: abductor digiti minimi, ODM: opponens digiti minimi. Dashed line represents the preselected level of change required for any change to be considered actual change.

MMT of the wrist and the thumb of both the treated (T) and untreated (UT) limb demonstrated no change in score (less than or equal to 2).

A frequency count was performed on the muscles of the fingers in both the treated and untreated hand. In Participant 1's untreated hand, 3 out of 27 muscles had increases in MMT score of two or more and one muscle had a decrease of two or more. In Participant 1's treated hand, 12 out of 27 muscles had increases in MMT score of two or more, 11 of these were included in the grouping of muscles that were hypothesized to change due to participation in FES therapy. Note that none of 27 muscles had decrease in MMT scores. Therefore, 61% of the muscles expected had increases of strength greater than two. In addition, a muscle (opponens digiti minimi) outside of the grouping of muscles where change was expected also had an increase in MMT strength score of two or more. The muscles across the digits were then combined in an effort to capture the adaptation in a given muscle; the results are presented in Figure 3.

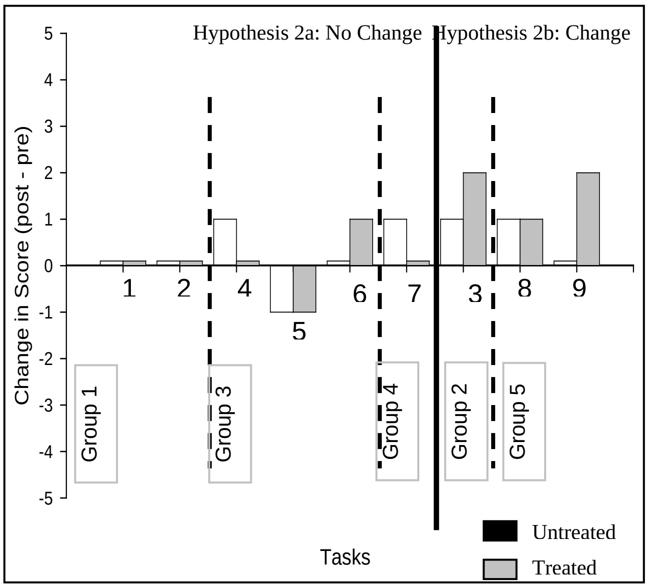

Figure 4: Modified SHFT Results (Participant 1): Two of three tasks that were hypothesized to change had an increase in score of two. * Denotes an increase of two or more. Tasks were grouped according to motor control demand. Group 1 = tenodesis grasps, Group 2 = active finger flexion, Group 3 = pinch grasps, Group 4 = active finger extension and wrist rotation, Group 5 = strong finger flexion.

When the results of the mSHFT were examined according to the task groups determined a priori, none of the tasks had a change in score of two or more in the untreated limb. The treated limb demonstrated in two of the three tasks (both of which require high skill and strength levels of the finger flexor muscles).

The RGTR task revealed that participation in FES therapy resulted in an increased ability of the participant to maintain successful object contact during the RGTR. Participant 1 had a significant increase in successful object contact scores in the arm that received the FES therapy (Treated limb $p \leq 0.001$) as previously reported [22].

In an effort to quantify the quality of force during the grasp and transport section of the RGTR task, the FSR signal variability was examined as outlined in the methods section of this paper. As presented in Figure 5, Participant 1 had a significant decrease in finger sensor FSR variability indicating that there was a consistent force related increase in the finger contact.

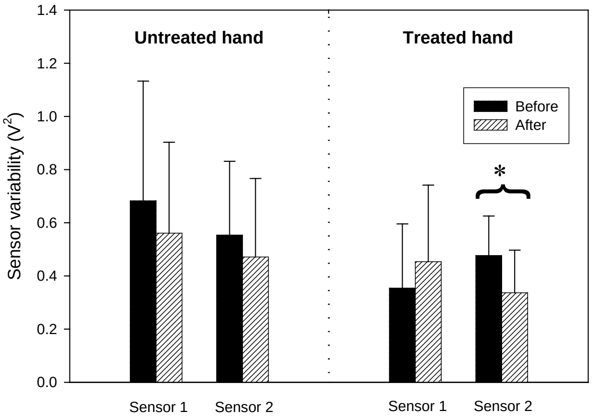

Figure 5: Participant 1 FSR variability during the RGTR task

B. Participant 2

Participant 2 has had a C4-5 motor incomplete (AIS C) SCI. The SCIM score was 42/100. Neither of these assessments changed following the three months of FES therapy. MMT of the wrist and the thumb of both the treated (T) and untreated (UT) limb demonstrated no change in score.

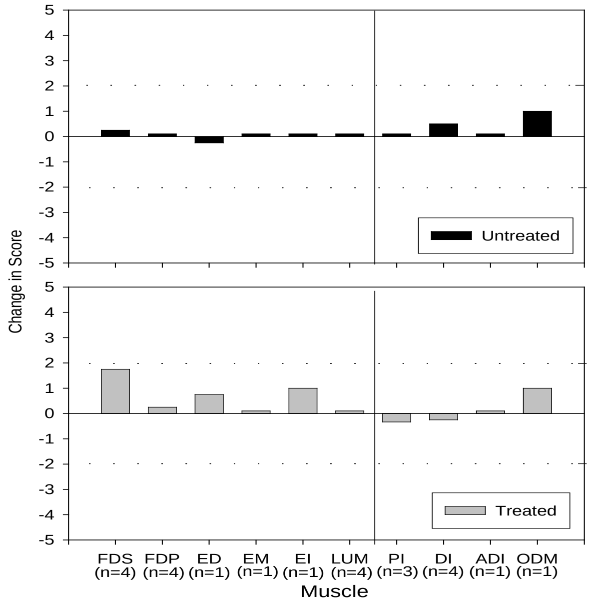

Figure 6: Average Change in MMT Scores by Muscle for Fingers (Participant 2): FDS: flexor digitorum superficialis, FDP: flexor digitorum profundus, ED: extensor digitorum, EM: extensor minimi, EI: extensor indicids, LUM: lumbricals, PI: palmar interossi, DI: dorsal interossi, AbDM: abductor digiti minimi, ODM: opponens digiti minimi. Dashed lines represent the preselected level of change required for for pre-determined clinical significance.

A frequency count was performed for the MMT data for the muscles controlling the movements of the fingers in both the treated and untreated hands (27 muscles per hand) finger digits were tested independently. In Participant 2's untreated hand, none of the muscles examined showed increases in MMT scores of two or more. Participant 2's program was designed to attempt movement acquisition in digit II-V flexors and extensors. Following FES therapy, this individual had 4/27 muscles (assessed across four digits) controlling the movements on his fingers which had an increase in MMT score of two or more. Additionally, none of the muscles on his untreated hand had an increase of MMT score. The MMT muscles scores for each the digits were then combined in an effort to capture the adaptation in a given muscle (Figure 6), showing that although neither the treated of untreated limbs had change sufficiently enough to met the a priori level of actual change, the treated hand generally showed more change that the untreated hand.

The mSHFT scores for Participant 2 are presented in Figure 7.

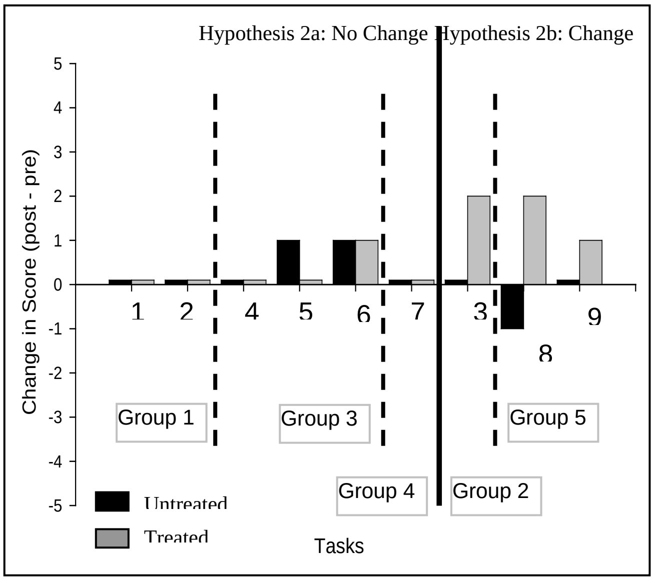

Figure 7: Modified SHFT Results (Participant 2): Two of three tasks that were hypothesized to change had an increase in score of two. * Denotes a change of two or more. Group 1 = tenodesis grasps, Group 2 = active finger flexion, Group 3 = pinch grasps, Group 4 = active finger extension and wrist ulnar and radial deviation, Group 5 = strong finger flexion.

When the tasks were examined according to the motor control involved, it was found that none of the tasks in the untreated limb had a change of score of two of more. The treated limb demonstrated in two of the three tasks (both of which require high skill and strength levels of the finger flexor muscles) had an improvement in score of two or more.

Participant 2 had a significant increase in successful object contact scores in the arm that received the therapy (Treated limb p = 0.046) as previously reported [22] in the RGTR task.

The FSR signal variability was examined, as outlined in the methods section of this paper, to quantify the quality of force during the grasp and transport component of the RGTR task. As presented in Figure 8, Participant 2 had a significant increase in thumb sensor FSR variability in the untreated limb, meaning that there was a more consistent force related increase in the thumb contact.

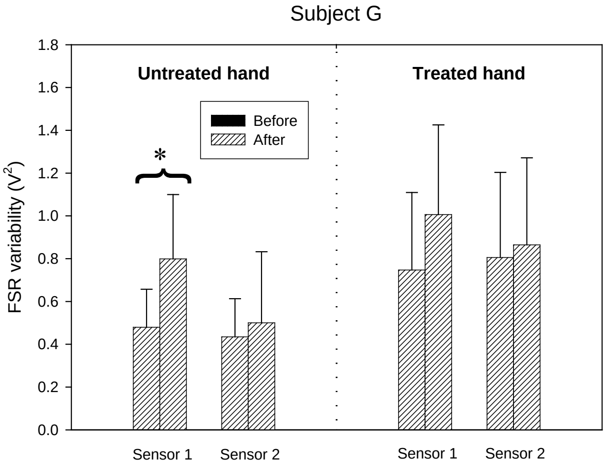

Figure 8: P2 FSR variability during the RGTR task

Force variability has been shown to increase monotonically with mean force in the able-bodied population [26]. Therefore, a more forceful grip will yield a greater measure of variability. In the literature it has been proposed that increase in force variability with strength can be compensated for by normalizing the standard deviation by dividing it with the mean force value [27]. In the present study we have not performed the proposed normalization because the output of the FSRs used in the study did not have a liner relationship between the force and the FSRs' voltage output, i.e., the sensitivity of the measured decreased as force increased,

Although both participants had differing deficits and consequently requiring different FES therapy strategies, both individuals had similar responses to FES therapy, (Table 5). There was an increase in strength for the FES treated muscles. Additionally, the increase in strength appeared to affect the both individuals ability to perform integrated motor tasks as well as grasp performance.

IV. DISCUSSION

A. *Wrist Strength*

While neither participant experienced increases in MMT scores (greater than 2), in muscles of the wrist, it is important to note that the initial raw MMT scores of both individuals were three or more. According to Schwartz et al. (1992) once an individual has good movement (movement against gravity - which both participants had) the MMT has been shown to be less sensitive to changes in muscle strength [20]. Therefore, it could be that individuals who participated in the present study had changes in wrist flexor and extensor strength, but the measurement approach was not sensitive enough to detect potential changes. Alternatively, no significant change occurred in the writs muscles.

B. *Thumb Strength*

Likewise, there were no demonstrated increases in strength in muscles controlling the action of the thumb. There are three possible explanations for the lack of change in the MMT scores in the muscles controlling the action of the thumb: 1) no change occurred, 2) inconsistent stimulation response, and/or 3) measurement error (measurement sensitivity). Which one of the three possible explanations is the appropriate one cannot determine at this point in time because of the way the study was carried out.

Table 5: Summary of Both Participants' Results: **Bold** indicates results that were similar across both participants.

	Participant 1	**Participant 2**
SCI injury	C6 Sensory Incomplete	C4-5 Motor Incomplete
Duration of Injury	9 years	8 years
FES Goals	Strengthen wrist flexors, extensors, and digit III – V flexors.	Strengthen wrist extensors
	Activate digit I - III flexors, and digit I-V extensors	Activate wrist flexors, digit I-V flexors and digit I-V extensors
SWM	No substantial change	No substantial change
MMT Totals (/180)	Treated **increase** of 40 points	Treated **increase** of 12 points
	Untreated **increase** of 5 points	Untreated **increase** of 4 points
Wrist Muscles	No substantial change	No substantial change
Thumb Muscles	No substantial change	No substantial change
Finger Maucles	**11/18 muscles with substantial increase** (**flexors** and extensors) in treated hand.	**4/18 muscles with substantial increase** (**flexors**) in treated hand.
mSHFT	Substantial **increase in score of tasks requiring finger flexor strength** in treated hand	Substantial **increase in score of tasks requiring finger flexor strength** in treated hand
Overall Successful Object Contact Score	**Significant increase** ($p \leq 0.005$) in treated hand only	**Significant increase** ($p=0.046$) in treated hand only
Target A Success	Treated hand increased by 21	Treated hand did not change
	Untreated hand increased by 5	Untreated hand decreased by 6
Target B Success	Treated hand **increased by 11**	Treated hand **increased by 10**
	Untreated hand decreases by 4	Untreated hand increased by 5

C. Fingers' Strength

Both participants demonstrated increased strength of the muscles controlling the action of the fingers. Participant 1's program was designed to strengthen existing movement in digit III-V flexors and to acquire movement in his digit II-V extensors and digit II flexors which was achieved with moderate success. Interestingly Participant 1's opponens digiti minimi, which was not a targeted muscle, demonstrated a similar increase in the MMT scored. This MMT score may result from the increased digit V flexor strength. Participant 2's program was designed to promote movement in the digit II-V flexors and extensors, which was achieved with modest success. At this point in time one can not speculate what was the main reason for the observed changes. Examination of the neurological change in the central nervous systems (both cortical, sub-cortical and spinal cord levels) and/or muscle tissue changes should be able to provide insight into the observed changes.

MMT is a surrogate measure for force generation, but it does not measure actual function restoration. None the less both participants, who initially demonstrated poor voluntary activation (at best a palpable contraction, with no associated movement), following FES therapy demonstrated some degree of improved voluntary activation of finger movements (at worst full ROM without gravity). The improvement in voluntary activation may be indicative that there are not only the peripheral muscular changes but also that there changes to the central nervous system. These findings are very much in line with our previous studies that examined FES therapy in sub-acute SCI patients and sub-acute stroke patients [17,30,32].

D. Additional Hand Movement Assessments

Both Participant 1 and Participant 2 showed improvements in integrated hand function, as measured by the mSHFT, following FES therapy. These tasks required the individual to flex their fingers with their wrist in a neutral or flexed position. FES therapy enabled both individual to perform new and some old tasks with improved dexterity, force and speed, i.e., improved overall performance.

Despite the obvious task performance improvement in the RGTR in the treated limb following FES therapy, there was no overall treatment effect that was seen in FSR variability. There was a significant difference between which hand was treated in the quadriplegic group in terms of FSR variability on the first sensor only. The accepted definition of force variability is the standard deviation of steady-state force [23,24]. This definition has also been applied to indirect measures of force, such as pressure [25]. In the present study, we applied this definition to the FSR signals, which are non-linearly related to force. Our analysis does not directly analyze the force variability, but a force-related phenomenon that was nonlinear. Therefore, another more accurate investigation of the force variability after FES therapy should be considered. .

Levels of change were calculated from pre-existing data from the MMT and mSHFT. The results in this study should be interpreted with care until the responsiveness of these measures is determined for persons with varying deficits. Likewise, it is important to determine the amount of strength change required to define clinical improvement as the rationale for change in score of 2 was somewhat arbitrary as no studies, to date, have been conducted for muscles of the fingers or thumb. The non-linearity of the MMT scale should also be considered. These issues encourage further studies into how muscle strength of the hand should be assessed and how the MMT scale demonstrates responsiveness. Likewise, to date, changes in the mSHFT, which is an observational measure with inherent bias, have not been replicated to determine significance with respect to functional restoration. However, the quantitative analysis of the RGTR task and the results for object contact show promise as a new strategy to measure improvement in addition to reflect motor learning

However, our study demonstrates that using FES in an integrated therapeutic approach affected restoration and improvement of hand function in individuals with chronic SCI. That by itself suggests that these patients, contrary to established belief in the rehabilitation field, still poses a potential for improvement many years post SCI. Also, these findings suggest that the FES therapy holds a promises with respect to restoring hand function in individuals with chronic SCI and that longitudinal studies that will examine use of the FES therapy for restoration of upper limb function are required.

Donaldson et al. [11], McDonald et al. [10], Popovic D et al.[15], Popovic MR. et al.[14], and Snoek et al. [16] all reported that following the application of a neuroprosthetic there was reported improvement of motor abilities. In some cases the neuroprosthesis was discarded as the movements it supplemented or augmented became possible without the device. More recently, Popovic MR et al [17], have shown that FES therapy has the potential to be used as an effective treatment strategy in restoring grasp function in individuals with acute cervical SCI and they reported that individuals with both complete and incomplete SCI, who received FES in addition to their regular therapy, had significant improvements in the tasks that they could perform with their upper extremity [17]. This is further supported by the recent systematic review by Kloosterman et al who also conclude that new standards for training and motor-learning need to be established [28].

V. CONCLUSIONS

This study demonstrated that the FES therapy has a potential as a therapeutic intervention to improve hand function in chronic, cervical SCI. The intervention strategy for this population must be customized, purposeful, progressive, goal orientated, and meaningful for the participant. The findings also suggest that the FES therapy causing positive change but that the measurement tools used to date to capture these changes are not sensitive enough to elucidate the underlying mechanisms that cause the observed changes. Further refinement of the measurement strategies is warranted if the efficacy of the FES therapy is to be determined. Establishment of protocols that incorporate specificity of approach and multiple outcome measures is important in order to translate the FES therapy into practice.

REFERENCES

[1] Tator CH. Biology of neurological recovery and function restoration after spinal cord injury. Neurosurgery 1998; 42(4): 696-707.

[2] Curt A, Dietz V. Neurographic assessment of intramedullary motoneuron lesions in cervical spinal cord injury: Consequences for hand function. Spinal Cord 1996; 34(6): 326-332.

[3] Pickett W, Simpson K, Walker J, Brison RJ. Traumatic spinal cod injury in Ontario, Canada. The Journal of Trauma 2003; 55(6):1070-1076.

[4] Anderson KD. Targeting recovery: priorities of the spinal cord-injured population. J Neurotrauma. 2004; 21(10): 1371-1383.

[5] Snoek GJ. Survey of the needs of patients with spinal cord :impact and priority for improvement in hand function in tetrapleagics. Spinal Cord 2004; 42:p 526-532.

[6] Waters RL, Sei IH, Gellman H, Tonnella M. Functional hand surgery following tetraplegia. Arch Phys Med Rehab 1996; 77(1): 86-94.

[7] Ditunno JF, Cohen ME, Haunck WW, Jackson AB, Sipski ML. Recovery of upper-extremity strength in complete and incomplete tetraplegia: A multicenter study. Arch Phys Med Rehab 2000; 81(4): 389-393.

[8] Becker D, Sadowsky CL, McDonald JW. Restoring function after spinal cord injury. The Neurologist 2003; 9(1): 1-15.

[9] Bracken MB, Shepard MJ, Holford TR, Leo-Summers L, Aldrich EF, Fazl M, Fehlings M, Herr DL, Hitchon PW, Marshall LF, Nockels RP, Pascale V, Perot PL, Piepmeier J, Sonntag VKH, Wagner F, Wilberger JE, Winn HR, Young W. Adminstration of methylprednisolone for 24 or 48 hours of tirilazad mesylate for treatment of acute spinal cord injury. Journal of American Medical Association 1997; 277(20): 1597-1604.

[10] McDonald JW, Becker D, Sadowsky CL, Jane, JA, Conturo, TE, Schultz, LM. Late recovery following spinal cord injury. Journal of Neurosurgery 2002; 97(2 Suppl): 252-265.

[11] Donaldson N, Perkins TA, Fitswater R, Wood DE, Middleton F. FES cycling may promote recovery of leg function after incomplete spinal cord injury. Spinal Cord 2000; 38(11): 680-682.

[12] Muslumanogu L, Aki S, Ozturk Y, Soy D, Filiz M, Karan A, Berker E. Motor, sensory and functional recovery in patients with spinal cord lesions. Spinal Cord 1997; 35(6): 386-389.

[13] Curt A, Schwab ME, Dietz V. Providing the clinical basis for new interventional therapies: Refined diagnosis and assessment of recovery after spinal cord injury. Spinal Cord 2004; 42(1): 1-6.

[14] Popovic MR, Keller T, Pappas IP, Dietz V, Morari M. Surface-stimulation technology for grasping and walking neuroprosthesis: Improving quality of life in stroke/spinal cord injury subjects with rapid prototyping and portable FES systems. IEEE Engineering in Medicine and Biology 2001; 20(1): 82-93.

[15] Popovic D, Stoianovic A, Pjanovic A, Radosavljevic S, Popovic M, Jovic S, Vulovic D. Clinical evaluation of the Bionic Glove. Arch Phys Med Rehab 1999; 80(3): 299-304.

[16] Snoek GJ, Lizerman MJ, Stoffers TS, Zilvold G. Use of the NESS Handmaster to restore hand function in tetraplegia: Clinical experiences in ten patients. Spinal Cord 2000; 38(4):244-249.

[17] Popovic MR, Thrasher TA, Adams ME, Takes V, Zivanovic V, Tonack MI. Functional electrical therapy: Retraining grasping in spinal cord injury, Spinal Cord, 44(3):143-151, 2006.

[18] ASIA 2002 American Spinal Injury Association Reference Manual for International Standards for Neurological and Functional Classification of Spinal Cord.

[19] Catz A, Itzkovich M, Steinberg F, Philo O, Ring H, Ronen J, Spasser R, Gepstein R, Tamir A. The Catz-Itzkovich SCIM: A revised version of the spinal cord independence measure. Disability and Rehabilitation 2001; 23(6): 263-268.

[20] Schwartz SS, Cohen ME, Heribson GJ, Shah A. Relationship between two measures of upper extremity strength: Manual muscle test compared to hand held myometry. Arch Phys Med Rehab 1992; 73(11): 1063-1068.

[21] Kalsi-Ryan SK, Beaton D, McIlroy W, Fehlings M, Verrier M. Quantification of Multi-modality sensation of the hand in cervical spinal cord injury. Journal of Spinal Cord Medicine 2006; 29(3): 311.

[22] Miller, RC, Popovic, MR, McIlroy, WE, Verrier MC. Upper Extremity Functional Electrical Stimulation: Case Study of Neuromuscular Restorative Therapy. Conference Proceedings of the 10th Annual conference of the International Functional Electrical Stimulation Society,2005; 320-322.

[23] Schiffman JM, Luchies CW. The effects of motion on force control abilities. Clin Biomech 2001; 16(6):505-513.

[24] Alberts JL, Butler AJ, Wolf SL. The effects of constraint-induced therapy on precision grip: A preliminary study. Neurorehabil Neural Repair 2004;18(4):250-258.

[25] Yan JH. Tai chi practice reduces movement force variability for seniors. J Gerontol A Biol Sci Med Sci 1999; 54(12):629-634.

[26] Selen LP, Beek PJ, Dieen JH. Can co-activation reduce kinematic variability? A simulation study. Biol Cybern 2005; 93(5):373-381.

[27] Deutsch KM, Newell KM. Children's coordination of force output in a pinch grip task. Dev Psychobiol 2002; 41(3):253-264.

[28] Kloosterman MG Snoek GJ Jannik MJ. Systematic review of the effects of exercise therapy on the upper extremity of patients with spinal cord injury. Spinal Cord. 2008; in press.

[29] Sollerman C, Ejeskär A. Sollerman hand function test. A standardised method and its use in tetraplegic patients. Scand J Plast Reconstr Surg Hand Surg. 1995;29(2):167-176.
[30] Thrasher TA, Flett HM, Popovic MR. Gait training regimen for incomplete spinal cord injury using functional electrical stimulation. Spinal Cord, 2006; 44(6):357-361.
[31] Popovic MR, Keller T. Modular transcutaneous functional electrical stimulation system. Medical Engineering and Physics. 2005; 27(1):81-92.
[32] Thrasher TA, Zivanovic V, McIlroy W, Popovic MR. Rehabilitation of reaching and grasping function in severe hemiplegic patients using functional electrical stimulation therapy. Journal Neurorehabilitation and Neural Repair. 2008; 22(6):706-714.