Research article

Influence of different rehabilitation therapy models on patient outcomes: Hand function therapy in individuals with incomplete SCI

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Objectives: The primary objective was to compare the benefits of single (COT1) versus double (COT2) dose of conventional occupational therapy (COT) in improving voluntary hand function in individuals with incomplete, sub-acute C3–C7 spinal cord injury (SCI). The secondary objective was to compare these two interventions versus functional electrical stimulation therapy plus COT (FES + COT).
Design: Retrospective analysis.
Setting: Inpatient spinal cord rehabilitation center, Toronto.
Participants: Individuals with traumatic incomplete sub-acute SCI.
Interventions: Data from Phases I and II (ClinicalTrials.gov ID NCT00221117) randomized control trials were pooled together for the purpose of this study. Participants in the COT1 group received 45 hours of therapy, the COT2 group received 80 hours of therapy, and the FES + COT group received 40 hours of COT therapy +40 hours of FES therapy.
Outcome measures: We analyzed the functional independence measure (FIM) and the spinal cord independence measure (SCIM) self-care sub-scores.
Results: The mean change scores on the FIM self-care sub-score for the COT1, COT2, and FES + COT groups were 12.8, 10, and 20.1 points, respectively. Similarly, the mean change scores on the SCIM self-care sub-score for the COT1, COT2, and FES + COT groups were, 2.6, 3.16, and 10.2 points, respectively.
Conclusion: Increased rehabilitation intensity alone may not always be beneficial. The type of intervention plays a significant role in determining functional changes. In this instance, receiving one (COT1) or two (COT2) doses of COT resulted in similar outcomes, however, FES + COT therapy yielded much better outcomes compared to COT1 and COT2 interventions.

Keywords: Conventional occupational therapy, Functional electrical stimulation, Hand function, Therapy, Intensity, FIM, SCIM

Introduction

According to a recent report published by the Rick Hansen Institute and Urban Futures, close to 86 000 Canadians are presently living with spinal cord injury (SCI), and an estimated 4300 new cases of SCI occur in Canada every year.[1] Of the 86 000 individuals with SCI, roughly 45% have tetraplegia. As individuals with tetraplegia are often unable to use their arms and hands following their injuries, it is not surprising that regaining/improving arm and hand function is a priority.[2]

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Despite intensive rehabilitation following SCI, functional recovery seldom occurs in these patients.[3] Most rehabilitation practices have embraced the often emphasized lesson of activity-based neurorehabilitation. Many practitioners have adopted the concept that what the patient does during therapy is not critical (as long as one applies a neurorehabilitation type of therapy), but that it is of great importance how long and how intensive the therapy is.[2,4] In other words, it is often believed that the therapy intensity is more relevant than the actual therapy modality.[2,4] On the other hand, in the recent series of articles published in the SCI Rehab Project, the authors have shown that increased hours

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of certain rehabilitation therapies, including increased occupational therapy, result in lower functional independence measure (FIM) motor scores at the time of patient discharge from the rehabilitation facility.[5,6] Furthermore, in these articles, the therapies that involved range of motion and stretching, self-feeding, and upper body dressing, were narrowed down as being associated with lower scores.

At the same time, considerable efforts have been made on the part of both researchers and clinicians to develop therapies that have the potential to enhance recovery of arm and hand function. Some interventions are working: (a) by permanently substituting the function compromised by SCI,[7,8] (b) in combination with already existing rehabilitation techniques and therapies,[9,10,11,12] and (c) by substituting therapists and/or existing therapies.[13,14,15] So far, only three therapies (i.e. short-term interventions aimed at improving voluntary upper limb function) from those listed above have shown positive outcomes in the SCI population, namely, the work by Kowalczewski *et al.*,[13] the functional electrical stimulation (FES) therapy proposed by our team,[9,12,16] and the therapy proposed by Beekhuizen and Field-Fote[17] that uses massed practice and sensory stimulation.

In this article, we will provide evidence that simply increasing the intensity of occupational therapy activities in the individuals with incomplete SCI does not result in better outcomes. Instead, we present evidence that by combining the FES therapy for upper limb developed by our team[9,12,16] with conventional occupational therapy (COT), one can generate better functional outcomes as measured by FIM and spinal cord independence measure (SCIM) self-care sub-scores.

Over the past 10+ years, our laboratory has conducted Phases I and II randomized control trials (RCTs) in individuals with sub-acute traumatic cervical SCI to evaluate the efficacy of our FES therapy.[9,12,16] In all of our trials, FES therapy was tested against single or double doses of COT. Since the eligibility criteria for these two RCTs was traumatic, incomplete, sub-acute (<6 months) cervical SCI, and the outcome measures were the same, the results of these studies could be compared. What we considered very interesting and relevant was comparing the difference in clinical outcomes between a single dose of COT (COT1) and a double dose of COT (COT2). Hence, the primary objective of the study was to compare the benefits of the single dose (COT1) versus double dose (COT2) of COT in improving voluntary hand function in individuals with traumatic, incomplete, sub-acute C3 – C7 SCI. Our hypothesis was that the double dose of COT (COT2) would be more effective in improving upper limb function as compared to the single dose of COT (COT1), as measured by SCIM and FIM self-care sub-scores. We also compared single dose of COT (COT1) and double dose of COT (COT2) versus FES therapy + single dose of COT (FES + COT). This comparison was the secondary objective of the study, and was done with the intention of assessing the importance of this type of therapy versus simply more intensive therapy. We hypothesized that participants who received two doses of COT (COT2) and those who received FES + COT would have larger gain in function, as compared to participants who received only one dose of COT (COT1), as measured by SCIM and FIM self-care sub-scores. Here, we present the results of that retrospective analysis performed on all data pooled from the previous Phases I[9] and II[12] RCTs published earlier.

Methods

Data used in this article were pooled from Phases I[9] and II[12] RCTs, both conducted at our laboratory between 2003 and 2011. Phase I trial recruited individuals with both complete and incomplete sub-acute (<6 months) C3 – C7 SCI. For the purpose of this retrospective analysis, only data for individuals with incomplete SCI (American Spinal Injury Association (AISA) Impairment Scale (AIS) B, C, and D) were used. Phase II trial only recruited individuals with incomplete (AIS B, C, and D) sub-acute (<6 months) C3 – C7 SCI. Potential participants for both studies were screened with regard to type of injury, level of injury, duration post-injury, and ability to grasp.[9,12] Eligible participants were identified through staff referrals, poster campaign, and local advertisements during their initial inpatient rehabilitation following traumatic SCI. Both studies were approved by Toronto Rehabilitation Institutes Research Ethics Board.

Eligibility criteria

Inclusion criteria

(a) Individuals who had sustained a traumatic incomplete SCI between C3 and C7, AIS B, C, or D, less than 6 months prior to the baseline assessment; (b) individuals 18 years of age or older; and (c) individuals unable to grasp and manipulate various objects, either unilaterally or bilaterally, to allow independent performance of activities of daily living (ADLs) (i.e. eating, dressing, and grooming).[12]

Exclusion criteria

(a) Individuals who had contraindications for FES, such as a cardiac pacemaker, skin lesions, or a rash at a

potential electrode site; (b) individuals who suffered from cardiovascular conditions such as uncontrolled hypertension or autonomic dysreflexia requiring medication; or (c) individuals with denervated muscles (i.e. individuals who, beside SCI, also sustained partial or complete damage of the peripheral nerves that were innervating muscles of interest).[12]

The study participants had normal or near normal passive range of motion in the joints of both upper limbs. The participants' demographics, including baseline FIM and SCIM self-care sub-scores and upper extremity strength scores on key AIS muscle groups, can be found in Table 2.

Study protocol and randomization

Subjects were randomized using two sets of sealed envelopes. Each unmarked envelope contained a single sheet of paper with a printed number. A second set of envelopes was marked with numbers and contained a single sheet specifying the group allocation. The randomization schedule was done using the *randperm* function in Matlab (The Mathworks Inc., Natick, MA, USA) seeded with an arbitrary clock value. After the subject selected a random number from the set of unmarked envelopes, the corresponding marked envelope was opened, revealing the group allocation. The allocation sequence was generated by the principal investigator as he was not involved in any subject assessments or treatment sessions. Subject screening and consent were carried out by the research coordinator who was not involved in providing the treatment, performing the outcome assessments, or performing the data analysis. The randomization allocation ratio was 1:1.[12]

Outcome measures

Therapists who were blinded to participant group allocation performed all outcome assessments for both studies. The primary outcome measure for both studies was the FIM. The secondary outcome measures were SCIM and the Toronto Rehabilitation Institute Hand Function Test (TRI-HFT).[12] For the 2006 study,[9] entire FIM and SCIM scores were used, whereas for the 2011 study,[8] the FIM and SCIM self-care sub-scores were analyzed. Since the entire FIM and SCIM assessments were performed for the 2006 study, we were able to extract FIM and SCIM self-care sub-scores for the study participants. For the purpose of this manuscript, FIM and SCIM self-care sub-scores are analyzed and presented. The FIM and SCIM are widely used functional measures in SCI population.[18,19] As the scoring for the TRI-HFT has evolved between Phases I and II studies, in order to better distinguish hand function changes in the SCI population (please note that this test in original form[9] is still used for stroke population, while the new version of the scoring[20] is used for SCI population only[12,16]), the TRI-HFT scores from the two studies could not be compared. Therefore, for the purpose of this study, only the self-care sub-scores of FIM and SCIM assessments were analyzed.

Intervention

In both studies, the participants were randomized to the intervention group (FES therapy group) or the control group (COT group) upon completion of baseline assessments. In the Phase I trial,[9] based on group allocation, the control group received 1 hour of COT and the intervention group received 1 hour of FES therapy. In the Phase II trial,[12] the control group received 2 hours of COT and the intervention group received 1 hour of COT + 1 hour of FES therapy. For the sake of ease in reading the document, we designated: (a) all participants that received 1 hour of COT to the *COT1 group*; (b) all participants that received 2 hours of COT to the *COT2 group*; and (c) all participants that received 1 hour of COT + 1 hour of FES therapy to the *FES + COT group*. The participants of the COT1 group received therapy for 45 minutes a day, 5 days a week for 12 weeks (45 minutes $\times 5 \times 12 = 45$ hours of total therapy), participants of the COT2 group received therapy for 60 minutes $\times 2$ times per day, 5 days per week for 8 weeks (120 minutes $\times 5 \times 8 = 80$ hours of therapy in total), and the FES + COT group received therapy for 60 minutes $\times 2$ times per day, 5 days a week for 8 weeks (120 minutes $\times 5 \times 8 = 80$ hours of therapy in total). The 60-minute FES sessions for the FES + COT group included 15 minutes of donning and doffing time.

The COT1 group participants received the 45 minutes of therapy as a part of routine rehabilitation practices at our hospital. The COT2 group received 1 hour of therapy as a part of routine rehabilitation practices and the additional hour was delivered as a part of their participation in the research project. The FES + COT group also received 1 hour of conventional therapy as a part of routine rehabilitation practices, and the additional hour of the FES therapy. All study participants received care at the inpatient hospital as per hospital protocols, which involved receiving other rehabilitation therapies including physiotherapy and recreation therapy.

Although no written record of the therapy carried out at individual sessions was maintained, the therapy program was designed by an experienced therapist

based on a patient's individual needs. The therapists involved in both studies worked exclusively at an SCI rehabilitation facility. All of the therapists involved in delivering therapies in our study, irrespective of group allocation, were selected from this pool of therapists and were highly experienced (10+ years of experience) in treating SCI population. All exercises/activities were selected from the toolbox described in the COT intervention paragraph below. To measure treatment compliance, we kept an attendance log for all participants and the therapists were required to fill out the log at each session. Occasionally, patients did miss sessions due to medical issues unrelated to the study participation, and the missed sessions were tagged at the end of the therapy program so that all study participants received the pre-determined number of sessions as per their group allocation.

COT consisted of routinely used strengthening and stretching exercises and practice of ADLs. The COT included: muscle facilitation exercises emphasizing the neurodevelopmental treatment approach; task-specific, repetitive functional training; strengthening and motor control training using resistance to available arm motion to increase strength; stretching exercises; electrical stimulation applied primarily for muscle strengthening (this is not FES or FES therapy); training in ADLs including self-care involving compensatory upper extremity movements as appropriate; and caregiver training.[9,12] Registered occupational therapists designed the rehabilitation program for individual participants based on their individual needs by selecting techniques from the list stated above.

FES therapy consisted of performing ADLs while being assisted with electrical stimulation. The stimulation parameters used were: (a) balanced, biphasic, current-regulated electrical pulses; (b) pulse amplitude from 8 to 50 mA (typical values 15–30 mA); (c) pulse duration 250 μs; and (d) pulse frequency 40 Hz. The FES therapy began by designing stimulation protocols to generate power (circular grip and lateral pinch) and precision (opposition with two and three fingers) grasps on demand. The stimulation sequences (protocols) for power and precision grasps were developed for each patient individually using the Compex Motion electric stimulator (Compex SA, Ecublens, Switzerland).[21] Compex Motion is a fully programmable transcutaneous (surface) stimulator that uses self-adhesive surface electrodes. The power grasp was used for grasping bigger and heavier objects such as water bottles and coffee mugs. Lateral pinch was used for grasping smaller and thinner objects such as keys and paper. Muscles that were stimulated during therapy were the following: *wrist flexors* – flexor carpi radialis and flexor carpi ulnaris; *wrist extensors* – extensor carpi radialis longus and brevis, and extensor carpi ulnaris; *finger flexors* – flexor digitorum superficialis and flexor digitorum profundus; *finger extensors* – extensor digitorum; *thumb abductors* – median nerve or abductor pollicis brevis and abductor pollicis longus; *thumb flexors* – flexor pollicis brevis and flexor pollicis longus; and *thumb oppositors* – opponens pollicis. Of note, not all the aforementioned muscles were stimulated in every subject. During therapy, the command for activating the stimulation sequence was issued with a pushbutton. In all cases, FES was delivered while the individual was performing functional tasks.

In Phases I and II studies, both the control and intervention groups received identical attention from the treating therapist; however, in Phase II, the overall time exposed to hand-related therapy was doubled as compared to Phase I study.

The primary and secondary outcome measures were performed at baseline, upon completion of therapy and at 6 months following baseline assessment. Our total sample size for each of these groups were COT1 ($n = 5$), COT2 ($n = 12$), and FES + COT ($n = 10$). In Popovic *et al.*,[12] the FES + COT group reported had nine individuals ($n = 9$) because the TRI-HFT data for one participant was corrupted; however, the FIM and SCIM self-care sub-score data were intact, and therefore, we included it in the analysis of this study making $n = 10$ for the FES + COT group presented in this article.

Statistical analysis

Baseline characteristics of the three groups were compared, i.e. level of injury, age, and time since injury using Fisher's exact test and one-way analysis of variance (ANOVA) respectively, P-value of significance was set at $P < 0.05$. Baseline FIM and SCIM self-care sub-scores for the three groups were compared using one-way ANOVA. Change scores were calculated for the COT1, COT2, and FES + COT groups on FIM and SCIM self-care measures before and after completion of therapy sessions. The three groups were compared using Kruskal–Wallis test. The sample size in the study was small. The data, strictly speaking, were not normally distributed, and the number of samples in each category was not equal. More importantly, the data variance in each group was not equal either. This made us conduct both ANOVA (F test) and Kruskal–Wallis (χ^2) tests. As both analyses gave almost identical results, we decided to present only

Kruskal–Wallis test results. The analysis was carried out using SPSS program, version 19 (IBM, Armonk, NY, USA). Significance was determined at $P < 0.05$. The detailed results of individual trials are published elsewhere.[9,12] Here, we show the results of comparisons between COT1, COT2, and FES + COT.

Results

All three groups were comparable with respect to time since injury and age ($P = 0.367$ and $P = 0.129$). No baseline differences among the three groups were identified based on the FIM and SCIM self-care sub-scores ($P = 0.676$ and $P = 0.138$, respectively). However, a statistically significant difference between the groups was identified with respect to the level of injury ($P = 0.011$). The participants in the COT1 group had a higher level of injury, indicating greater impairment, compared to participants in the COT2 group. Group and individual participant demographics for all the three study groups are listed in Tables 1 and 2, respectively.

Participants in all the three groups received the full predetermined number of therapy sessions (the COT1 group – 45 minutes/session × 5 sessions/week × 12 weeks = 45 hours; the COT2 group – 60 minutes/session × 2 sessions/day × 5 days/week × 8 weeks = 80 hours; and the FES + COT group – 60 minutes/session × 2 sessions/day × 5 days/week × 8 weeks = 80 hours.) as initially planned and as described in the Methods section. Occasionally, when participants missed sessions owing to medical issues unrelated to the study, the therapy program continued until the total number of sessions across participants of each group was reached, namely, 45 hours of therapy for the COT1 group, 80 hours of therapy for the COT2 group, and 80 hours of therapy for the FES + COT group.

Upon completion of therapy, irrespective of group allocation, all groups showed improvements. Individual participant FIM and SCIM self-care sub-scores at baseline and discharge are listed in Table 3. Participants in the COT1 and COT2 groups did not show differences in improvement on either FIM or SCIM self-care sub-scores, in spite of the fact that participants in the COT1 group had higher levels of injury, and supposedly greater impairment, while the participants in the COT2 group had lower levels of injury with greater function and received a double dose of COT. However, when the COT1 and COT2 groups were compared to the FES + COT group, the FES + COT group showed considerable improvements, approaching statistical significance on the FIM self-care sub-score and statistically significant improvements on SCIM self-care sub-scores, as compared to the COT1 and COT2 groups ($P = 0.062$ and $P = 0.000$, respectively).

Consumer perception interviews done in the 2006 study identified no participant concerns related to "readiness" and "engagement" while enrolled in the research study. And although no such measures were used in the 2011 study, we found that all of the study participants were highly motivated as identified by our treating therapists.

The following are the summaries of the results:

Results pertinent to the FIM self-care sub-score (Table 4)

(1) For the COT1 group, the mean ± standard deviation at baseline was 6.8 ± 1.78 and post-therapy that increased to 19.6 ± 9.04 (improvement of 12.8 points).
(2) For the COT2 group, the mean ± standard deviation at baseline was 7.83 ± 3.18 and post-therapy that increased to 17.83 ± 10.82 (improvement of 10 points).
(3) For the FES + COT group, the mean ± standard deviation score at baseline was 8.1 ± 2.37 and post-therapy that increased to 28.2 ± 11.31 (improvement of 20.1 points).

Results pertinent to the SCIM self-care sub-score (Table 4)

(1) For the COT1 group, the mean ± standard deviation score at baseline was 0.8 ± 0.83 and post-therapy that increased to 3.4 ± 1.34 (improvement of 2.6 points).
(2) For the COT2 group, the mean ± standard deviation score at baseline was 3.25 ± 3.07 and post-therapy that increased to 6.41 ± 4.98 (improvement of 3.16 points).
(3) For the FES + COT group, the mean ± standard deviation score at baseline was 1.9 ± 1.66 and post-therapy that increased to 12.1 ± 5.15 (improvement of 10.2 points).

Since very few participants were able to come back for the 6-month follow-up assessment, we were unable to compare the results of long-term follow-up for the COT1, COT2, and FES + COT groups.

Discussion

Recently, there has been a growing interest in understanding how intensity of treatment delivered by different rehabilitation disciplines influences patient outcomes.[5,6] As seen in the results of this study, the participants in the COT2 group had the worst performance on the FIM self-care sub-score and only marginally better performance on the SCIM self-care sub-score, as compared to the participants of the COT1 group. This finding becomes even more important in the light of the fact that participants in the COT1 group had higher levels of injury compared to participants of the COT2 group. This essentially suggests that the double

Table 1 Participant group demographic

Feature	COT1	COT2	FES + COT
Age (years)			
Mean age	60.8	44.75	43.2
Sex (*n*)			
Males	5	9	8
Females	0	3	2
Level of SCI (*n*)			
C3	3		1
C4	2	7	3
C5		4	1
C6		1	5
C7			
Time since SCI (days)			
Mean time	43.6	58.33	69.9

COT1, conventional occupational therapy one dose; COT2, conventional occupational therapy 2 doses; FES + COT, FES therapy + conventional occupational therapy; SCI, spinal cord injury.

dose of COT may not substantially improve patient outcomes as measured by the FIM and SCIM self-care subscores and that this may apply irrespective of the level of cervical spine injury. In other words, there was no difference in hand function improvements between the single-dose (COT1) and the double-dose (COT2) COT groups, contrary to our hypothesis. Also, these results question long-established belief that more therapy is

Table 2 Individual participant demographics

Subject	Sex	Age	Cause of injury	Neurological level at baseline	AIS scores	AIS Upper extremity score at baseline			Intervention start date in days after SCI
						Right	Left	Total	
COT1 group									
AABN	M	51	Fall	C3	NA	NA	NA	NA	76
AABP	M	64	MVA	C3	NA	NA	NA	NA	15
AACX	M	56	Fall	C3	NA	NA	NA	NA	33
AADC	M	63	Fall	C4	NA	NA	NA	NA	41
AADH	M	70	MVA	C4	NA	NA	NA	NA	53
COT 2 group									
AAGI	M	61	MVA	C4 – C5	C	6	15	21	102
AAGV	F	52	MVA	C5 – C6	C	10	10	20	51
AAGY	F	56	Fall	C4	C	5	3	8	79
AAGZ	F	54	Fall	C5	B	8	8	16	32
AAHC	M	65	MVA	C4	C	2	3	5	66
AAIS	M	21	Diving	C5	C	9	10	19	34
AAIT	M	20	MVA	C4	B	15	15	30	74
AAIV	M	40	MVA	C4	C	2	2	4	64
AAJJ	M	29	MVA	C6	C	10	12	22	22
AAJK	M	51	Work injury	C4	B	8	7	15	44
AAJP	M	28	Diving	C4	B	2	4	6	69
AAJS	M	60	MVA	C5	C	6	5	11	63
FES + COT group									
AAGG	M	53	Fall	C6	C	10	10	20	84
AAGK	M	22	Fall	C6 – C7	B	16	13	29	134
AAGL	M	54	MVA	C3 – C7	D	10	11	21	37
AAGN	M	18	Fall	C6 – C7	C	20	25	45	45
AAGQ	M	29	MVA	C4 – C5	B	5	5	10	53
AAGU	M	28	Fall	C6 – C7	C	15	16	31	33
AAGW	F	66	Fall	C6	C	17	14	31	47
AAJG	F	47	Fall	C5 – C6	B	7	8	15	60
AAJO	M	57	Fall	C4	B	3	2	5	42
AAGO	M	63	Fall	C4	C	NA	NA	NA	134

COT1, conventional occupational therapy one dose; COT2, conventional occupational therapy 2 doses; FES + COT, FES therapy + conventional occupational therapy; SCI, spinal cord injury; NA, not available; MVA, motor vehicle accident; M, male; F, female; Rt, right hand; Lt, left hand; AIS, American Spinal Injury Association (AISA) Impairment Scale.

Table 3 Individual participant FIM and SCIM self-care sub-scores at baseline and discharge

Subject	FIM self-care sub-score at baseline	FIM self-care sub-score at discharge	SCIM self-care sub-score at baseline	SCIM self-care sub-score at discharge
COT1 group				
AABN	6	23	2	4
AABP	6	18	0	2
AACX	10	33	1	4
AADC	6	15	1	5
AADH	6	9	0	2
COT 2 group				
AAGI	6	10	0	2
AAGV	8	26	5	8
AAGY	7	7	0	1
AAGZ	6	25	1	5
AAHC	6	27	2	5
AAIS	7	25	7	10
AAIT	15	35	9	19
AAIV	6	6	5	7
AAJJ	14	29	3	5
AAJK	6	8	6	10
AAJP	7	10	1	2
AAJS	6	6	0	3
FES + COT group				
AAGG	6	10	0	6
AAGK	11	31	2	18
AAGL	6	35	2	15
AAGN	11	40	4	16
AAGQ	11	28	1	8
AAGU	10	40	5	17
AAGW	8	40	3	18
AAJG	6	15	1	7
AAJO	6	28	0	6
AAGO	6	15	1	10

FIM, functional independence measure; SCIM, spinal cord independence measure; COT1, conventional occupational therapy one dose; COT2, conventional occupational therapy 2 doses; FES + COT, FES therapy + conventional occupational therapy.

always beneficial. This study provides initial evidence that doubling the dose of COT did not produce greater improvements in individuals with sub-acute incomplete, traumatic C3–C7 SCI. Although the number of participants in the single- and double-dose COT groups was fairly modest, this finding is still very intriguing. These findings are in tune with recently published studies from the SCI Rehab Project that suggests certain rehabilitation approaches, which are considered best practices, might not be effective, and may even result in inferior outcomes.[5,6]

From the results presented in this article, one can also conclude that the participants in the FES + COT group improved considerably better on both FIM and SCIM self-care sub-scores, as compared to the COT1 and COT2 groups. The improvements on both FIM and SCIM self-care sub-scores for the FES + COT group reached clinically relevant levels. Specifically, the changes of 20.1 points on FIM self-care sub-score and 10.2 points on SCIM self-care sub-score are equivalent to having an individual with SCI who was totally dependent in ADLs, improve during the course of therapy to the point that he/she is able to carry out most of the tasks of ADLs independently.

Our study suggests that what is actually done with patients matters, specifically in the case of individuals with sub-acute incomplete, traumatic C3 – C7 SCI. The FES therapy not only allowed participants to use

Table 4 Participant group mean ± SD on FIM and SCIM self-care sub-scores

	COT1 (mean ± SD)		COT2 (mean ± SD)		FES +COT (mean ± SD)	
	Pre	Post	Pre	Post	Pre	Post
FIM self-care sub-score	6.8 ± 1.8	19.6 ± 9.0	7.8 ± 3.2	17.8 ± 10.8	8.1 ± 2.4	28.2 ± 11.3
SCIM self-care sub-score	0.8 ± 0.8	3.4 ± 1.3	3.3 ± 3.1	6.4 ± 5	1.9 ± 1.7	12.1 ± 5.6

FIM, functional independence measure; SCIM, spinal cord independence measure; COT1, conventional occupational therapy one dose; COT2, conventional occupational therapy 2 doses; FES + COT, FES therapy + conventional occupational therapy.

paralyzed muscles, but also facilitated task-specific use of the upper extremity during execution of routinely performed tasks in day-to-day activities. Strength training alters spinal motor neuron excitability and induces synaptogenesis within the spinal cord; however, skill training induces synaptogenesis, synaptic potentiation, and the reorganization of movement representations within the motor cortex and the spinal cord.[22] Thus, with FES therapy, we are optimizing the interaction between exercise-induced changes and the SCI sequelae.

This study shows that the FES + COT group had superior outcomes as compared to COT groups (i.e. COT1 and COT2). This finding provides preliminary evidence that FES therapy has greater potential for improving upper limb function in individuals with sub-acute incomplete, traumatic C3 – C7 SCI, compared to COT, because it facilitates skillful performance of functional tasks.

Another important thing to consider is the participants who took part in these two trials were individuals with sub-acute SCI. At the time the therapies were delivered to the participants, their abilities were limited, and for some of these individuals, so was their tolerance and endurance to treatment. In light of this, one should strive to deploy a therapy that is the least exhausting and, at the same time, provides "optimal outcomes" for the same or less amount of therapy time. The nature and the manner in which the FES therapy facilitates recovery are fully in tune with these two requirements. As discussed in Popovic *et al.*,[12] with FES therapy we are essentially facilitating the movements the patient is unable to perform voluntarily; in so doing, the FES therapy is enabling the patient to engage all relevant neuromuscular structures responsible for the successful execution of the reaching and grasping tasks. More specifically, when a patient, trained with the FES system, attempts to carry out a grasping task, he/she is fundamentally generating the motor command voluntarily, i.e. proper upper limb motor imagery and a desire to move the arm. In the control theory, this is called the "command input". As the FES therapy facilitates the execution of a task by artificially contracting the muscles of the patient's paretic arm, the FES therapy essentially produces the "system's output", indicating that the command was executed successfully. The nature in which FES therapy delivers the muscle contractions is such that one can very accurately mimic the way in which the central nervous system (CNS) would actually perform that movement naturally. In other words, FES therapy produces the "system's output" that is as close to the actual movement as it can be. We believe that by providing both the "command input" and "system's output" to the CNS repetitively for prolonged periods of time, which the CNS is "used to" to produce and to receive before the injury, the FES therapy facilitates functional reorganization and retraining of intact parts of the CNS, and allows these newly engaged parts of the CNS to take over the function of the damaged part of the CNS.[7,8,11,12] One also has to take into consideration that for a proprioceptive system to provide adequate feedback information to CNS, the muscles need to be contracted at a specific level, and the joints have to go through proper range of movements, else the muscle spindles, Golgi tendon organs, and other proprioceptive sensors will not provide proper feedback to the CNS. Therefore, the sooner one deploys the FES therapy in early rehabilitation, the easier it is to tap into the neuroplasticity processes that are triggered in the CNS following the injury.

Use of these coordinated muscle contraction patterns, in combination with repetitive training, enhances the neuroplasticity and ultimately helps the CNS relearn tasks independently without the help of the FES system or the therapist. This, in turn, results in increased independence among trained participants, which then reduces burden of care for these individuals and makes them less dependent on others in activities of daily life. Szturm *et al.*[23] showed that repetitive task-oriented training is the key to neuronal reorganization and neuronal plasticity. FES therapy allows participants to use their hands in ways that would not be achievable voluntarily in the early stages of recovery, and in doing so facilitates early independence and motivation for rehabilitation. Also, FES therapy engages all relevant neuromuscular subsystems every single time, instead of engaging them sequentially, which is typical with other competing interventions. As a result, the amount of time needed to train the neuromuscular system with FES therapy is considerably shorter. These strategies are fully in tune with recent findings in the field of neuroplasticity and suggest that the proposed FES therapy is potentially a very effective method for retraining the neuromuscular system.

Study limitations

One of the study limitations is the small sample size of all the three groups, which demands caution in generalization of the results to a larger cohort. We are currently conducting a Phase III trial, which is a large multicenter trial, and the results of this trial will be able to shed further light into best practices for upper extremity rehabilitation in individuals with sub-acute incomplete SCI. Also, there was a significant difference between the

groups when compared for the level of injury, which is a potential limitation of the study. However, the group which had better function at baseline and who received two doses of COT (COT2) had inferior outcomes at the completion of the study as compared to the group which received only one dose of COT (COT1) and had inferior function at baseline. This result suggests that doubling COT may not be the answer to better patient outcomes.

We used FIM and SCIM self-care sub-scores as outcome measures because the literature at the time identified these measures as the gold standard for SCI population. Like most researchers in SCI, our team is fully aware that these measures lack sensitivity and content validity. In fact, to address this problem, our team at Toronto Rehab has developed upper extremity measures that measure physiological, as well as functional, change with much more precision. These measures, namely the Graded Redefined Assessment of Strength, Sensibility, and Prehension[24] and the TRI-HFT[20], are rigorously tested for psychometric properties and we strongly encourage the use of these in future trials.

Conclusion

In this article, we have shown that in individuals with incomplete, traumatic, sub-acute C3–C7 SCI, one can expect the same level of upper limb improvement, regardless of whether the individuals receive one or two doses of COT. The results of this study also provide preliminary evidence that FES therapy may be more effective than COT and that large-scale studies should be performed to determine if in fact FES therapy should be considered as the best practice for improving voluntary hand function in individuals with incomplete, traumatic, sub-acute C3–C7 SCI.

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Disclaimer statements

Contributors Both NK and MRP have contributed to the conception of the work, interpretation of the data and the drafting of the article. SB has provided expertise with data analysis and interpretation. All three authors have read the manuscript and approved the final version for publication and take full accountability for all aspects of the work.

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Conflicts of interest At the time the studies were conducted, no conflict of interest existed for either of the two authors. However, presently Milos R. Popovic is a share holder in the company MyndTec Inc. that intends to develop and manufacture FES-based devices in the near future and Naaz Desai is a paid consultant who is assisting with clinical aspects of this development.

Ethics approval Ethical approval was obtained from Toronto Rehabilitation Institute – Research Ethics Board and the University of Toronto – Research Ethics Board.

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