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Author/s:

Zoghi, M;Galea, M

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# Brain Motor Control Assessment Post Early Intensive Hand Rehabilitation After Spinal Cord Injury

Maryam Zoghi<sup>1</sup> and Mary Galea<sup>2</sup>

<sup>1</sup>Department of Rehabilitation, Nutrition and Sport, School of Allied Health, La Trobe University – Melbourne Campus, Melbourne, Victoria, Australia; <sup>2</sup>Australia Rehabilitation Research Centre, Department of Medicine (Royal Melbourne Hospital), The University of Melbourne, Parkville, Victoria, Australia

**Background:** The Brain Motor Control Assessment (BMCA) is a surface electromyography (sEMG)–based measure of motor output from the central nervous system during a variety of reflex and voluntary motor tasks. **Objective:** The aim of this study was to assess the pattern of voluntary movements in patients with spinal cord injury (SCI) to investigate whether BMCA could add more resolution to clinical assessments and the recovery path of these patients. **Method:** Ten participants were recruited from the Royal Talbot Rehabilitation Centre as part of a multicenter randomized controlled trial. Four participants received usual care while the other 3 participants received usual care plus an intensive task-specific hand training program in conjunction with functional electrical stimulation for 8 weeks. BMCA assessments were completed for 7 participants at this center 4 times over a period of 1 year. **Results:** Generalized linear model analysis showed a significant main effect of task ( $p < .001$ ) and assessment time ( $p = .003$ ) on the Similarity Index. However, there were no significant interactions among the factors ( $p > .05$ ). Based on ARAT or summed upper limb strength scores, some participants showed significant improvement after 8 weeks of rehabilitation, however this improvement was not reflected in the pattern of muscle activation that was captured by BMCA. **Conclusion:** The quantifiable features of BMCA through surface EMG may increase the resolution of SCI characterization by adding subclinical details to the clinical picture of lesion severity and progression during rehabilitation. **Key words:** brain motor control assessment, spinal cord injury, surface EMG

Neurorehabilitation after spinal cord injury (SCI) is based on the concept that rehabilitative training recruits neuronal systems that remain intact after the injury to take over the impaired function. Understanding the neural mechanisms underlying recovery will contribute to the development of evidence-based rehabilitation therapies.

In usual clinical practice, people with SCI are evaluated using the International Standards for Neurological and Functional Classification of SCI (ISNCSCI)<sup>1</sup> and are classified according to the American Spinal Injury Association Impairment Scale (AIS). This evaluation involves a sensory and motor examination to determine the neurological level of the injury and whether the injury is complete or incomplete according the ISNCSCI definitions. Combining these evaluations with neurophysiological evaluations that could provide more details about patients' functional abilities

(eg, the activation of synergistic muscles with concurrent inhibition of antagonistic muscles necessary to efficiently perform functional volitional movement [pattern of movements]) would be beneficial for tailoring rehabilitation programs for each individual patient.

Discrepancies between neuropathological and clinical findings after SCI led to development of the Brain Motor Control Assessment (BMCA), which can add more resolution to the clinical evaluation of patients with SCI.<sup>2</sup> This protocol is a surface EMG (sEMG)–based measure of motor output from the central nervous system (CNS) during a variety of reflex and voluntary motor tasks of the upper<sup>3</sup> and lower limbs<sup>4</sup> performed under strictly controlled conditions. Even though the BMCA can provide valuable information about patients with SCI and has been used in evaluating lower limb function in several studies, there is limited reporting of similar information about upper limb function.

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Corresponding author: Dr. Maryam Zoghi, Department of Rehabilitation, Nutrition and Sport, School of Allied Health, La Trobe University, Plenty Road & Kingsbury Drive, Melbourne VIC 3086, Australia; e-mail: m.zoghi@latrobe.edu.au

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The study presented here was part of a multicenter randomized controlled trial, SCIPA Hands-On,<sup>5,6</sup> that was undertaken through 7 SCI units in Australia and New Zealand (see Harvey et al<sup>6</sup> [2016] for full description of the trial and the results of the study). However, the BMCA assessment was conducted in only one center due to lack of equipment and expertise in the other centers. In the randomized controlled trial, participants received usual care or usual care plus an intensive task-specific hand training program provided through an instrumented exercise workstation (ReJoyce) in conjunction with functional electrical stimulation (FES) for 8 weeks.

The aim of this study was to assess the pattern of voluntary movements in patients in each group over time and investigate whether BMCA could add more resolution to the recovery path of these patients.

## Method

### Participants

Ten participants with subacute tetraplegia who were undergoing inpatient rehabilitation in 1 of the 7 participating SCI units as part of a multicenter randomized controlled trial were recruited. Three

participants were withdrawn from this site after the baseline clinical assessments. The demographic information of the other 7 participants is presented in **Table 1**. All participants gave their written informed consent before the assessments were carried out. All procedures conformed with the Declaration of Helsinki, and the protocol was approved by the Human Research Ethics Committees.

The inclusion criteria<sup>5</sup> were age 18 years old or older and able to provide informed consent, sustained traumatic SCI (C2 to T1,  $\leq 6$  months previously), inpatient in a rehabilitation center for 12 weeks as part of a standard rehabilitation, and suitable for FES intervention. Exclusion criteria<sup>5</sup> were other type of neurological injury; trauma or surgery to the target hand or upper limb within the preceding 12 months; amputation of any digits on the target hand; not able to sit out of bed for at least 2 hours per day over 3 consecutive days; extensive fixed contractures in the target hand; severe spasticity in the target hand; likely to experience autonomic dysreflexia or hypotension in response to FES; any contraindications to FES such as cardiac pacemaker, epilepsy, forearm fracture, or pregnancy; impaired vision or inability to view a computer screen; other serious medical condition.

**Table 1.** Demographic information and Brain Motor Control Assessment (BMCA) schedules

Participant (Sex)	AIS score	Neurological level	Intervention group/ Target hand	BMCA			
				1 <sup>st</sup> Ax (dpi)	2 <sup>nd</sup> Ax (dpi)	3 <sup>rd</sup> Ax (dpi)	4 <sup>th</sup> Ax (dpi)
1 (F)	D Incom	Sensory: R: C6, L: T3 Motor: R: C7, L: C8	Control/R	130	215	347	542
3 (M)	C Incom	Sensory: R: C4 L: C4 Motor: R: C5, L: C5	Control/R	38	130	228	427
4 (M)	D Incom	Sensory: R: C4, L: C4 Motor: R: C7, L: C6	Exp/R	67	179	246	478
5 (M)	D Incom	Sensory: R: C4, L: C4 Motor: R: C6, L: C6	Control/R	59	143	234	423
6 (M)	A Com	Sensory: R: C4, L: C4 Motor: R: C6, L: C8	Exp/R	89	208	281	460
7 (M)	B Incom	Sensory: R: C7, L: C7 Motor: R: C7, L: C7	Control/L	50	134	232	421
8 (M)	D Incom	Sensory: R: C4, L: C5 Motor: R: C5, L: C5	Exp/L	75	159	299	NA

Note: AIS = American Spinal Injury Association Impairment Scale; Ax = assessment; Com = complete; dpi = days post injury; Exp = experimental; F = female; Incom = incomplete; L = left; M = male; NA = not assessed; R = right.

## Procedure

The attending medical practitioner and occupational therapist screened potential participants and identified the target hand (a reduced ability to grasp as determined by the clinical judgment of the hospital therapist and able to tolerate sufficient FES to enable the target hand to grasp and release). Then the participants were randomized to experimental or control groups (**Table 1**). Control participants received usual care while experimental participants received usual care plus an intensive 8-week intensive task-specific hand training program provided through an instrumented exercise workstation (ReJoyce) in conjunction with FES program (5 times per week) directed at the target hand. This training for each participant in the experimental group was commenced 3 weeks after the randomization.

Participants practiced different functional hand tasks (eg, reaching, grasping, manipulating, pulling, rotating, and releasing) by using different manipulanda on the ReJoyce to play computer games. The functional tasks were assisted by applying FES on forearm and wrist muscles. As the hand function improved, the level of the exercises was increased through more advanced computer games. Each training session lasted 1 hour.

The FES electrodes (5 x 5 cm) were incorporated into a customized garment. During the training session, participants could wirelessly trigger the FES (50 per second, 200  $\mu$ s biphasic) using toothclicks whenever they needed to open or close their hands. The following assessments were performed on participants in both groups before training (baseline), after 8 weeks of training, and 6 months and 12 months after the baseline assessment. A 3-week period was allocated to complete all the posttraining assessments including BMCA and each follow-up assessment.

### Upper limb BMCA

The upper limb BMCA protocol was performed with participants lying supine. The sEMG of 15 muscles (7 muscles from each upper limb and rectus abdominis) was recorded continuously throughout the protocol<sup>3</sup> with self-adhesive pregelled disposable surface electrodes (Noraxon

Dual electrodes, Scottsdale AZ). The muscles were pectoralis major, deltoid (middle fibers), biceps, triceps, wrist flexor muscle group, wrist extensor muscle group, and rectus abdominis. EMG signals were amplified (x1000) by Zero Wire electrodes (Cometa, Milan, Italy) and then filtered (20-500 Hz) and digitized online (1 kHz sampling rate) using a PowerLab recording system (ADInstruments Ltd).

Eight unilateral voluntary tasks were assessed on both sides. These tasks were shoulder abduction/adduction, elbow flexion/extension, wrist flexion/extension with palm up, and wrist extension/flexion with palm down. All voluntary tasks were cued by two 5-second tones with a brief pause (less than 1 second) between them. Participants were asked to start the first task at the tone and not to start the second task until they heard the second tone. Ten tendon tap responses from biceps and triceps were also recorded from both sides (every 5 seconds). A customized tendon hammer was used to be able to record the tendon responses with similar strike (consistent energy and independent of orientation and relative position).<sup>3</sup>

### Modified Action Research Arm Test

Unilateral hand and upper limb function of the target hand was assessed by the modified Action Research Arm Test (ARAT) in the sitting position. The ARAT has excellent reliability and low ceiling effects.<sup>7</sup> It consists of 4 subtests, including grasp, grip, pinch, and gross movement.<sup>8</sup> All tasks were scored on a 4-point scale from 0 to 3, where 0 reflects poor hand function and 3 reflects good hand function (maximum score, 57). A higher number reflects better hand function.

### Summed upper limb strength of the target hand

The strength component of the Graded and Redefined Assessment of Strength, Sensibility and Prehension (GRASSP) was used to assess upper limb strength of the target hand (maximum score = 50). This consists of a 6-point Manual Muscle Test<sup>9</sup> of 10 muscle groups for the following functions: shoulder flexion, elbow flexion/extension, wrist extension, finger flexion/extension, thumb flexion

(flexor pollicis longus), finger abduction (first dorsal interosseous and abductor digiti minimi), and thumb opposition.

### Data reduction

Three participants (participants 2, 9, and 10) withdrew from the trial after the baseline assessment. Therefore their data were not included in the analysis. We previously generated a prototype response vector for each phase of each voluntary task from 19 neurologically intact participants (38 limbs) (see details in Zoghi et al<sup>3</sup> [2013]). These values were used to calculate the Similarity Index (SI), which compares the relative distribution of sEMG activity across the set of muscles chosen for the voluntary tasks.<sup>3</sup> A value of 1.0 for the SI means that the test participant had an identical distribution of sEMG activity across muscles to the neurologically intact group for that task. The SI values were used to evaluate the progression of participants with SCI during their rehabilitation over time.

Generalized linear model (GLM) analysis was used to assess the main effects of Group: experimental vs control; Side: right vs left; Tasks: 8 unilateral tasks on both sides; and Assessment Time (Ax time): 1st Ax (baseline), 2nd Ax (after 8 weeks training), 3rd Ax (6 months post recruitment), and 4th Ax (12 months post recruitment) on SI. A significance level of  $p < .05$  was adopted for all comparisons. This analysis was conducted using IBM SPSS Statistics 22 software (IBM, Armonk, NY).

### Results

The assessment sessions have been reported based on the number of days post SCI (**Table 1**). GLM analysis showed a significant main effect of Task ( $p < .001$ ) and Ax time ( $p = .003$ ) on SI. However, there were no significant interactions among the factors ( $p > .05$ ).

The individual SI changes over time can be seen for all tasks in control and experimental groups in **Figures 1** and **2**, respectively. The SI values for participant 3 were higher for most of the tasks during the 4th Ax (12 months after the 1st Ax) compared to the 3rd Ax. However, participant 7

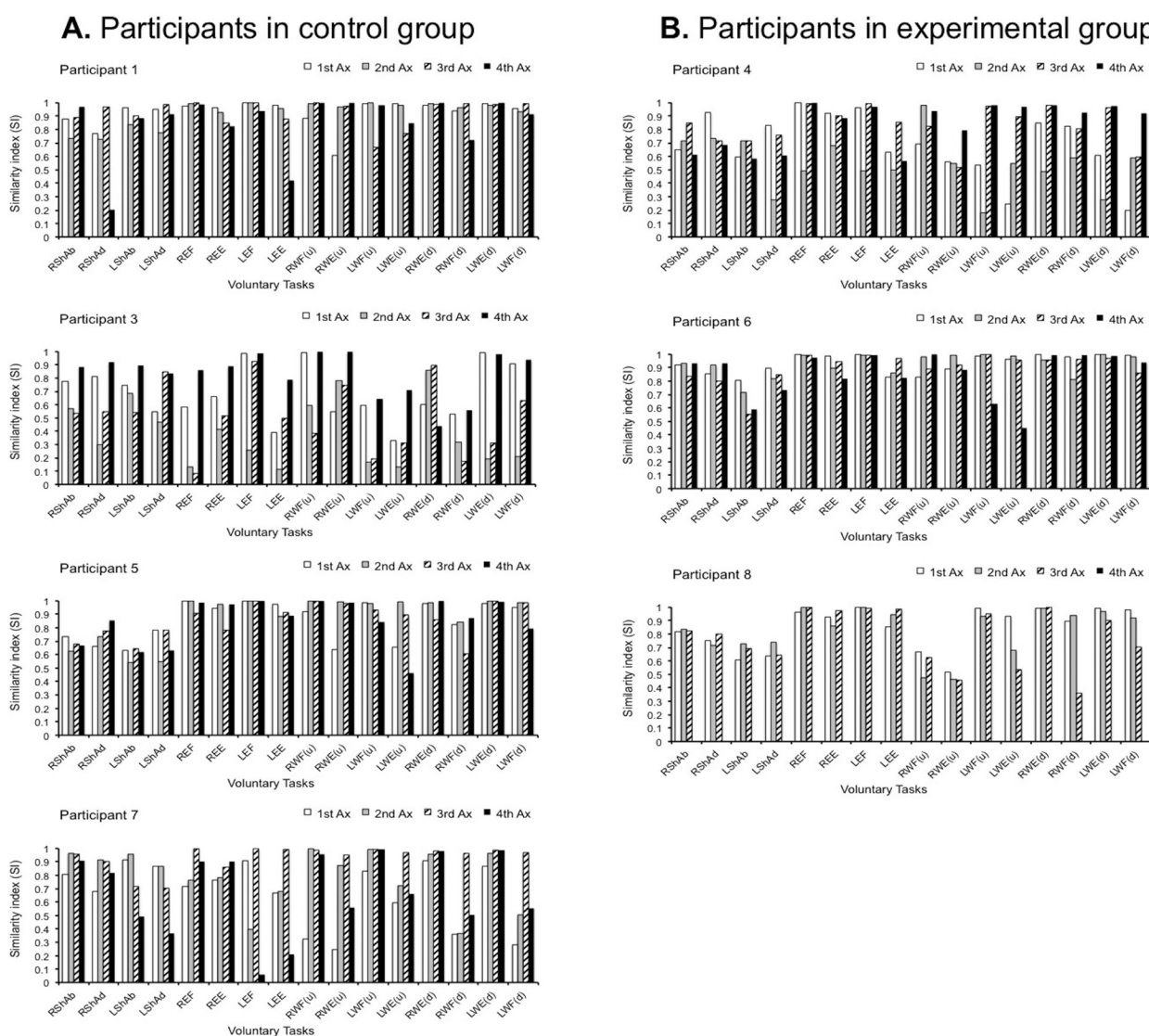
showed the opposite result. His SI values were lower for most of the tasks during the 4th Ax compared to the 3rd Ax. Meanwhile the SI values for participants 1 and 5 remained at similar level for most of the tasks during 3rd and 4th Ax (**Figure 1A**). In the experimental group, the SI values were changed for some of the tasks over time (**Figure 1B**).

One example of raw EMG data during one of the voluntary tasks can be seen in **Figure 2A** for all assessment sessions (**Figure 2**). Since only 7 participants had BMCA assessment done in one center, the findings in regard to one of the tasks (wrist extension with palm down) are presented with more detail for each individual in each group to observe any changes that can not be detected by other clinical assessment after an intervention (**Figure 3**). The target hand for training and FES treatment was “right” side for all participants except participant 7 in the control group (**Table 1**).

**Figure 3** shows the distribution of muscle activation during right and left wrist extension with palm down in a neurologically intact participant and also in participants with SCI in both groups over 12 months. The neurologically intact participant could activate the prime movers during the task with no involuntary activity in the other muscles, however, most of the participants with SCI were not able to do so and they showed activation of muscles irrelevant to the task (wrist extension) on both sides.

Two participants in the experimental group (P6 and P8) achieved maximum ARAT scores at baseline and all the other assessment sessions over the 12-month period (**Figure 4A**). Another 4 participants (P1, P4, P5 and P7) were scored 28, 23, 33, and 23 at baseline and they scored 52, 54, 57, and 48 at their second assessment session, respectively. Five participants achieved or maintained the maximum score of 57 at the end of the 12-month follow-up period (**Figure 4A**). The distribution of the sum of muscle strength in the experimental group was between 38-48/50 at all assessment sessions. However, in the control group, this distribution was between 12-49/50 throughout a year (**Figure 4B**).

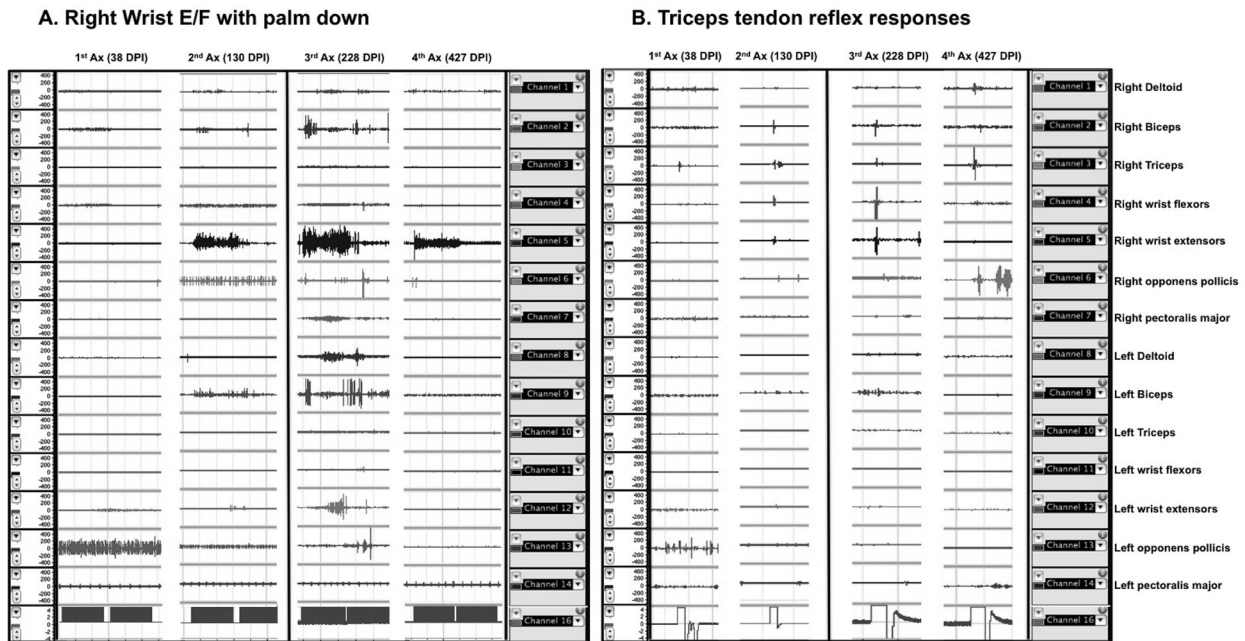
The results of the tendon tap responses are summarized in **Table 2**. Multilevel tendon tap responses can be seen in some patients in both groups over time (**Table 2**). **Figure 2B** shows the triceps



**Figure 1.** Individual Similarity Index (SI) changes over time for all tasks in both groups. Panel A (control group): Participant 3 shows improvement in SI values for most of the tasks during the 4th Ax (12 months after the 1st Ax) compared to the 3rd Ax. However, participant 7 showed the opposite result. His SI values were lower for most of the tasks during the 4th Ax compared to the 3rd Ax. Meanwhile the SI values for participants 1 and 5 remained at similar level for most of the tasks during the 3rd and 4th Ax. Panel B (experimental group): The SI values were changed for some of the tasks over the 12-month period. Note that participant 8 did not attend his last assessment session (12 months). R = right; Ax = assessment; EE = elbow extension; EF = elbow flexion; L = left; ShAb = shoulder abduction; ShAd = shoulder adduction; WE(d) = wrist extension with palm down; WF(d) = wrist flexion with palm down; WE(u) = wrist extension with palm up; WF(u) = wrist flexion with palm up.

tendon tap responses from one participant (P3). Five participants from both groups (3 participants from the control group and 2 participants from the experimental group) showed multilevel tendon tap responses in addition to coactivation of unnecessary muscles during voluntary tasks on

both sides (**Figure 2B**). Four participants showed multilevel tendon tap responses from the baseline assessment all the way through the last assessment. However, one participant from the control group showed these responses in his second assessment up to the last assessment.



**Figure 2.** Individual raw data from participant 3. Panel A: Raw surface EMG (sEMG) activities of 14 muscles from both sides during right wrist extension/flexion with palm down during assessments (Ax) 1 through 4. The last channel shows the 5-second cue “tone markers” during the task. The co-contraction of irrelevant muscles during right wrist extension/flexion (E/F) was increased during the 2nd and 3rd Ax on both sides. Panel B: Triceps tendon tap responses over the 12-month period. It shows multilevel tendon tap responses on both sides. The last channel shows the time of the tapping. The responses to only one tap were shown for each Ax session.

**Discussion**

Seven participants with different levels of SCI in the cervical region were assessed up to 4 times with the BMCA protocol in a randomized controlled trial. Four of these participants received usual care while the other 3 participants received usual care plus an intensive 8-week hand rehabilitation program by using FES (5 times per week). Information regarding the pattern of muscular activation during upper limb tasks in patients with SCI is very limited in the literature. This is the first time that BMCA was used in a randomized controlled trial on upper limbs and therefore we are not able to compare these data with any other studies in this regard. Since BMCA was performed only in one center, the data were reported as observational study.

Two participants in the experimental group (P6 and P8) achieved maximum ARAT scores at baseline and all the other assessment sessions over the 12-month period (**Figure 4A**). However, they both showed some involuntary coactivation of

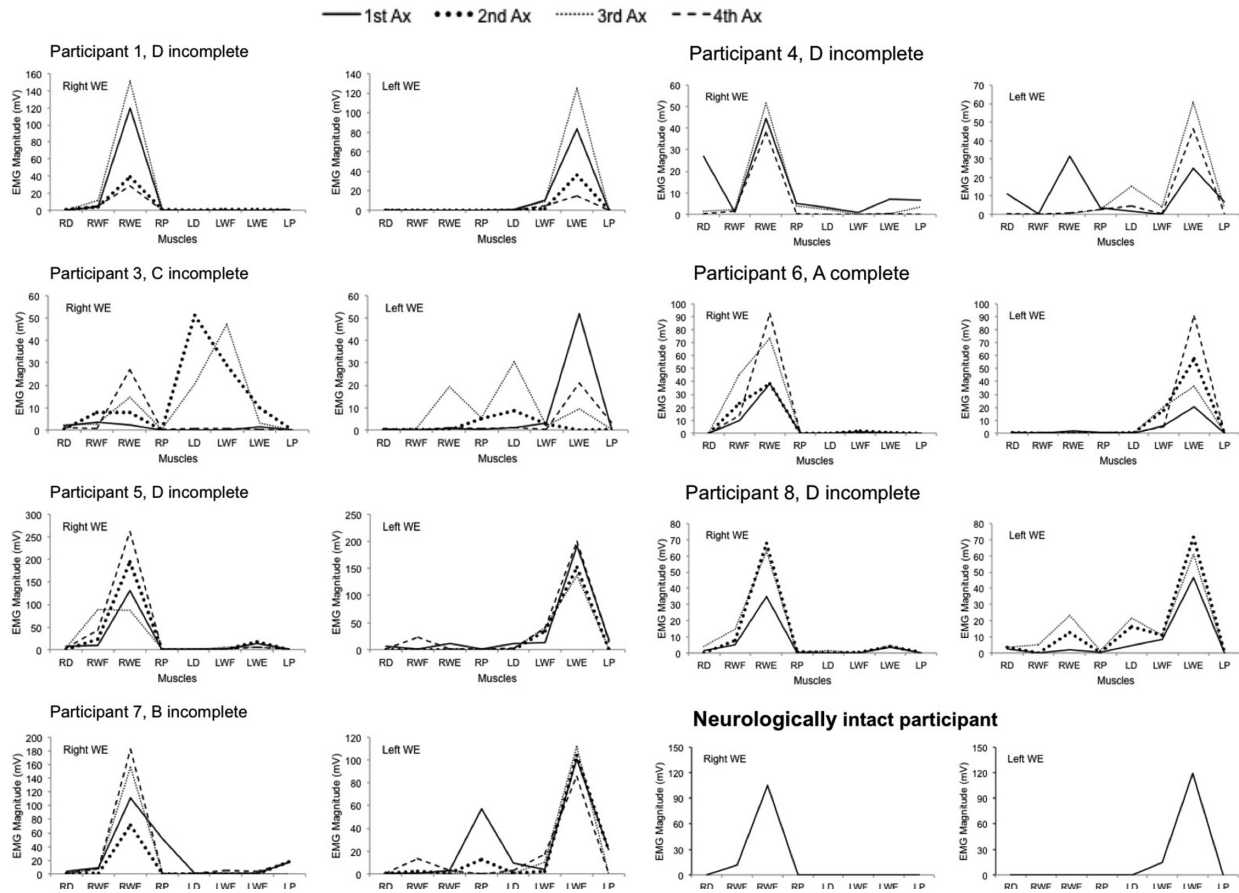
irrelevant muscles during wrist extension (with palm down) on both sides that were captured by BMCA (especially P8). Therefore, being able to achieve a perfect score in ARAT does not provide any insight regarding the quality of the achieved movements and how they could complete the required tasks.

Another 4 participants (P1, P4, P5, and P7) were scored 28, 23, 33, and 23 at baseline, and they scored 52, 54, 57, and 48 at their second assessment session, respectively. Based on their ARAT scores, they showed significant improvement after 8 weeks of rehabilitation, however this improvement is not reflected in the pattern of muscle activation in either of these cases. It can be seen that even P4, after having extra intensive hand training and FES on forearm and wrist muscles, did not show any changes in the pattern of muscle activation during wrist extension (**Figure 3**).

The distribution of the sum of muscle strength in the experimental group was between 38-48/50 at all assessment sessions. However, in the control group,

## A. Participants in control group

## B. Participants in experimental group

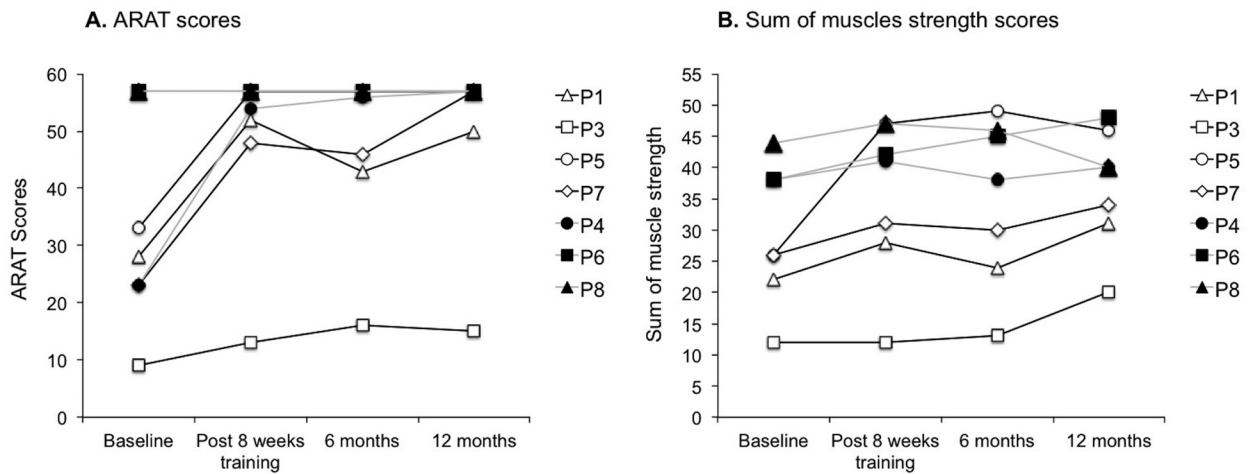


**Figure 3.** The distribution of EMG activities in different muscles on both sides during right and left wrist extension with palm down in a neurologically intact participant and also in participants with SCI in both groups ([A] control and [B] experimental) over 12 months. The neurologically intact participant could activate the prime movers during the task with no involuntary activity in the other muscles, however most of the participants with SCI were not able to do so and they showed activation of muscles irrelevant to the task (wrist extension [WE]) on both sides.

this distribution was between 12-49/50 throughout a year (**Figure 4B**). One of the participants in the control group (P5) showed considerable improvement in strength of his upper limb muscles after 8 weeks rehabilitation (from 26 at baseline to 47/50 at the time of the second assessment). However, similar distribution of muscle activation can be seen at both times of assessment during the wrist extension task on both sides.

In this study, 5 participants from both groups also showed multilevel tendon tap responses in addition to coactivation of unnecessary muscles during voluntary tasks on both sides. This behavior has been reported in previous studies as well.<sup>10,11</sup>

Tendon tap responses and coactivation of unnecessary muscles during a task are the markers that can be used to investigate the existence of supraspinal influences over the motor circuitry of the examined muscles.<sup>12</sup> Supraspinal centers can influence the spinal reflexes by sending direct input to alpha or gamma motoneurons, stimulating the segmental inhibitory interneurons, and acting on propriospinal neurons that extend to other segmental levels. It has also been shown that the loss of brain control over spinal segments often yields a condition where the central state of excitability within the propriospinal interneuron networks is very high, which promotes the



**Figure 4.** Modified Action Research Arm Test (ARAT) and summed upper limb strength scores for each participant over the 12-month period. Panel A: Participants 6 and 8 achieved maximum ARAT scores at baseline, and they could maintain the maximum scores in all the other assessment sessions over 12 months. Another 4 participants (P1, P4, P5, and P7) were scored 28, 23, 33, and 23 at baseline and they scored 52, 54, 57, and 48 at their second assessment session, respectively. Five participants achieved or maintained the maximum score of 57 at the end of the 12-month follow-up period. Panel B: The distribution of the sum of muscle strength in the experimental group was between 38-48/50 at all assessment sessions. However, in the control group, this distribution was between 12-49/50 throughout a year.

**Table 2.** Tendon tap responses from biceps and triceps during 4 assessment sessions in 7 participants with SCI

Participant/ Intervention group	1 <sup>st</sup> Ax		2 <sup>nd</sup> Ax		3 <sup>rd</sup> Ax		4 <sup>th</sup> Ax	
	Biceps	Triceps	Biceps	Triceps	Biceps	Triceps	Biceps	Triceps
1/Control	√	√	√	√	√	√	√	√
3/Control	MLR	MLR	MLR+	MLR+	MLR+	MLR+	MLR	MLR
4/Experimental	MLR	MLR	MLR+	MLR+	MLR+	MLR+	MLR	MLR
5/Control	MLR	MLR	MLR	MLR	MLR	MLR	MLR	MLR
6/Experimental	NR	√	NR	√	NR	√	Few Rs	√
7/Control	NR	NR	MLR	MLR	MLR	MLR	MLR	MLR
8/Experimental	MLR	MLR	MLR+	MLR+	MLR+	MLR+	Not assessed	

*Note:* The tendon tap responses are markers that can be used to investigate the existence of supraspinal influences over the motor circuitry of the examined muscle. Multilevel tendon tap responses can be seen in some patients in both groups over time. MLR = multilevel response; NR = no response; R = response, √ = normal response.

activation of motor units serving antagonistic, ipsilateral, and contralateral musculature.<sup>13</sup>

It has been shown that the corticospinal projections to forearm motoneurons in humans consist of both direct cortico-motoneuronal connections and non-monosynaptic pathways in the cervical cord in parallel.<sup>14</sup> However, it has been proposed that the greater the dexterity in a species,

the higher the involvement of the direct cortico-motoneuronal connections and the lesser the contribution of the C3-C4 propriospinal system in controlling the muscle functions.<sup>15</sup>

After SCI, the propriospinal system plays an important role in functional recovery of upper limb movements by re-establishing the corticospinal commands through new connections

with propriospinal fibers that could bypass the lesion site and form new intraspinal circuits to shape motor function.<sup>16</sup>

In the present study, participants in the experimental group had an extra 8 weeks of hand function training assisted by FES in addition to their usual care program. FES produces dromic and antidromic current through the stimulated nerve. These pulses send inputs directly to the spinal cord and cause contractions that in turn send sensory feedback to the spinal cord from the muscle and joint receptors.<sup>17</sup> Even though we assessed a small number of participants, it can be speculated that increasing the sensory bombardment of spinal cord and propriospinal systems through FES does not increase the multilevel hyperexcitability in this population. Coactivation of unnecessary muscles or multilevel tendon reflex responses was seen in participants in both groups (experimental and control). However, this observation needs to be confirmed in a larger group of patients with SCI.

BMCA is a valuable assessment tool that can add resolution to the clinical evaluation of patients with SCI throughout their rehabilitation process. Reporting findings with BMCA even in a small number of patients will help to increase our knowledge in regard to the effects of different rehabilitation interventions on movement patterns and residual supraspinal effects. This technique has the potential to assist researchers and clinicians

to assess the effects of different treatment techniques on supraspinal influences over spinal cord levels and neural plasticity in patients with neurological disorders and assist them to improve the therapeutic interventions in a way that patients could reach their full potentials. However, the sample size in future studies needs to be increased significantly to be able to provide significant results in this population.

Since the ultimate goal for patients is to be able to perform the functional movement as similar as possible to normal pattern, BMCA could provide very valuable information to guide researchers and clinicians to develop the most appropriate treatment protocol for patients with neurological disorders.

## Conclusion

Neurorehabilitation interventions aim to minimize the impact of the SCI on function and to maximize the restoration of functional capabilities. To achieve this goal, therapists need to be able to assess their patients with more resolution, so they can tailor their treatment plans based on an individual's needs. The quantifiable features of surface EMG may increase the resolution of SCI characterization by adding subclinical details to the clinical picture of lesion severity and progression during rehabilitation.

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