

ORIGINAL ARTICLE

Reliability of surface EMG as an assessment tool for trunk activity and potential to determine neurorecovery in SCI

MD Mitchell, MB Yarossi, DN Pierce, EL Garbarini and GF Forrest

Study Design: Reliability and validity study.**Objective:** This study investigates the responsiveness and reliability of the brain motor control assessment (BMCA) as a standardized neurophysiological assessment tool to: (i) characterize trunk neural activity in neurologically-intact controls; (ii) measure and quantify neurorecovery of trunk after spinal cord injury (SCI).**Setting:** Kessler Foundation Research Center, West Orange, NJ.**Methods:** A standardized BMCA protocol was performed to measure surface electromyography (sEMG) recordings for seven bilateral trunk muscles on 15 able-bodied controls during six maneuvers (inhalation, exhalation, neck flexion, jendrassik, unilateral grip). Additionally, sEMG recordings were analyzed for one chronic SCI individual before electrical stimulation (ES), after ES of the lower extremities while supine, and after active stand training using body-weight support with bilateral ES. sEMG recordings were collected on bilateral erector spinae, internal and external obliques, upper and middle trapezius, biceps and triceps. For each maneuver a voluntary response index was calculated: incorporating the magnitude of sEMG signal and a similarity index (SI), which quantifies the distribution of activity across all muscles.**Results:** Among all maneuvers, the SI presented reproducible assessment of trunk-motor function within (ICC: 0.860–0.997) and among ($P \geq 0.22$) able-bodied individuals. In addition, potential changes were measured in a chronic SCI individual after undergoing two intensive ES protocols.**Conclusion:** The BMCA provides reproducible characterization of trunk activity in able-bodied individuals, lending credence for its use in neurophysiological assessment of motor control. Additionally, the BMCA as an assessment tool to measure neurorecovery in an individual with chronic SCI after intense ES interventions was demonstrated.*Spinal Cord* (2015) **53**, 368–374; doi:10.1038/sc.2014.171; published online 2 December 2014

INTRODUCTION

Spinal cord injury (SCI) is predominantly characterized by the degree of loss of motor and sensory function an individual sustains. The current standard protocol for clinical assessment of SCI is the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) which includes tests of motor- and cutaneous-sensory function, American Spinal Cord Association Impairment Scale (AIS) classifications of A, B, C and D and assignment of sensory and motor neurological levels.^{1,2} For motor function only the upper and lower limbs are assessed with five muscle groups for each-limb included. The trunk is not evaluated, making assessment of the neurologic level of SCI in the thoracic region dependent solely on the sensory evaluation.

The brain motor control assessment (BMCA) is a comprehensive neurophysiological protocol created to measure the activity of multiple muscles through surface electromyographic (sEMG) recordings.^{3–7} sEMG has been used extensively in a variety of upper-motor-neuron disorders to quantify patterns of motor activity.^{3,6,8} The ability of the BMCA to provide reproducible, quantifiable measurements of sEMG has been verified for the muscles of the upper and lower extremities in able-body individuals.^{3–6} The BMCA has also been verified as an assessment tool to describe the neurophysiological gains in the ability of individuals with acute and chronic SCI to activate motor control on

command for lower extremity muscles.^{3,5,6} Recently, upper-limb tasks were added to the published lower-limb tasks⁵ to identify the rate at which the motor units are recruited and the ability to organize and recruit the appropriate muscle groups.⁴ To our knowledge, there is limited research to show the addition of thoracic muscles to the BMCA to characterize motor function of the trunk for either able-bodied controls or SCI individuals.

The purpose of this study is to demonstrate reproducibility of the BMCA for eliciting similar sEMG activation patterns of selected trunk muscles for able-body individuals during specified BMCA maneuvers. We hypothesize that the BMCA will provide reliable and reproducible quantification of trunk-muscle activity in the able-body individuals. In addition, we present data for one SCI individual to demonstrate the potential of the BMCA as an assessment tool to measure the gains in trunk-motor control in individuals with chronic SCI after two electrical stimulation (ES) interventions.

MATERIALS AND METHODS

Subjects and assessment protocol

Neurophysiological assessments were conducted on 15 male able-body individuals with no reported neurophysiological or musculoskeletal disorders and one chronic SCI male individual. Subject demographics (age, height, weight and handedness) for the 15 able-body individuals are listed in Table 1.

Prototype response vectors (as described below) were generated from these subjects (29 ± 4 years, 22–36 years). The individual with SCI was aged 34 (AIS A, C5/C6, and 1 year 7 months post injury at initial assessment). Assessments were conducted on the SCI individual prior to ES interventions, after 61 sessions of bilateral ES of lower limbs while supine (ES alone) and after 51 sessions of intense active-stand training using body-weight support with bilateral ES of the lower limbs (ST+ES). ES was applied *via* bifurcated leads and self-adhesive reusable surface electrodes. Electrodes were applied over the motor points of both legs on the following muscles: rectus femoris, biceps femoris, gastrocnemii, and anterior tibialis. Two electrodes were used for each muscle (5 cm \times 10 cm oval electrodes on the rectus femoris and biceps femoris with an active area of 40.5 cm² and 5 cm² electrodes on the gastrocnemii and anterior tibialis with an active area of 23.4 cm²). The stimulation unit was the Rehabilicare IF 3WAVE System (Rehabilicare, A Division of Compex Technologies, New Brighton, MN, USA) with a removable DC 3.6 V rechargeable Lithium-ion battery that powered the device. In the neuromuscular electrical stimulation mode the Rehabilicare IF 3WAVE unit delivered a biphasic square wave, with a possible 0–10 s ramp-up time (in 1 s increments), an on time of 1–30 s (in 1 s increments), a 0–10 s ramp-down time (in 0.5 s increments), and an off time of 1–60 s (in 1 s increments). For our protocol, symmetrical 300 μ s biphasic pulses at 35 Hz were delivered (over a duty cycle of 11 s on, 60 s off), with an overlap during each contraction between the upper and lower leg. Therefore, gastrocnemii and anterior tibialis muscles were contracted first for 4 s. The biceps femoris and rectus femoris were then contracted for 7 s, while other musculature was still being stimulated (11 s total stimulation). Rest followed with 60 s no stimulation. Timing and phasing of contractions was selected to promote muscle groups to contract and relax alternately in an overlapping fashion. The stimulation protocol was adapted from our previous work⁹ where it was postulated that ES activation during dynamic standing increased muscle activity, to increase blood flow to the stimulated muscles. Therefore, ES and loading may have a significant effect on improving the integrity of the paralyzed musculoskeletal system following SCI. Participants were acclimated to ES prior to the training to determine the maximum tolerable level of neuromuscular stimulation that could be applied during training. Subjects were stimulated to a predetermined ES intensity during pretesting evaluation to produce both visible- and palpable-muscle contractions in all of the muscles during supine and standing. For the ES alone, stimulation

was applied in the supine position. During the ST+ES, the individual stood using a body-weight support treadmill system with an overhead harness and the lower extremities loaded. All training sessions were of 1 hour duration. sEMG during supine BMCA recordings were analyzed pre- and post-ES alone and post ST+ES.

An expanded BMCA protocol which includes a five-minute relaxation period and a series of reflexive, voluntary- and passive-motor tasks conducted with the individual in the supine position was employed to collect sEMG on 14 trunk muscles.³ For each maneuver there were three repetitions with timed auditory cues for movement onset/termination. Event onset and cessation for each repetition were manually marked in real time by an examiner with the use of a foot-switch pressure sensor. The same examiner administered the assessments for all of the able-body individuals and the SCI individual using the same measurement techniques.

Pairs of stainless steel high gain, differential input design sEMG electrodes (Motion Lab Systems, Baton Rouge, LA, USA) with an inter-electrode distance of 18 mm were placed on the following muscles bilaterally: upper trapezius, middle trapezius/erector spinae T5 and erector spinae T12. External obliques were placed just below the ribcage, along a line connecting the most inferior point of the costal margin and the contralateral pubic tubercle. Internal obliques were placed 1 cm medial to anterior-superior iliac spine.¹⁰ Grounds were placed on the clavicles. sEMG data were acquired using a 10-channel MA100 and 16-channel MA300 (Motion Lab Systems). Prior to electrode placement, skin was prepared by shaving all hair, cleansing with 70% isopropyl alcohol and lightly abrading the skin.^{4,9}

Data were collected through 'Vicon' (Denver, CO, USA) at a sampling rate of 2520 Hz. Quantification of sEMG was completed through custom programs written in MATLAB (MathWorks, Natick, MA, USA). A bandpass filter of 20–300 Hz with a 60 Hz line filter was applied during data processing while an empirical mode decomposition filter used in our laboratory and previously reported¹¹ was applied to remove heart-rate signal-artifact embedded in the sEMG signal. The bandpass filtering 20–300 Hz is potentially not ideal, as it may mask out considerable signal content related to trunk-muscle EMG. Further research related to the BMCA in our laboratory will consider extending the bandwidth to above 1 kHz, ideally 10 kHz.

Spasms recorded during sEMG testing of the SCI individual were removed by visual inspection. Data were reported for the six reinforcement maneuvers: including inhalation, exhalation, neck flexion with resistance, Jendrassik and right and left-unilateral grip. For each repetition steady-state sEMG was determined by manual selection to identify periods which sustained amplitudes $>10 \mu$ V.⁴ If the amplitude did not exceed 10μ V, the examiner-labeled timing was used. Table 2 summarizes the muscles assessed during each maneuver, the maneuvers used and the spinal level tested by each muscle.¹² Root mean square (RMS) sEMG amplitudes were calculated for each repetition and averaged over each maneuver as previously reported.⁵

The multi-muscle RMS sEMG during each maneuver were further evaluated by adapting a 'vector-based analyses method', termed the voluntary response index (VRI), and previously developed for the lower-limb BMCA protocol.⁶ The VRI calculation has been shown to have strong-face validity, sensitivity and specificity¹³ and good test-retest reliability for set-motor tasks of the lower limbs.⁷ The computation of the VRI incorporates two values associated with sEMG: the magnitude of the signal and the similarity index (SI). The magnitude of the VRI quantifies the total muscle activity during each maneuver as an average of the RMS over all repetitions for all muscles of interest and equates to the length of the response vector (RV) of the test subject. The SI is calculated for each phase of each maneuver as the inner product, or cosine of the angle, between the test-subject RV and prototype-RV (PRV). The PRV for each maneuver was generated by averaging the individual RVs from the 15 able-body controls for inhalation, exhalation, neck flexion and jendrassik. As sEMG data on the biceps and triceps were available for only 10 able-body controls, the PRV during right- and left-unilateral grip was calculated by averaging only these 10 individuals.

As neurorecovery in the ipsilateral and contralateral muscles was suspected to be distinguishable after SCI, the VRIs were first calculated by separating the bilateral muscles by right- and left-hand side muscles (henceforth referred to as right muscles only and left muscles only). As handedness has been shown to have a significant impact in upper-extremity muscle activity,^{14–19} the VRIs were

Table 1 Demographics of fifteen able-body individuals used to generate the prototype response vectors and voluntary response indices

Subject	Gender	Age (years)	Height (cm)	Weight (kg)	Handedness ^a
1 ^b	M	23	183	82	R
2 ^b	M	33	183	88	R
3 ^b	M	32	173	73	R
4 ^b	M	33	170	73	L
5 ^b	M	28	191	98	L
6	M	30	178	84	L
7	M	29	183	77	R
8	M	26	188	84	R
9	M	23	175	76	R
10	M	22	168	70	R
11	M	32	191	88	R
12	M	30	168	68	L
13	M	36	173	88	R
14	M	29	160	83	L
15	M	29	185	82	R
SCI	M	34	180	67	R

All subjects were male (29 ± 4 years of age, 22–36 years of age). Mean height was 177.9 ± 9.3 cm and mean weight was 80.9 ± 8.1 kg. Ten subjects were right-hand dominant and five were left-hand dominant.

^aHandedness was determined by subject's self report.

^bSubjects excluded from the calculations of the Similarity Index and magnitude for right and left-unilateral grip as surface electromyography was not collected on the biceps and triceps of these individuals.

additionally calculated based upon handedness (dominant side versus non-dominant side).

Once the SIs and magnitudes were calculated for the able-body individuals, they were then calculated in the same manner for the SCI individual. The SI provides a value between 0 and 1.0 (theoretically from -1 to $+1$)⁶ which quantify how closely the multi-muscle distribution of activation in a test-subject pattern matches the PRV developed from the total group.

Clinical measures for the SCI individual included the Activity-based Balance Level Evaluation (ABLE scale) and the Sitting Posture/Balance assessments. The ABLE scale is derived from the Modified Functional Reach Test and the Berg Balance Scale and includes items which test balance in the domains of sitting, standing and walking.²⁰ For the SCI individual considered in this pilot study, only the seated items of the ABLE scale were considered. To further assess the balance of the individual while seated the Sitting Posture/Balance assessment was completed as well.

We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research. Informed consent and institutional review board approval was obtained through the Kessler Foundation Center.

Table 2 The trunk muscles assessed during the Brain Motor Control Assessment are listed with their spinal roots and the maneuvers in which they were considered to be involved as either a primary or accessory muscle

Muscles	Spinal root	Maneuvers
Biceps brachii	C5	Unilateral grip
Trapezius	C6	Jendrassik, unilateral grip
Triceps	C7	Unilateral grip
Erector spinae T5	T5	Inhalation, neck flexion, jendrassik
External obliques	T8	Inhalation, exhalation
Internal obliques	T10	Inhalation, exhalation, neck flexion, jendrassik, unilateral grip
Erector spinae T12	T12	Neck flexion

Table 3 Complete list of muscle groups chosen for each maneuver

Maneuver	Muscle combination	Similarity index	Magnitude	Similarity index	Magnitude	Similarity	Magnitude
		bilateral muscles	bilateral muscles	right only	right only	index left only	left only
		(μV)		(μV)		(μV)	
Inhalation	EO/T5	0.90 ± 0.10	10.1 ± 9.1	0.97 ± 0.07	8.8 ± 9.3	0.74 ± 0.26	3.7 ± 2.7
	IO/EO/T5	0.75 ± 0.17	23.0 ± 18.8	0.81 ± 0.14	18.5 ± 15.0	0.74 ± 0.25	12.1 ± 13.2
	IO/T5	0.76 ± 0.17	22.8 ± 18.8	0.82 ± 0.14	18.3 ± 15.0	0.80 ± 0.26	11.7 ± 13.4
Exhalation	IO/EO	0.84 ± 0.22	44.6 ± 40.8	0.85 ± 0.26	25.3 ± 16.7	0.86 ± 0.24	34.5 ± 39.4
	IO/T5	0.77 ± 0.12	16.0 ± 11.0	0.89 ± 0.10	10.9 ± 7.6	0.78 ± 0.13	10.3 ± 7.6
Neck flexion	T5/T12	0.77 ± 0.15	15.0 ± 15.8	0.89 ± 0.10	11.2 ± 16.0	0.75 ± 0.19	7.2 ± 6.6
	IO/T5	0.87 ± 0.10	64.1 ± 52.3	0.96 ± 0.10	49.4 ± 36.3	0.79 ± 0.26	32.6 ± 45.5
Jendrassik	IO/Trap	0.87 ± 0.14	51.0 ± 36.8	0.88 ± 0.25	33.1 ± 29.2	0.93 ± 0.10	36.2 ± 26.6
	T5/IO/Trap	0.84 ± 0.11	86.2 ± 51.5	0.90 ± 0.14	64.1 ± 38.5	0.78 ± 0.15	53.4 ± 40.94
Unilateral grip (left) ^a	Bi/Tri	—	—	—	—	0.96 ± 0.04	88.9 ± 76.7
	IO/Bi/Tri	—	—	—	—	0.96 ± 0.04	89.0 ± 76.7
	Trap/Bi/Tri	—	—	—	—	0.96 ± 0.04	89.4 ± 77.0
	Trap/IO/Bi/Tri	—	—	—	—	0.96 ± 0.04	89.5 ± 77.0
Unilateral grip (right) ^a	Bi/Tri	—	—	0.95 ± 0.05	116.1 ± 81.6	—	—
	IO/Bi/Tri	—	—	0.95 ± 0.05	116.2 ± 81.6	—	—
	Trap/Bi/Tri	—	—	0.95 ± 0.05	116.2 ± 81.7	—	—
	Trap/IO/Bi/Tri	—	—	0.95 ± 0.05	116.3 ± 81.6	—	—

Key for muscle abbreviations: Trapezius (Trap) Internal Obliques (IO), External Obliques (EO), Middle trapezius/Erector Spinae T5 (T5), Erector Spinae T12 (T12), Biceps Brachii (Bi), Triceps Brachii (Tri).

The most appropriate muscle combinations are italicized and bolded, identified by the greatest mean similarity index and smallest s.d., for each maneuver. The SI values and magnitudes (mean ± s.d.) are listed for the bilateral muscle combination, right muscles only and left muscles only. As specific instructions were not given for unattended hand during unilateral grip, the right muscles were not considered during left-unilateral grip and the left muscles were not considered during right-unilateral grip.

^aSI and magnitude for left- and right-unilateral grip were calculated for the involved side only as specific instructions for the noninvolved hand were not provided during the testing sessions.

Statistical analysis

The overall muscle activity during each repetition was determined by calculating the SI values for the distribution of the seven bilateral muscles for inhalation, exhalation, neck flexion and Jendrassik. As the BMCA has been validated under strictly controlled conditions⁶ and no strict instructions were provided for the uninvolved hand during unilateral grip, the SI value for the uninvolved hand were found to be variable and therefore right- and left-unilateral grip SIs were calculated solely from the right and left muscles, respectively (i.e., the SI for the left side muscles was not calculated for right-unilateral grip and vice versa). The intraclass correlation coefficient (ICC) of the SI values for each repetition was calculated (PASW Statistics 18 (SPSS, Hong Kong, China): two-way mixed model, absolute agreement, $\alpha=0.05$) for each maneuver to determine the repeatability of the patterns of recruitment within subjects.

The SI scores were analyzed using two-way fixed-effect analysis of variance model with main factors of maneuvers and subjects ($\alpha=0.05$). The least-squared mean SI scores were tested for difference among maneuvers and among subjects using F-test. ICCs for single maneuvers were also calculated based on the above analysis of variance model to quantify the reliability and reproducibility of the six maneuvers (PASW Statistics 18 (SPSS)).

The SI scores combining both left and right sides of the body were analyzed first. The same analyses were then repeated for left-side only and right-side only. Lastly, the analyses were conducted for handedness, dominant and non-dominant, separately.

RESULTS

For each able-body subject the ICC of the SI value for each repetition in each maneuver was calculated. The ICCs within subject ranged from 0.860 for Jendrassik to 0.997 for unilateral right grip.

Possible muscle recruitment patterns for each maneuver based upon calculation of right and left side muscles are summarized in Table 3. For the combination of left and right side data, the 'best' combination of muscles (or patterns of recruitment) based on highest mean value and minimum s.d. are shown in bolded italics. The lowest mean value (with the most variability) in the SI was observed during the neck

flexion maneuver (0.77 ± 0.12). The combined left/right group shows a small ICC (0.0003) across the six maneuvers. Between-subject variability was not significant ($P=0.31$).

When the analyses were completed for the left-side only data, similar muscles were selected as 'best' (Table 3). The ICC between maneuvers was 0.0007 and the between-subject variability was not significant ($P=0.37$). For the right side analyses, the muscles selected as 'best' were consistent to the combined group and left-side only data. The ICC between maneuvers was 0.04 with no significant difference between subjects ($P=0.22$).

When the analyses were completed with consideration of handedness, the 'best' muscle groups were consistent in all maneuvers except the Jendrassik (Table 4). However, the 'best' muscle group for handedness during the Jendrassik was consistent with that for the left muscles only and the two muscle groups within the bilateral muscles have the same mean SI value (0.87), with the difference in determining which is 'best' being a comparison of the s.d. of 0.10 and 0.14. In addition, the means and s.d. of the SI and magnitude were not significantly different ($P>0.52$). There were no significant difference between subjects ($P=0.11$ and 0.71 for dominant and non-dominant, respectively).

Right and left AIS scores for motor, light touch and pin prick pre and post-ES alone and post ST+ES for the individual with SCI are listed in Table 5. In addition to the AIS, the ABLE and Sitting Posture/Balance assessments²⁰ were completed. Prior to either intervention, the SCI individual could not: (i) sit unsupported during the ABLE or (ii) perform reaching tasks or bring both hands to his nose or behind his head during the Sitting Posture/Balance tasks. After ES alone, the SCI individual could sit unsupported, complete the reaching tasks and bring both hands to his nose or behind his head. The individual maintained these improvements post ST+ES, with less perceived exertion on the Sitting Posture/Balance tasks compared to post-ES alone.

VRI values for left/right combined, left only and right only in the SCI individual are shown in Figures 1, 2 and 3, respectively. Pre-intervention SI values ranged from 0.13 (Jendrassik right/left combined) to 1.00 (inhalation right only). Magnitude values were 0.0–7.6 μV . After ES alone, SI values ranged from 0.57 (right/left combined inhalation) to 1.00 (right only Jendrassik). Magnitudes ES alone ranged between 0.8–42.8 μV . Post ST+ES SI values ranged from 0.18

(left only exhalation) to 1.00 (right only inhalation and Jendrassik). Magnitudes ranged from 0.4–31.3 μV .

DISCUSSION

For decades, the ISNCSCI AIS classification has been and remains the clinical 'gold' standard to classify neurorecovery after SCI, but what is lacking is an outcome measure with sufficient sensitivity to determine motor changes as indicators of recovery.^{21,22} There is now expanding research to use neurophysiological measures such as the BMCA^{3,4,7} to more clearly quantify motor recovery or control of both upper and lower extremities. This pilot study has expanded the current literature to show that well controlled neurophysiological testing and analyses can produce repeatable muscle responses to characterize trunk-motor activity. While this pilot study did not check if skin impedance was under 5 k Ω , as the previous BMCA studies have and note that this should be conducted in future studies, the ICC values for our data in 15 neurologically-intact individuals provide evidence of intra-subject validity and sensitivity for use of the SI value to measure the pattern of recruitment during standardized maneuvers for trunk characterization (0.860–0.997) and suggests that the skin impedance was not detrimental to the present results. While the s.d. within the SI values of the able-bodied individuals for the maneuvers themselves (Table 3) do range from 0.04 to 0.26, these s.d. are half the values of the accepted s.d. published for SIs in individuals with SCI (0.48).¹³ Moreover, the consistency in the computed SIs (approaching 1) among our neurologically-intact subjects for different maneuvers demonstrate

Table 5 Right and left AIS scores for the one SCI individual

	RIGHT			LEFT		
	Motor	Light touch	Pin prick	Motor	Light touch	Pin prick
Pre-ES	15	15	13	12	13	11
Post-ES alone	16	16	14	12	14	11
Post-ST+ES	15	17	13	13	14	14

Pre-ES is pre-electrical stimulation interventions. Post-ES alone is after 60 sessions of bilateral ES of the lower limbs while supine and post-ST+ES is after 51 sessions of intense-active-stand training using body-weight support with bilateral ES of the lower limbs. The increase in right motor score between pre-ES and post-ES alone is associated with an increase from 0–1+ at the T1 level. This was not sustained through post-ST+ES. The increase in left motor from post-ES alone to post-ST+ES is associated with an increase from 2–3 at C7.

Table 4 Complete list of muscle groups chosen for each maneuver

Maneuver	Muscle combination	Similarity index dominant side	Magnitude dominant side	Similarity index non-dominant side	Magnitude non-dominant side
			(μV)		(μV)
Inhalation	EO/T5	0.81 ± 0.32	11.2 ± 11.4	0.79 ± 0.24	8.8 ± 9.7
	IO/EO/T5	0.70 ± 0.24	20.6 ± 19.1	0.66 ± 0.29	24.0 ± 20.5
	IO/T5	0.84 ± 0.20	8.0 ± 7.0	0.63 ± 0.31	8.5 ± 8.3
Exhalation	IO/EO	0.89 ± 0.08	30.4 ± 26.6	0.92 ± 0.11	40.0 ± 46.8
Neck flexion	IO/T5	0.79 ± 0.13	12.8 ± 10.3	0.81 ± 0.14	12.3 ± 14.1
	T5/T12	0.78 ± 0.13	12.0 ± 19.2	0.81 ± 0.23	7.8 ± 6.5
Jendrassik	IO/T5	0.87 ± 0.24	45.4 ± 39.2	0.85 ± 0.20	43.1 ± 52.1
	IO/Trap	0.89 ± 0.18	42.2 ± 41.4	0.87 ± 0.17	43.8 ± 43.1
	T5/IO/Trap	0.84 ± 0.11	66.5 ± 47.2	0.80 ± 0.12	52.5 ± 39.2
Unilateral grip	Bi/Tri	0.93 ± 0.07	48.9 ± 40.0	0.95 ± 0.05	40.5 ± 45.7

Key for muscle abbreviations: Trapezius (Trap) Internal Obliques (IO), External Obliques (EO), Middle trapezius/Erector Spinae T5 (T5), Erector Spinae T12 (T12), Biceps Brachii (Bi), Triceps Brachii (Tri).

The most appropriate muscle combinations are italicized and bolded, identified by the greatest mean similarity index and smallest s.d., for each maneuver. The SI values and magnitudes (mean ± s.d.) are listed for the dominant and non-dominant side.

Note: dominance was provided by self report.

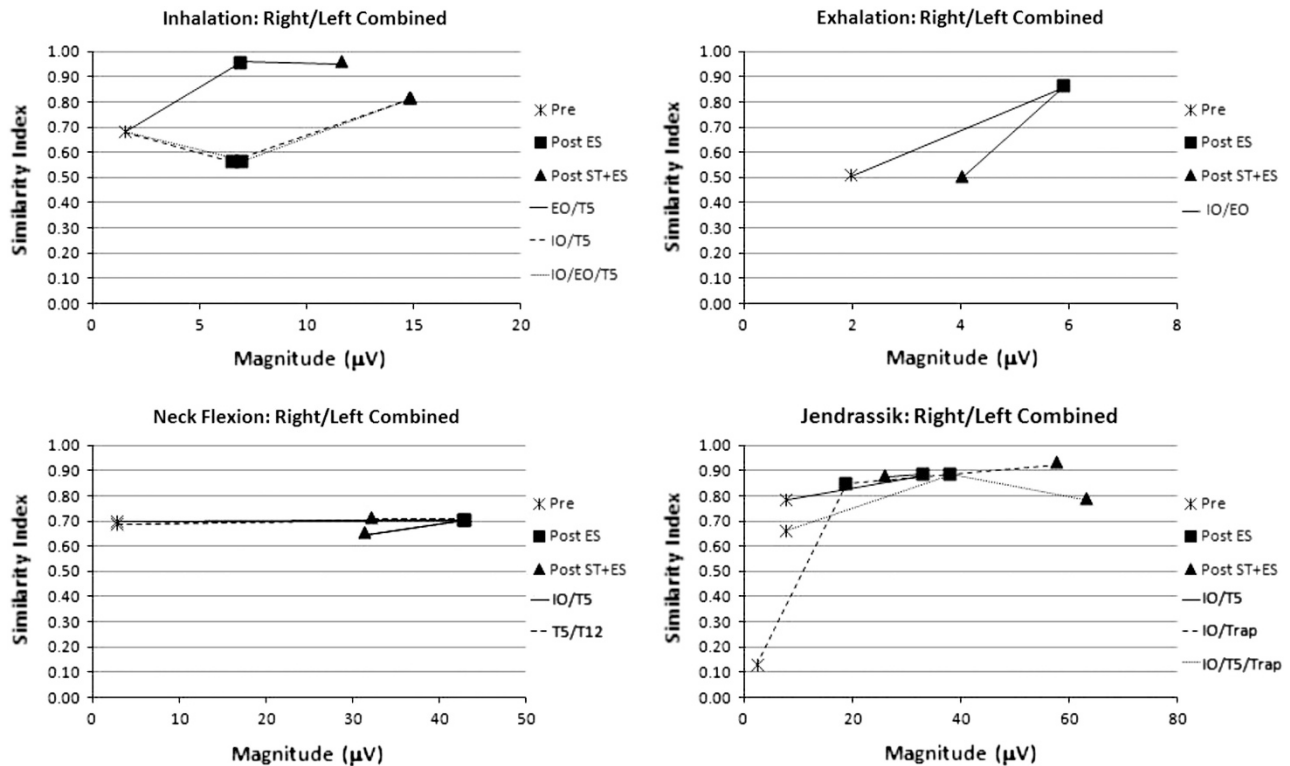


Figure 1 Similarity index (SI) and magnitude (μV) trends for the right and left muscles combined in one individual with spinal cord injury. The SI and magnitude were calculated pre intervention (pre), post 61 sessions of bilateral electrical stimulation of the lower extremities in the supine position (post ES) and post 51 sessions of intense active stand training using body weight support with bilateral ES of the lowerlimbs (post ST+ES). Each of the muscle combinations investigated in the able body population is shown (with the “best” muscle combination, as chosen in the able body individuals, represented by the solid line). The increasing SI and magnitude post interventions for this one individual demonstrate potential trends for neurorecovery concomitant to the clinical gains demonstrated during the ABLE and Sitting Posture/Balance assessments. EO, external obliques; IO, internal obliques; T12, erector spinae T12; T5, erector spinae T5; Trap, trapezius.

the repeatability and reproducibility of patterns of muscle recruitment among subjects for different maneuvers to suggest that an objective (quantitative), highly sensitive and accurate trunk-characterization protocol can be designed based on sEMG signals.⁶ As our novel data collection during supine for neurologically-intact individuals provided consistent SI values, a limitation of our protocol is the lack of inclusion of intercostal muscles particularly relevant for inhalation (and exhalation). Further studies should include the intercostal muscles.

While it was suspected that ipsilateral/contralateral control is an important factor after SCI, it is well documented in the literature that handedness is a critical consideration in upper-extremity movement as well.¹⁵ Therefore, in addition to calculating the VRIs for right- and left-side only muscles, the VRIs for dominant/non-dominant hand were calculated. While the ‘best’ muscles determined during the Jendrassik based upon handedness were inconsistent with those determined during ipsilateral/contralateral control, the SI values for the two muscle groups under consideration had the same mean for the bilateral muscles and the ‘best’ group considered during the left muscles only is consistent with the ‘best’ group for handedness. Hence, as the trends in handedness closely follow the trends found in right and left side muscles and ipsilateral/contralateral neurorecovery is of importance after SCI,¹⁴ the remaining discussion pertaining to the SCI individual focuses upon the VRIs as calculated for right- and left-side muscles only.

The determination of the prime mover or agonist/antagonist muscle groups is of primary importance for the calculation of the SI and VRI⁶ during each maneuver. However, for the characterization of trunk activity for each of these maneuvers during supine, the appropriate combinations of muscles have not been previously reported. Our pilot study determined the ‘best’ muscle combinations for each maneuver in supine based on SI and magnitude RMS sEMG. Further these data provided a template (Table 3) to compare multi-muscle distribution of activation and inhibition for our SCI test-subject pattern to match the PRV developed from able-bodied subjects for the same volitional task.

The multi-muscle distribution template (Figures 1–3) for one individual after SCI showed an increase in the VRI, particularly for right/left combination and right alone during neck flexion and Jendrassik after ES alone. These increases reflect increases in muscle activity (magnitude), with patterns of recruitment (SI) approaching ‘normal’ recruitment in trunk as defined by the PRV.⁶ These trends in the VRI follow the gains in the ABLE and Sitting Posture/Balance assessments. The SCI individual gained the ability to support his trunk in sitting and reaching after the ES alone, concomitant to the gains in sEMG magnitude within the VRI. Clinically, after the ST+ES, the SCI individual was able to perform the Sitting Posture/Balance tasks with less exertion and improved efficiency of task specificity,⁶ as demonstrated by the decreased magnitudes within the VRI for neck flexion. The increase or maintenance of the SI to approach 1 pre-intervention through post-ST+ES verifies that the individual is potentially recruiting ‘normal’ patterns of muscles and not compensating with alternate

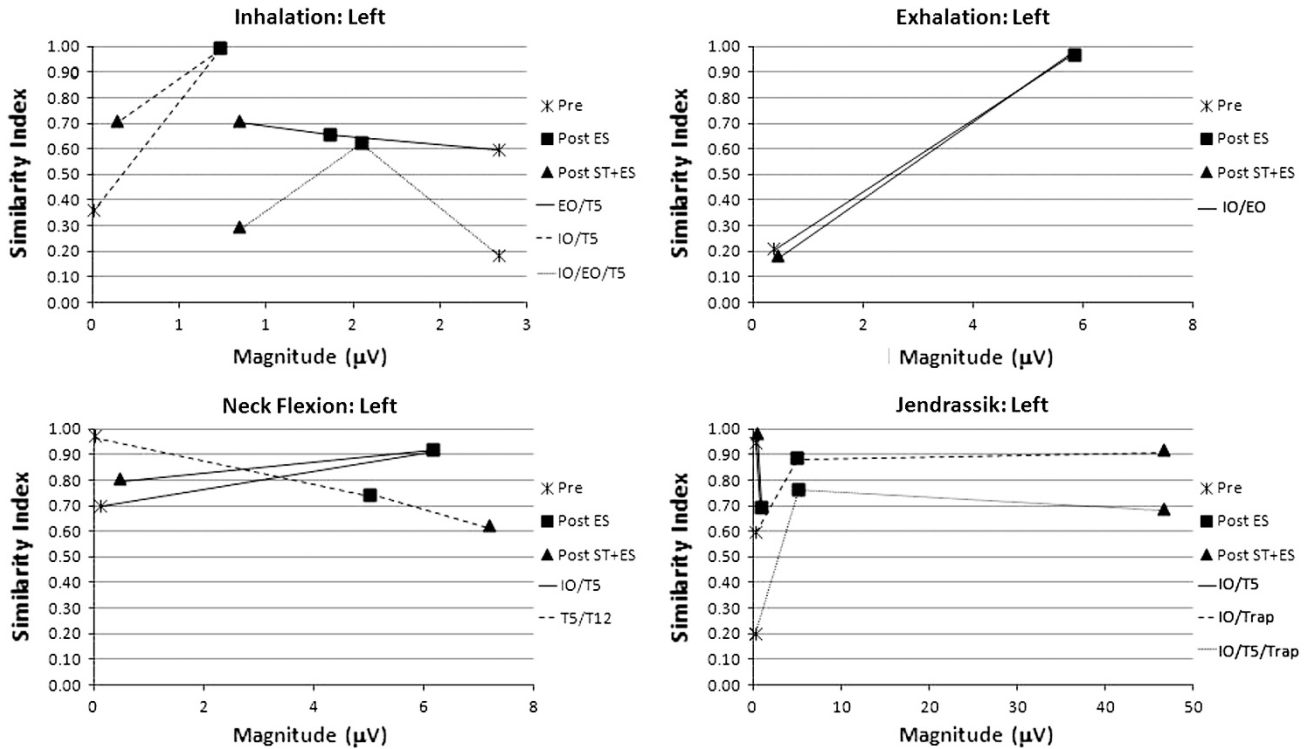


Figure 2 Similarity index (SI) and magnitude (μV) trends for the left muscles only in one individual with spinal cord injury. Each of the muscle combinations investigated in the able body population is shown (with the “best” muscle combination, as chosen in the able body individuals, represented by the solid line). Potential trends in neurorecovery may be present, but as this is only one individual with high level involvement on the left side, additional studies must be conducted to validate the ability of the SI and magnitude to quantify neurorecovery in the trunk. EO, external obliques; IO, internal obliques; T12, erector spinae T12; T5, erector spinae T5; Trap, trapezius.

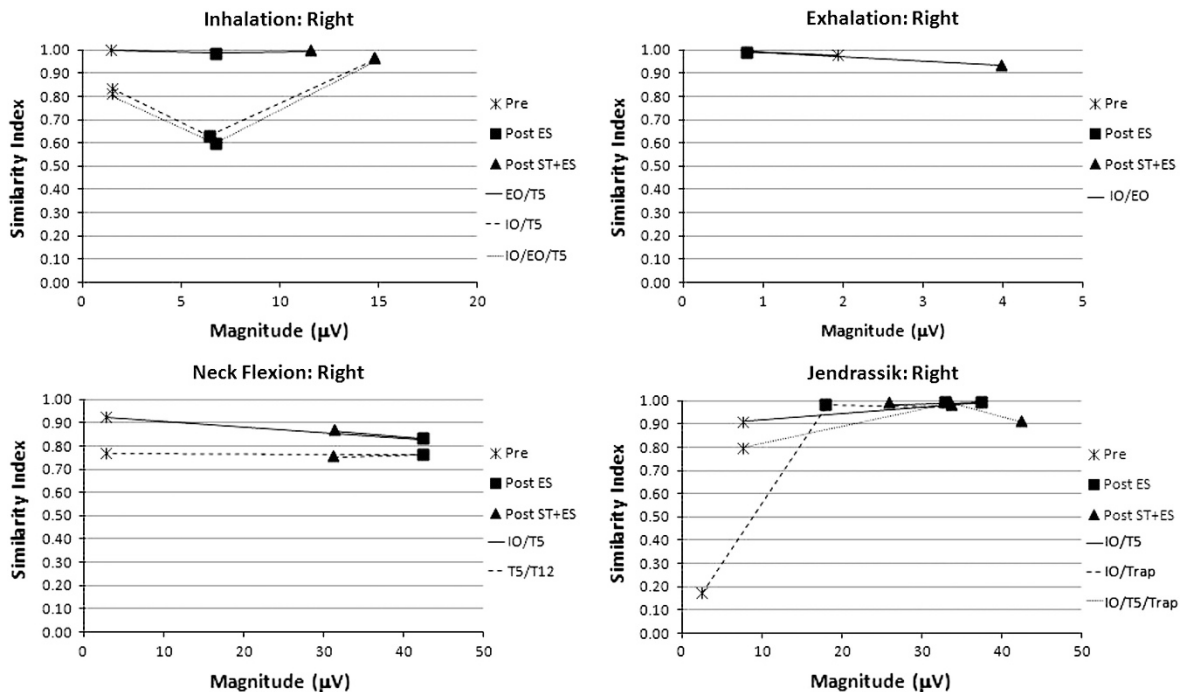


Figure 3 Similarity index (SI) and magnitude (μV) trends for the right muscles only in one individual with spinal cord injury. Each of the muscle combinations investigated in the able body population is shown (with the “best” muscle combination, as chosen in the able body individuals, represented by the solid line). The trends within this one individual demonstrate that SI and magnitude have the potential to quantify neurorecovery post interventions, particularly identifying the importance of training adaption of trunk muscles for improvement in respiration following fifty-one sessions of stand retraining. EO, external obliques; IO, internal obliques; T12, erector spinae T12; T5, erector spinae T5; Trap, trapezius.

muscles to conduct tasks. Furthermore, magnitude increased during inhalation after ST+ES (Figures 1–3), particularly in the right/left combination and the right alone. Although, our data are for only one individual, these increases in magnitude potentially identify important training adaptations of trunk muscles for improvement in respiration following 51 sessions of stand retraining. From a methodological standpoint, the most important advantage of the vector-based VRI analysis after SCI is the fact that it allows us to examine the intra-subject relationship for magnitude of activity and its distribution (SI) as a measure of recovery or control.⁸ For our one SCI individual the different muscle combinations for each maneuver showed a positive trend—an increase in SI for an increase in magnitude after ES alone. After ST+ES, there was an overall increase in magnitude and SI (inhalation). As our results for trunk VRIs are consistent to ISNCSCI upper-extremity motor scores which show that for this one individual greater-neurological impairment is on the left side, our results indicated that the neurophysiological differences represented by ipsilateral/contralateral EMG were distinguishable and well defined to characterize the trunk/thoracic region. This could hold significant clinical implication and therefore future assessments should investigate analysis of the right and left muscles separately to characterize functional neurorecovery after SCI. All of these results for our SCI individual must be cautiously stated. Moving forward we have to increase our sample size to show repeatability and validity among different individuals with SCI having varying levels of neurological impairment.

Another insight of the pilot study is the difference between the maneuvers. The significant difference found between maneuvers suggests that the BMCA is not only a reliable assessment of trunk-muscle activity, but also possesses the potential to measure neurological levels of recovery within individuals. As multiple patterns of recruitment and muscles were identified for each maneuver, the BMCA demonstrates potential to identify specific levels at which neurorecovery has occurred and could be used to provide a sensitive longitudinal assessment of neurorecovery.

CONCLUSION

Our study has shown reproducibility of the BMCA for eliciting similar sEMG activation patterns of selected trunk muscles for able-body individuals during specified-standardized BMCA maneuvers. The potential for the neurophysiological assessment tool to measure interim points of trunk recovery not recorded or detected by the ISNCSCI motor scores could have ‘real’ significance for both clinical measures of recovery and outcome measures during clinical trials.

DATA ARCHIVING

There were no data to deposit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGEMENTS

We appreciate the subjects who participated in this study and to Arvind Ramanujam, Jerome Allen and Venkata Gade, for their assistance in data collection, Rakesh Pilkar, for his preparation of the filter toolbox used in this study and Jeffrey Zhang, for his assistance with the statistical analysis. This study was supported by the New Jersey Commission on Spinal Cord Research grant (07-3063-SCR-E-0) and Kessler Foundation Center.

- 1 Marino RJ, Barros T, Biering-Sorensen F, Burns SP, Donovan WH, Graves DE *et al*. International standards for neurological classification of spinal cord injury. *J Spinal Cord Med* 2003; **26**: S50–S56.
- 2 American Spinal Injury Association. *Reference Manual for the International Standards for Neurological Classification of Spinal Cord Injury*. American Spinal Injury Association: Chicago, IL. 2003.
- 3 Sherwood AM, Priebe MM, Graves DE. Consistency of multi-channel surface EMG recordings: application in spinal cord injured subjects. *J Electromyogr Kinesiol* 1997; **7**: 97–11.
- 4 Sherwoodq AM, McKay WB, Dimitrijevic MR. Motor control after spinal cord injury: assessment using surface EMG. *Muscle Nerve* 1996; **19**: 966–979.
- 5 McKay WB, Ovechkin AV, Vitaz TW, Terson de Paleville DG, Harkema SJ. Neurophysiological characterization of motor recovery in acute spinal cord injury. *Spinal Cord* 2011; **49**: 421–429.
- 6 Lee DC, Lim HK, McKay WB, Priebe MM, Holmes SA, Sherwood AM. Toward an objective interpretation of surface EMG patterns: a voluntary response index (VRI). *J Electromyogr Kinesiol* 2004; **14**: 379–388.
- 7 Lim HK, Sherwood AM. Reliability of surface electromyographic measurements from subjects with spinal cord injury during voluntary motor tasks. *J Rehabil Res Dev* 2005; **42**: 413–422.
- 8 McKay WB, Ovechkin AV, Vitaz TW, Terson de Paleville DGL, Harkema SJ. Long-lasting involuntary motor activity after spinal cord injury. *Spinal Cord* 2011; **49**: 87–93.
- 9 Forrest GF, Angeli CA, Ferreira CK, Machin D, Harkema SJ. Musculoskeletal changes following electrical stimulation and loading training paradigms. *Soc Neurosci* 2009; 176/AA10.
- 10 Delagi EF, Iazzetti J, Perotto AO, Morrison D. *Anatomical Guide for the Electromyographer: The Limbs and Trunk*. Charles C Thomas: Springfield, IL, 2011.
- 11 Pilkar RB, Yarossi M, Forrest G. Empirical mode decomposition as a tool to remove the functional electrical stimulation artifact from surface electromyograms: preliminary investigation. *Conf Proc IEEE Eng Med Biol Soc* 2012; **2012**: 1847–1850.
- 12 Kendall FP, McCreary EK, Provan PG, Rodgers MM, Romani WA. *Muscles: Testing and Function with Posture and Pain*. Lippincott Williams & Wilkins: Baltimore, MD, 2005.
- 13 Lim HK, Lee D, McKay WB, Priebe MM, Holmes SA, Sherwood AM. Neurophysiological assessment of lower-limb voluntary control in incomplete spinal cord injury. *Spinal Cord* 2005; **43**: 283–290.
- 14 Shabbot BA, Sainburg RL. Differentiating between two models of motor lateralization. *J Neurophysiol* 2008; **100**: 565–575.
- 15 Wang J, Sainburg RL. The dominant and nondominant arms are specialized for stabilizing different features of task performance. *Exp Brain Res* 2007; **178**: 565–570.
- 16 Bagesteiro LB, Sainburg RL. Handedness: dominant arm advantages in control of limb dynamics. *J Neurophysiol* 2002; **88**: 2408–2421.
- 17 Gordon NM, Rudroff T, Enoka JA, Enoka RM. Handedness but not dominance influences variability in endurance time for sustained, submaximal contractions. *J Neurophysiol* 2012; **108**: 1501–1510.
- 18 Farina D, Kallenberg LAC, Merletti R, Hermens HJ. Effect of side dominance on myoelectric manifestations of muscle fatigue in the human upper trapezius muscle. *Eur J Appl Physiol* 2003; **90**: 480–488.
- 19 Merletti R, De Luca CJ, Sathyan D. Electrically evoked myoelectric signals in back muscles: effect of side dominance. *J Appl Physiol* 1994; **77**: 2104–2114.
- 20 Ardolino EM, Hutchinson KJ, Pinto Zipp G, Clark M, Harkema SJ. The ABLE Scale: the development and psychometric properties of an outcome measure for the spinal cord injury population. *Phys Ther* 2012; **92**: 1046–1054.
- 21 Marino RJ, Barros T, Biering-Sorensen F, Burns SP, Donovan WH, Graves DE *et al*. ASIA Neurological Standards Committee 2002 International standards for neurological classification of spinal cord injury. *J Spinal Cord Med* 2003; **26**: S50–S56.
- 22 Marino RJ, Graves DE. Metric properties of the ASIA motor score: subscales improve correlation with functional activities. *Arch Phys Med Rehabil* 2004; **85**: 1804–1810.