J Neurosurg Spine (Suppl) 17:77–86, 2012

Quantitative and sensitive assessment of neurophysiological status after human spinal cord injury

Kun Li, Ph.D.,[1,2] Darryn Atkinson, M.P.T.,[2,3] Maxwell Boakye, M.D., M.P.H.,[1,2] Carie Z. Tolfo, D.P.T.,[2] Sevda Aslan, Ph.D.,[2] Matthew Green, B.S.,[2] Barry McKay, B.S.,[4] Alex Ovechkin, M.D., Ph.D.,[5,6] and Susan J. Harkema, Ph.D.[1,2,5–7]

Departments of [1]Neurological Surgery, [3]Anatomical Sciences and Neurobiology, and [5]Physiology and Biophysics; [6]Kentucky Spinal Cord Injury Research Center; and [7]Neuroscience Collaborative Center, University of Louisville; [2]Frazier Rehab Institute; and [4]Norton Neuroscience Institute, Louisville, Kentucky

Object. This study was designed to develop an objective and sensitive spinal cord injury (SCI) characterization protocol based on surface electromyography (EMG) activity.

Methods. Twenty-four patients at both acute and chronic time points post-SCI, as well as 4 noninjured volunteers, were assessed using neurophysiological and clinical measures of volitional motor function. The EMG amplitude was recorded from 15 representative muscles bilaterally during standardized maneuvers as a neurophysiological assessment of voluntary motor function. International Standards for the Neurological Classification of Spinal Cord Injury (ISNCSCI) examinations were performed as a clinical assessment of lesion severity.

Results. Sixty-six functional neurophysiological assessments were performed in 24 patients with SCI and in 4 neurologically intact individuals. The collected EMG data were organized by quantitative parameters and statistically analyzed. The correlation between root mean square (RMS) of the EMG signals and ISNCSCI motor score was confirmed by Kendall correlation analysis. The Kendall correlation value between overall muscles/levels, motor scores, and the RMS of the EMG data is 0.85, with the 95% CI falling into the range of 0.76–0.95. Significant correlations were also observed for the soleus (0.51 [0.28–0.74]), tibialis anterior (TA) (0.53 [0.33–0.73]), tricep (0.52, [0.34–0.70]), and extensor carpi radialis (ECR) (0.80 [0.42–1.00]) muscles. Comparisons of RMS EMG values in groups defined by ISNCSCI motor score further confirmed these results. At the bicep and ECR, patients with motor scores of 5 had nearly significantly higher RMS EMG values than patients with motor scores of 0 ($p = 0.059$ and 0.052, respectively). At the soleus and TA, the RMS of the EMG value was significantly higher ($p < 0.01$) for patients with American Spinal Injury Association Impairment Scale motor scores of 5 than for those with ISNCSCI motor scores of 0. Those with C-7 ISNCSCI motor scores of 5 had significantly higher RMS EMG values at the tricep than those with motor scores of 4 ($p = 0.008$) and 0 ($p = 0.02$). Results also show that surface EMG signals recorded from trunk muscles allowed the examiner to pick up subclinical changes, even though no ISNCSCI scores were given.

Conclusions. Surface EMG signal is suitable for objective neurological SCI characterization protocol design. The quantifiable features of surface EMG may increase SCI characterization resolution by adding subclinical details to the clinical picture of lesion severity and distribution.
(http://thejns.org/doi/abs/10.3171/2012.6.AOSPINE12117)

Key Words • **spinal cord injury** • **surface electromyography** • **voluntary motor control**

Detailed characterization of the impact of SCI on CNS motor control processing is a complex and difficult task. Currently, the most widely used method of tracking the recovery of voluntary capability after SCI is the ASIA Impairment Scale.[17] In this framework, a group of selected muscles is quantitatively scored by a trained examiner for the purpose of determining SCI severity. The ASIA Impairment Scale, however, suffers from major limitations. First, for motor function, only the upper and lower limbs are assessed, with only 5 muscle groups for each limb included. Second, the trunk is not evaluated, making assessment of the neurological level of SCI in the thoracic region dependent solely on the sensory evaluation. Third, the scale is based on a subjective estimation of muscle strength and sacral sparing, and is unable to provide the information about the recruitment rate of the target muscle and the activation of synergis-

Abbreviations used in this paper: ASIA = American Spinal Injury Association; ECR = extensor carpi radialis; EMG = electromyography; FNPA = functional neurophysiological assessment; ISNCSCI = International Standards for the Neurological Classification of Spinal Cord Injury; RMS = root mean square; SCI = spinal cord injury; TA = tibialis anterior; ZPP = zone of partial preservation.

tic muscles with concurrent inhibition of antagonistic muscles that is necessary to perform functional volitional movement efficiently.[11]

Surface EMG signal, usually described in terms of the visually analyzed temporal patterns,[4,13,17] has been used to display quantitatively the patterns of motor unit activity in a variety of motor tasks.[3] Its ability to monitor the motor output of multiple muscles makes surface EMG a promising candidate for further SCI characterization, particularly in the thoracic segments that are currently not addressed by the ASIA Impairment Scale motor examination. In 1996, Sherwood et al.[14] concluded that the surface EMG activities present distinguishable and meaningful patterns that could be used for sensitive SCI characterization. They found that a completely paralyzed patient with SCI (ASIA Grade A) was able to evoke surface EMG activity repetitively when attempting to move his leg. Similar findings were presented by McKay et al.,[10] who concluded that > 60% of the persons investigated who were clinically categorized as having motor-complete lesions (ASIA Grade A or B) had residual translesional ability to modulate spinal motor excitability.

In 2004, Lee et al.[6] developed a vector-based analytical tool, the voluntary response index, which was derived from surface EMG signals. The voluntary response index consists of 2 elements, the similarity index and the magnitude of the response vector, which is a direct expression of the total amount of the recorded surface EMG. The reliability of using the voluntary response index to characterize SCI severity was validated in the original work by testing on 5 neurologically intact individuals and 2 patients with SCI. A larger validation study conducted by Lim et al.[7] in 67 patients with incomplete SCI provided further evidence of the validity and sensitivity of this technique. Using this EMG methodology, McKay et al.[9] showed that the amplitude of recorded surface EMG and computed similarity index increased during recovery, with a progressive decrease of onset-to-peak time and co-activation of multiple muscles. Surface EMG amplitude recorded from the prime mover muscle and the similarity index value significantly correlated with the ISNCSCI motor score.

These preliminary studies revealed the possibility and feasibility of using the surface EMG signal for objective and effective SCI characterization. In a recent study by Harkema et al.,[5] an individual who had complete motor paralysis below T-1 for > 3 years regained the ability to voluntarily move his toes, ankles, knees, and hips during epidural stimulation, identifying connectivity from supraspinal centers to the lumbosacral spinal cord. However, the underlying connectivity could not be detected using the ISNCSCI examination, and remained unknown due to the lack of an objective, quantitative, and sensitive neurophysiological measure that can probe residual supraspinal pathways during the natural course of recovery and in response to therapeutic interventions. In the current study, we performed an analytical, prospective cohort study with specific aims to develop a surface EMG–based, simple, effective, and objective FNPA protocol. Our hypotheses were as follows: that 1) surface EMG can detect significant differences among different ISNCSCI motor score groups; 2) EMG activity exists below the ZPP in ASIA Impairment Scale complete patients; 3) the amplitude of EMG correlates with ASIA Impairment Scale motor scores; 4) a progressive increase in EMG activity can be detected over time; 5) EMG can detect neural activity in thoracic segments; and finally 6) the pattern of EMG activity such as onset-to-peak time is significantly associated with recovery characteristics.

Methods

Study Design

This study used EMG data collected in patients with SCI and in neurologically intact volunteers by using the FNPA protocol. Data were processed and statistically analyzed to discover and confirm the correlations among EMG activity and the ASIA Impairment Scale grade, ISNCSCI motor score, and functional improvement in patients with SCI. The results suggest that an objective (quantitative), highly sensitive, and accurate SCI characterization protocol can be designed based on surface EMG signals.

Patient Population

All assessments were carried out after informed consent was obtained with the approval of the Institutional Review Board for human research of the University of Louisville. Twenty-eight volunteers, including 24 patients with SCI (16 acute and 8 chronic) and 4 neurologically intact individuals, participated in this research (Table 1). The ASIA Impairment Scale distribution of the patients with SCI was as follows: for patients with acute injury, 5 were classified as ASIA Grade A, 1 as Grade B, 2 as Grade C, and 8 as Grade D. For patients with chronic injury, 5 were classified as ASIA Grade A, 3 as Grade B, and 0 as Grades C and D. In total we had 10 patients with ASIA Grade A, 4 with Grade B, 2 with Grade C, and 8 with Grade D injury. Four of the 28 patients were female, and all were between 17 and 64 years of age (38.1 ± 15.1 years [mean ± SD]) at the time of injury. Six injuries were clinically diagnosed as central cord syndromes. A total of 66 assessments was analyzed, and of these, 32 assessments were done within 3 days of an ISNCSCI examination. The average time from injury to first assessment was 6 days (range 2–17 days) for patients with acute injury and 1439 days (range 244–6025 days) for patients with chronic injury. Persons with clinically recognizable concomitant head injury were not enrolled, and all enrolled participants were alert and able to cooperate with the study testing. No changes were made in clinical management for this study.

Clinical Assessment

As a standard clinical assessment of lesion severity, an ISNCSCI examination was performed within 48 hours of FNPA assessment whenever possible. The ISNCSCI examination provides a subjective motor score for 5 upper-limb muscles (C5–T1) and 5 lower-limb muscles (L2–S1) bilaterally, in addition to subjective sensory scores for both light touch and pinprick for C-2 through S3–4 der-

TABLE 1: Demographic and clinical characteristics in 28 patients with SCI*

Characteristic	Full Sample (no. of assessments)	Motor Complete†	Motor Incomplete‡	Neurologically Intact
sex				
men	24 (58)	13	7	3
women	4 (8)	1	3	1
mean age in yrs	38 ± 15			
injury level				
cervical	17	8	9	NA
thoracic	7	6	1	NA
time since injury (yrs)				
≤1	17			
>1	7			
total no. of patients		14	10	4

* There were 28 total volunteers who participated in 66 separate assessments. Of the 62 SCI assessments, in 32 there was an associated ASIA Impairment Scale examination within 3 days. Data are reported as number of volunteers or mean ± SD. Abbreviation: NA = not applicable (motor scores were not observed in our sample).
† ASIA Grades A and B.
‡ ASIA Grades C and D.

matomes. Anal sensation and voluntary anal contraction are assessed as a measure of motor and sensory function at the S-5 spinal level. For patients with acute injury, the ISNCSCI examinations were repeated at irregular intervals determined by patients' return visits to the SCI clinic. In patients with chronic injury, the ISNCSCI examinations took place within 48 hours of FNPA assessment in most cases.

Neurophysiological Assessment

Participants were tested using the FNPA, which is a modified and expanded protocol of volitional and reflex motor tasks that was developed from the brain motor control assessment method described above. Pairs of EMG electrodes were placed midbelly (unless otherwise noted) on the following muscles bilaterally: sternocleidomastoid, upper trapezius, scalene, biceps brachii, triceps brachii, ECR, flexor digitorum profundus, adductor policis brevis, abductor digiti quinti, external intercostals, rectus abdominus, erector spinae, rectus femoris, vastus lateralis, TA, and soleus. Electrode placement was altered for the rectus abdominus, with placement just distal to the ribs and approximately 2 in from midline. External intercostal recording electrodes were placed at the sixth intercostal space. Erector spinae electrodes were placed at the T-10 vertebral level, 2 cm lateral from midline. Volunteers participated in three 3-second movement trials, termed "events," for each muscle. Events were marked for analysis manually by a trained technician while the examiner instructed the participant as to the movement that was to be performed. Audible tones of 3-second duration cued the patient; the start of the tone signaled the beginning of the event and the cessation of the tone signaled the end. The EMG signals were recorded on a 32-channel Eclipse Neurological Workstation (AXON Systems, Inc.) with a sampling rate of 2 kHz per channel and a bandpass of 30 Hz to 2 kHz.

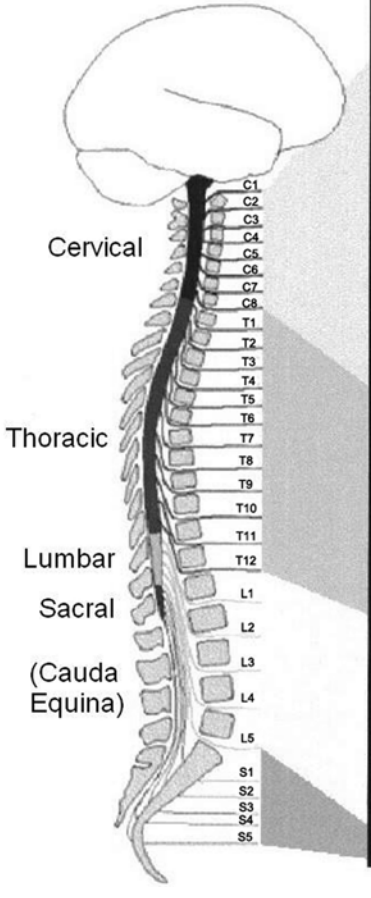
Figure 1 shows the muscles assessed with both the FNPA and ISNCSCI examinations, as well as the maneuvers used and the spinal level tested by each muscle. The ISNCSCI motor examination assesses 5 muscles from both the upper and lower extremities, representing spinal levels C4–T1 and L2–S1, respectively. The FNPA examination assesses muscles representing all spinal levels.

Data Processing and Statistical Analysis

Data were rectified and RMS values were calculated for each attempt per muscle. The means (which are expressed ± SD throughout) and RMS values per muscle were calculated from 3 attempts in all events except relaxation. Relaxation was divided into 30-second intervals. The means and RMS values were determined from 10 intervals in 5 minutes of relaxation per muscle per person. Data were down-sampled to 20 Hz for EMG envelope. The RMS of the EMG data was summarized with medians and interquartile extrema (25th and 75th percentiles), and graphically with boxplots and scatterplot, by muscle and ISNCSCI motor score at the spinal cord level corresponding to the given muscle. To compare RMS EMG among groups defined by the ISNCSCI motor score, a nonparametric Kruskal-Wallis test for clustered data was applied.[2] Correlations between ISNCSCI motor scores and RMS of the EMG values were estimated and tested using nonparametric Kendall correlations for clustered data.[8] All hypothesis tests were conducted at the $p = 0.05$ significance level.

Results

The EMG signals were observed from the trunk muscles in 19 patients with SCI in whom no ISNCSCI motor and/or sensory scores were obtained. The EMG activities were observed and recorded from the muscles below the ASIA Impairment Scale neurological level (see example in Fig. 2), which implied that surface EMG signals may



Spinal roots	Muscle	Maneuver	AIS Maneuver
CN XI, C1-C2	Sternocleidomastoid(C1-3)	Shoulder elevation	
C3	Upper Trapezius(C3-4)	Shoulder elevation	
C4	Scalene(C4-8)	Forced inspiration	
C5	Biceps Brachii	Elbow flexion	Elbow flexion
C6	Extensor Carpi Radialis(C6-7)	Wrist Extension	Wrist extension
	Flexor Carpi Radialis(C6-7)	Wrist Flexion	
C7	Extensor Digitorum Communis(C7-8)	Finger extension	
	Triceps Brachii(C7-8)	Elbow extension	Elbow extension
C8	Flexor Digitorum Profundus(C8-T1)	Finger flexion	Finger flexion
T1	Abductor Pollicis Brevis(C8-T1) Abductor Digiti Quinti(C8-T1)	Finger abduction	Finger abduction
T2-T5	Intercostals(C6-T10)	Trunk flexion Forced inspiration & expiration	
T6-9	Rectus Abdominus(T6-12)	Trunk flexion Forced inspiration & expiration	
T10-12	Erector Spinae	Trunk extension	
L1	Paraspinal, lumbosacral (L1-S1)	Hip extension	
L2	Rectus Femoris(L2-4)	Hip flexion	Hip flexion
L3	Vastus Lateralis(L2-4)	Knee extension	Knee extension
L4	Tibialis Anterior(L4-5)	Ankle dorsiflexion	Ankle dorsiflexion
L5	Extensor Digitorum Longus(L5-S1), Extensor Hallucis Longus(L5-S1)	Long toe extension	Long toe extension
S1	Soleus(L5-S2)	Ankle plantarflexion	Ankle plantarflexion

Fig. 1. Diagram and chart showing muscles and maneuvers. Muscles assessed using both the FNPA and the ISNCSCI examination are listed as well as the maneuvers used for testing and the spinal root level that each muscle represents. AIS = ASIA Impairment Scale.

bring higher sensitivity to SCI characterization. Bilateral surface EMG recordings also showed activity in muscles that were scored zero in both ISNCSCI motor and sensory scores in 4 patients. As shown in Fig. 3, upper-extremity responses were seen in multiple muscles in the segments immediately below the level of injury (C-4 for this patient) that were not detected in the clinical assessment. Table 2 shows the distribution of ISNCSCI motor scores at different injury levels corresponding to muscles of interest. Unfortunately, motor scores of 1 to 3 were sparsely populated and not suitable for strict statistical analysis. Therefore, the group comparisons of RMS EMG activity by ISNCSCI motor score were confined to motor scores 0 and 5, with the exception of level C-7 (triceps brachii [tricep]), for which motor score 4 was included as a group in the analysis.

Table 3 shows the summary statistics of RMS EMG activity sorted by the ISNCSCI motor score for each muscle of interest, and Fig. 4 provides a graphic summary of RMS EMG by muscle and motor score. When

TABLE 2: Distribution of ASIA Impairment Scale motor scores at spinal cord levels corresponding to muscles of interest*

		ASIA Impairment Scale Motor Scores (no. of volunteers)					
Associated Muscle	Level of Injury	0	1	2	3	4	5
bicep	C-5	5	1	0	2	3	34
ECR	C-6	6	1	0	2	3	33
tricep	C-7	7	4	1	1	11	26
TA	L-4	35	0	2	1	7	17
soleus	S-1	33	2	1	1	4	20
total		86	8	4	7	28	130

* Bicep = biceps brachii; tricep = triceps brachii.

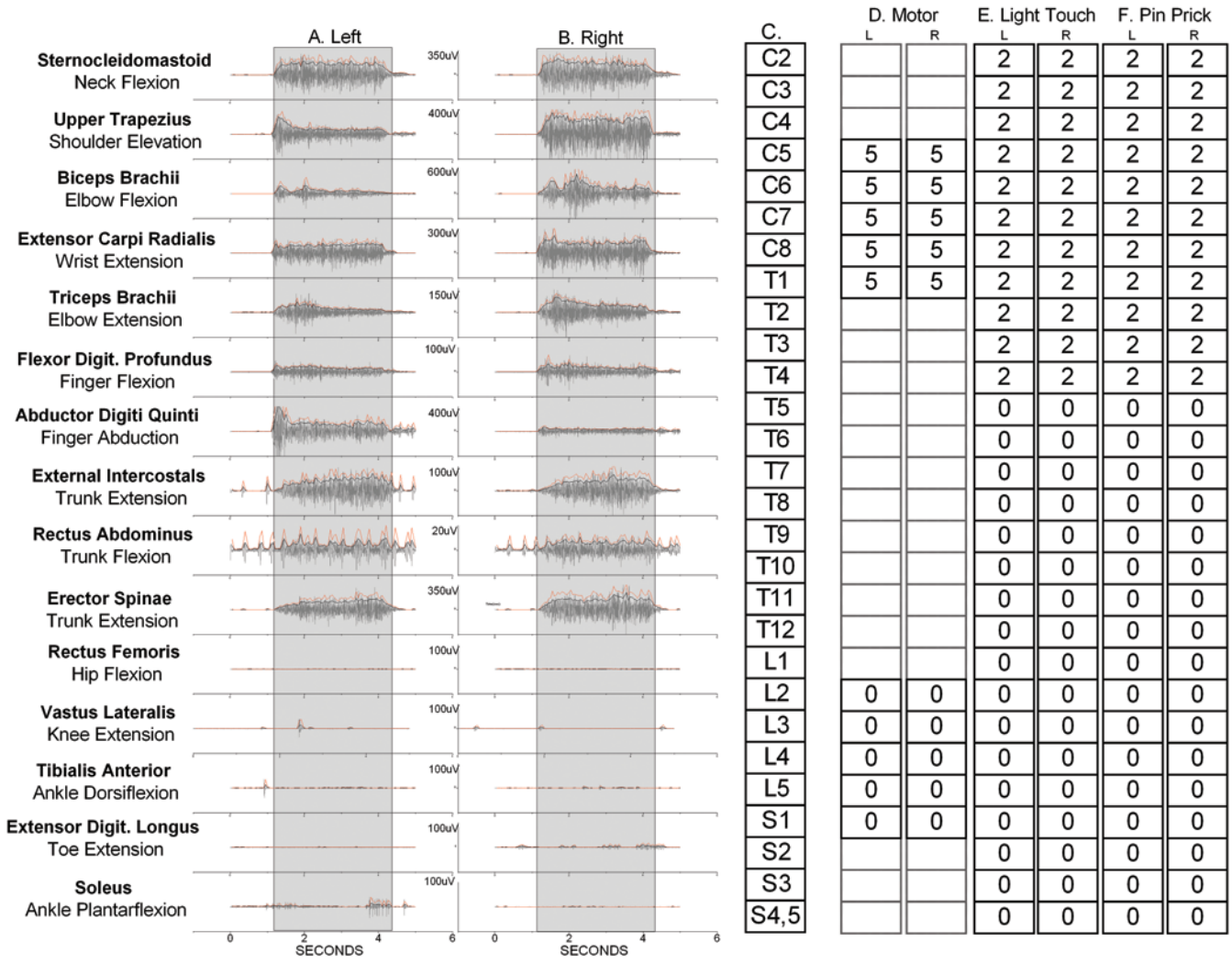


Fig. 2. Graph showing bilateral EMG activity (average of 3 trials) in a patient classified as T-4 ASIA Grade A (716 days postinjury) during standardized attempts at voluntary movements. The EMG activity shown *(gray lines)* represents the averaged EMG response from 3 trials over time for primary muscles responsible for each corresponding voluntary movement from the left **(A)** and right **(B)** sides. Each EMG response was down-sampled to 20 Hz and rectified. The mean ± SD of 3 responses over time was superimposed on the figure (*black* and *red lines*, respectively). Corresponding muscle spinal levels **(C)**, ISNCSCI motor scores **(D)**, light touch **(E)**, and pinprick **(F)**. The *shaded gray area* indicates the time of command for the specific voluntary movement. This patient clearly shows repeatable, voluntary muscle activity below the lowest intact motor and sensory level identified on the ISNCSCI examination. Digit. = digitorum.

TABLE 3: Summary statistics of the RMS of EMG activity at each muscle of interest by ISNCSCI motor score at the spinal cord level corresponding to the given muscle

		ISNCSCI Motor Score*					
Muscle	Level	0	1	2	3	4	5
bicep	C-5	1.7 [1.7, 1.7]	5.4	NA	52.1 [48.5, 55.7]	22.2 [19.7, 36.1]	75.3 [32.2, 131.9]
ECR	C-6	5.8 [4.2, 6.5]	29.2	NA	36.3 [28.6, 44.1]	34.2 [24.4, 40.8]	145.1 [82.1, 296.9]
tricep	C-7	1.7 [1.4, 5.0]	5.2 [2.6, 27.5]	0.7	17.2	13.5 [5.8, 16.2]	43.9 [13.2, 115.8]
TA	L-4	0.9 [0.6, 1.6]	NA	9 [4.8, 13.2]	29.2	62.7 [31.6, 114.5]	109.1 [70.4, 193]
soleus	S-1	0.8 [0.6, 1.4]	1.1 [1.0, 1.2]	26.8	39.6	44.8 [26.2, 63.4]	52.2 [22.7, 89.6]

* Values are presented as median, with interquartile extrema (25th and 75th percentiles) in brackets. Entries with single numbers indicate that ISNCSCI motor scores were observed only once.

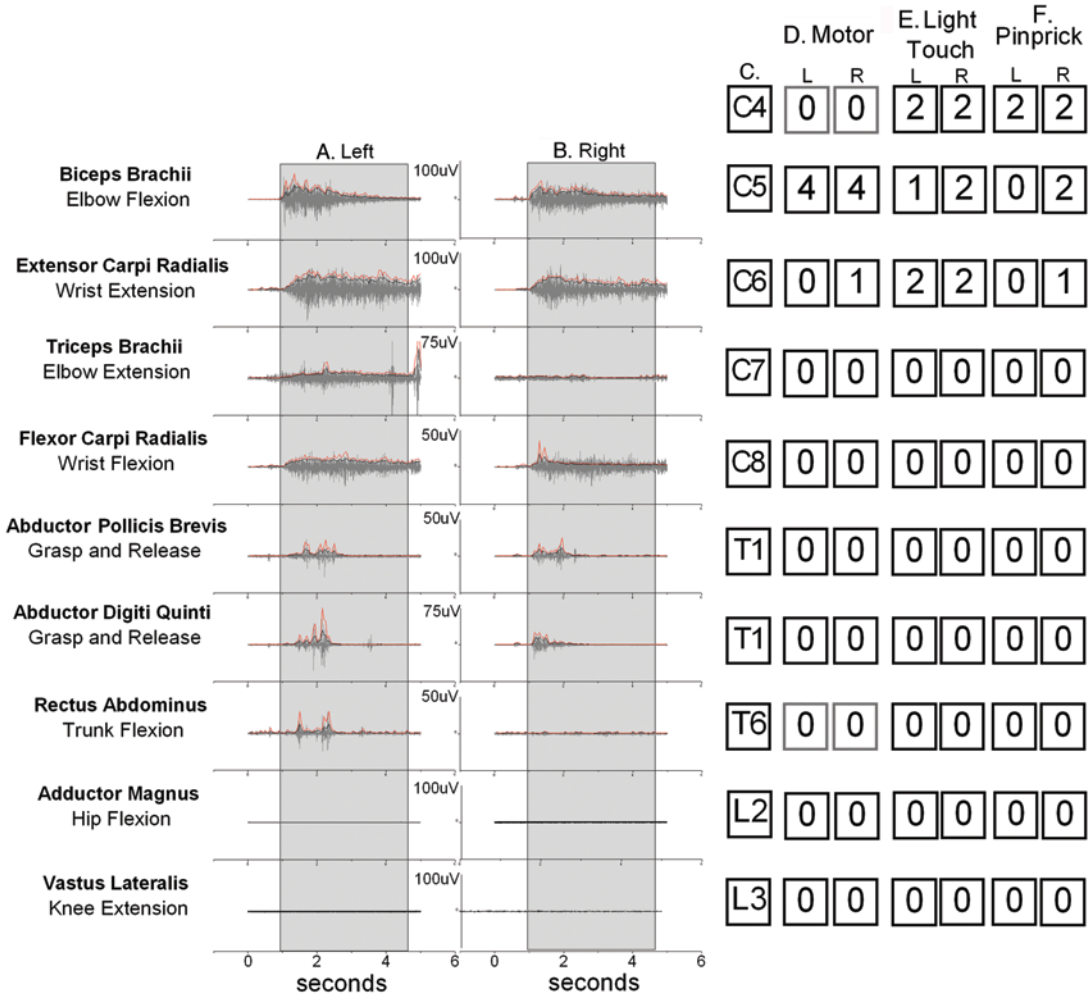


Fig. 3. Graph showing bilateral EMG activity in a patient classified as C-4 ASIA Grade A (17 days postinjury) during standardized attempts at voluntary movements. The EMG activity shown *(gray lines)* represents averaged EMG response from 3 trials over time for primary muscles responsible for each corresponding voluntary movement from the left **(A)** and right **(B)** sides. The mean ± SD of 3 responses over time was superimposed on the figure (*black* and *red lines*, respectively). Corresponding muscle spinal levels **(C)**, ISNCSCI motor scores **(D)**, light touch **(E)**, and pinprick **(F)**. The *shaded gray area* indicates the time of command for specific voluntary movement.

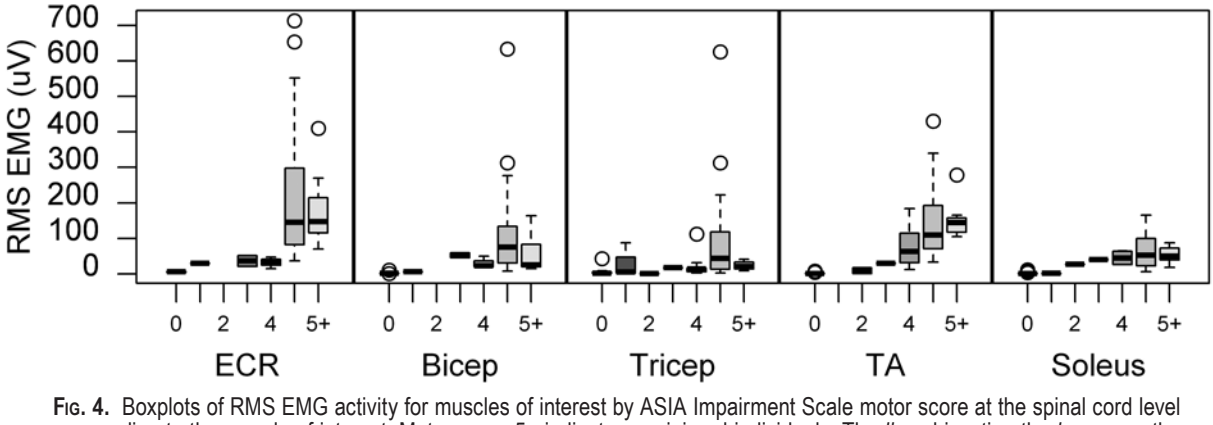


Fig. 4. Boxplots of RMS EMG activity for muscles of interest by ASIA Impairment Scale motor score at the spinal cord level corresponding to the muscle of interest. Motor score 5+ indicates noninjured individuals. The *lines* bisecting the *boxes* are the medians; the *edges of the boxes* are the interquartile range (25th and 75th percentiles); the *edges of the whiskers* represent the outlier-excluded range (minimum and maximum, excluding outliers); the *circles* represent outliers, which are points that lie beyond 1.5 * the interquartile range from the edge of the box.

TABLE 4: Results of correlation test and ISNCSCI motor score group EMG comparison

Muscle	Level	Correlation (95% CI)*	p Value†
bicep	C-5	0.25 (−0.11 to 0.60)	0.059
ECR	C-6	0.80 (0.42–1.00)	0.052
tricep	C-7	0.52 (0.34–0.70)	0.02
TA	L-4	0.53 (0.33–0.73)	<0.01
soleus	S-1	0.51 (0.28–0.74)	<0.01
overall		0.85 (0.76–0.95)	<0.01

* According to the nonparametric Kendall correlation test.
† According to the nonparametric Kruskal-Wallis test (ISNCSCI Score 0 vs 5).

including all muscles/levels, the motor scores and RMS EMG strongly correlated (Kendall correlation 0.85, 95% CI 0.76–0.95) (Table 4). Significant correlations were also observed for the soleus (0.51, CI 0.28–0.74), TA (0.53, CI 0.33–0.73), and tricep (0.52, CI 0.34–0.70). At the biceps brachii (bicep) and ECR, patients with a motor score of 5 had nearly significantly higher RMS EMG signals than patients with a motor score of 0 ($p = 0.059$ and 0.052, respectively). At the soleus and TA, the RMS EMG activity was significantly higher ($p < 0.01$) for patients with an ASIA Impairment Scale motor score of 5 than it was for those patients with an ISNCSCI motor score of 0. There was a sufficient number of ASIA Impairment Scale motor scores of 4 at the tricep (C-7) to include in the comparisons. Those with a C-7 ISNCSCI motor score of 5 had significantly higher RMS EMG signals at the tricep than those with a motor score of 4 ($p = 0.008$) and 0 ($p = 0.02$).

Our assessment of motor function performed using EMG readings recorded during voluntary movement was also sensitive to changes in motor function over time. As illustrated in Fig. 5, there is a quantitative change in EMG amplitude RMS values over time that indicates RMS EMG's ability to detect a change in motor function over time by using the FNPA protocol. Figure 6 illustrates the mean EMG distribution versus ASIA Impairment Scale motor score. It suggests the procedural increase of EMG

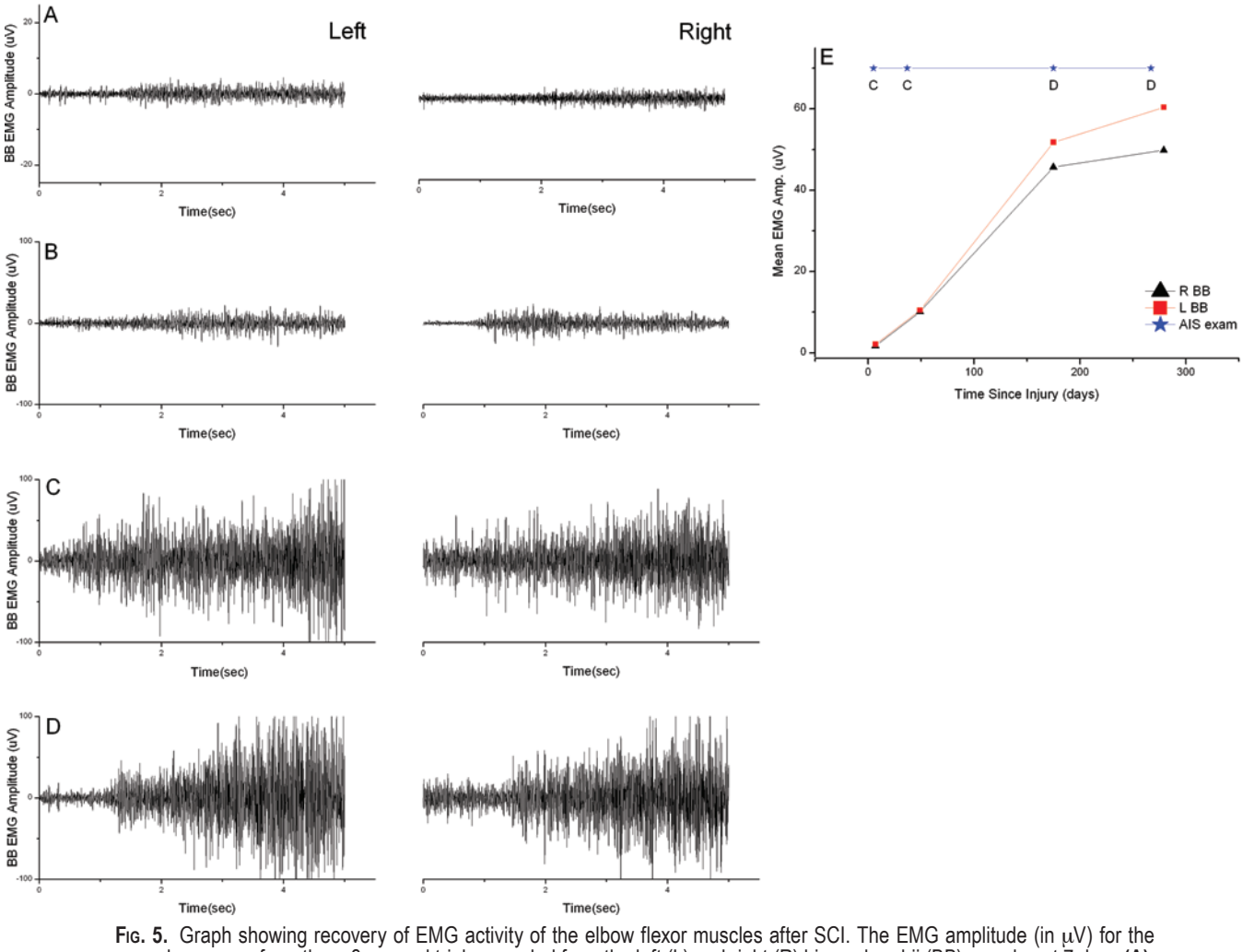


Fig. 5. Graph showing recovery of EMG activity of the elbow flexor muscles after SCI. The EMG amplitude (in μV) for the averaged response from three 3-second trials recorded from the left (L) and right (R) biceps brachii (BB) muscles at 7 days **(A)**, 49 days **(B)**, 175 days **(C)**, and 279 days **(D)** post-SCI. Change in RMS values for right and left biceps brachii from the same time points is shown in panel **E**. Also shown are the dates of the ISNCSCI examinations for this patient (5, 37, 175, and 267 days postinjury) as well as the ASIA Impairment Scale (AIS) classification for that examination.

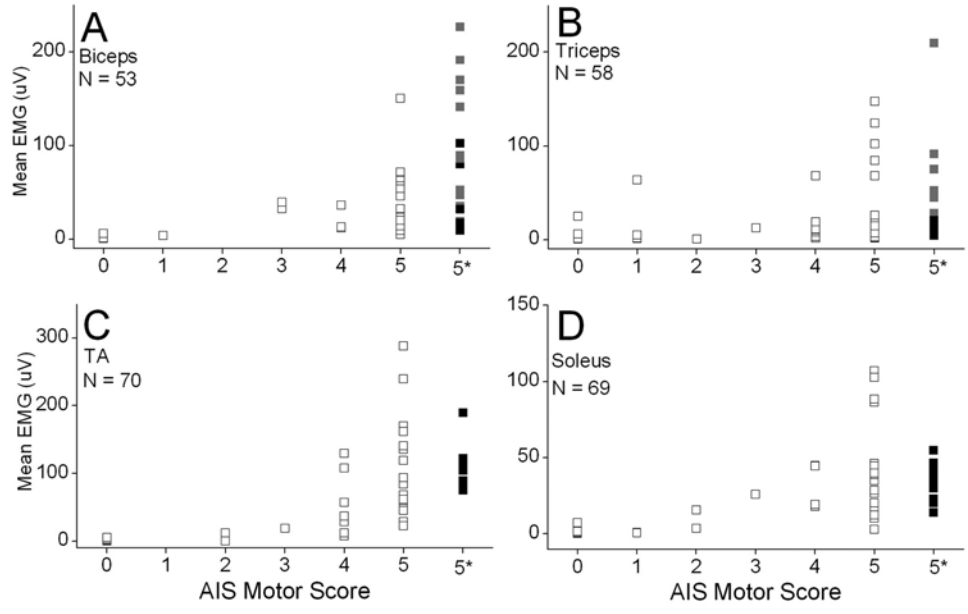


Fig. 6. Graphs showing a comparision of ISNCSCI motor scores and EMG amplitudes. The EMG amplitude (RMS) for the averaged response from three 3-second trials of standardized voluntary movements was recorded from **(A)** biceps brachii (biceps), **(B)** triceps brachii (triceps), **(C)** TA, and **(D)** soleus muscles in patients who were assessed using both FNPA and ISNCSCI motor evaluations within a 72-hour period.

amplitude with ASIA Impairment Scale motor score. Figure 7 shows the different levels of EMG amplitude and burst patterns in different muscles. It implies that the recruitment of the motor neuron can be identified in the EMG burst pattern. This change is detected before any positive motor score for the right biceps brachii muscle develops (at 7, 49, 179, and 275 days), and the pattern of EMG activity indicates another level of neural recovery.

Discussion

Basic scientists working with animal models of SCI have been testing a wide array of potential methods to protect spinal cord cells from further damage following injury, to replace subsequently lost cells, and to repair damaged neural circuitry.[16] However, translating these strategies to treat humans with SCI presents significant challenges. One of these challenges is the current lack of an objective, quantitative outcome measure with sufficient sensitivity to motor changes. We demonstrate an approach that improves the precision of the SCI characterization protocol based on well-defined quantitative EMG parameters. In this pilot study of 24 patients with SCI at cervical and thoracic levels, in which the FNPA protocol was used, the main findings are summarized as follows. 1) Correlation of EMG amplitudes with motor scores. This finding is consistent with the research of McKay et al.[12] We collected more data and performed statistical analysis to support this conclusion. 2) Trunk muscle activities were recorded and used for SCI characterization for the first time. 3) Correlation of increasing amplitude with recovery. 4) Detection of EMG activity in patients with no motor scores below injury.

The FNPA is an optimized neurophysiological assessment protocol that has significant advantages over other protocols based on motor evoked potentials, for which the characteristics, such as latency, have been reported by Curt et al.[1] as remaining unchanged during the recovery process of patients with SCI. Compared with motor evoked potential–based methodologies, FNPA has the ability to monitor coactivation of multiple muscles and to record EMG activity from trunk muscles, which makes it more suitable for tracking the functional recovery that is related to compensation and neural plasticity. The results show that muscle activity was detected in individuals who were diagnosed as clinically complete several segments below their level of lesion, which suggested that surface EMG can pick up subclinical changes beyond the resolution of ASIA Impairment Scale grades or ISNCSCI motor or sensory scores. One patient with acute SCI who had EMG activities below the ZPP and was categorized as ASIA Grade A converted to a higher score on the ASIA Impairment Scale in our experiment. Spiess et al.[15] reported the conversion rate of ASIA Grade A to higher scores as 28% (54 of 191). We observed a rate of 20% (1 of 5). However, when the conversion rate was conditioned by having EMG activity below ZPP, it increased to 50% (1 of 2) in our study. Although these rates may not be statistically significant due to the small sample size, this finding is absolutely worth further investigation.

Notable EMG activities also presented in the thoracic segment and were recorded from trunk muscles for which no ISNCSCI motor score can be assigned. This advantage may help us to achieve further SCI characterization and to fill a much-evident gap in the field. Statistical analyses confirmed that the progressive increase of surface EMG amplitude with recovery is significantly correlated to the ISNCSCI score. This result is consistent with previous studies[12] and opens a new window to the design of an EMG-based SCI characterization protocol. The sig-

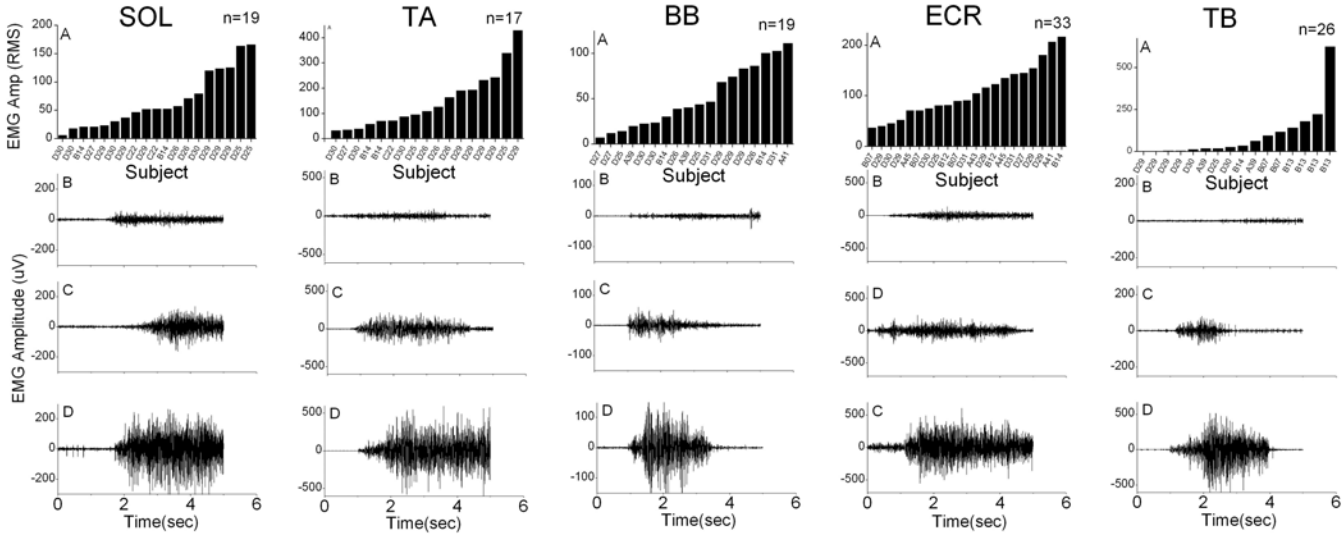


Fig. 7. Graphs showing variability in EMG activity of elbow flexors. **A:** Variability in EMG RMS values for patients whose biceps brachii, triceps brachii (TB), ECR, TA, and/or soleus (SOL) muscles were given an ISNCSCI motor score of 5/5, and whose level of injury was proximal to the muscle in question. The y axis gives the EMG amplitude (RMS), and the x axis gives individual participants' ID numbers. **B–D:** Examples of EMG burst patterns for low EMG amplitude **(B)**, intermediate EMG amplitude **(C)**, and high EMG amplitude **(D)**.

nificant differences in EMG activities among different ISNCSCI motor score groups were also addressed by statistical analyses, which indicated that the neurophysiological differences represented by EMG were distinguishable and well defined. Moreover, the variations of EMG characteristics, such as amplitude and onset-to-peak time, on the full ASIA Impairment Scale's range and on each ISNCSCI motor score group are continuous and quantifiable. These features make it feasible and possible to develop an EMG-based objective SCI characterization protocol with higher sensitivity and resolution. Another advantage of surface EMG is that it is able to detect the influence of supraspinal pathways that are not identifiable when using the ISNCSCI examination.[7] Results presented in this article suggest the possibility and feasibility of using the surface EMG signal for highly sensitive SCI characterization and statistically valid assessment of changes in neural recovery prior to discernable behavioral improvements. This may be most relevant when evaluating a single regenerative or repair intervention that may have an impact but must be combined with other combinatorial strategies to show a behavioral change ultimately.

Limitations of our study include small sample sizes. In particular, we did not have adequate data to compare recovery in patients with EMG below the ZPP versus recovery in those without EMG activity below the ZPP. That remains the focus of additional studies. Other than amplitude and onset-to-peak time, other EMG patterns such as the shape of the amplitude envelope and EMG energy distribution may also be significantly related to SCI recovery characteristics as well. However, the parameters that can be used to describe the EMG patterns effectively have not been well defined yet and were not used in our study, but they are the subjects of future studies. The distribution of EMG amplitude in each ISNCSCI motor score group is also worthy of further investigation. The results may give more statistical confidence to the accuracy of SCI characterization. Future studies are needed in a larger population of individuals with SCI for further demonstration of the statistical validity and reliability of these approaches.

Conclusions

Standardized numerical assessment of attempts at voluntary movement evaluated using surface EMG signals can provide important information regarding the current neurophysiological status of the patient after injury, and can detect changes during the recovery process. Therefore, surface EMG is a suitable and promising candidate for a highly sensitive framework design for SCI characterization. One important potential application of the FNPA protocol described here is to track recovery in clinical trials by monitoring subclinical improvements that are currently not detectable by the ASIA Impairment Scale system, particularly in thoracic segments where the ISNCSCI motor score is not applicable.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Harkema, Boakye, Aslan, McKay, Ovechkin. Acquisition of data: Atkinson, Tolfo, Aslan, Green, McKay, Ovechkin. Analysis and interpretation of data: Harkema, Li, Atkinson, Tolfo, Aslan, Green. Drafting the article: Li, Atkinson, Tolfo, Aslan, Green. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Harkema. Administrative/technical/material support: Harkema, Study supervision: Harkema, Boakye, McKay, Ovechkin.

Acknowledgments

The authors express their appreciation to the volunteers who participated in this study and acknowledge all the team members who kindly offered their help and support.

References

1. Curt A, Van Hedel HJ, Klaus D, Dietz V: Recovery from a spinal cord injury: significance of compensation, neural plasticity, and repair. **J Neurotrauma 25:**677–685, 2008
2. Datta S, Satten GA: Rank-sum tests for clustered data. **J Am Stat Assoc 100:**908–915, 2005
3. Gellhorn E: Patterns of muscular activity in man. **Arch Phys Med Rehabil 28:**566–574, 1947
4. Hallett M: Analysis of abnormal voluntary and involuntary movements with surface electromyography. **Adv Neurol 39:** 907–914, 1983
5. Harkema S, Gerasimenko Y, Hodes J, Burdick J, Angeli C, Chen Y, et al: Effect of epidural stimulation of the lumbosacral spinal cord on voluntary movement, standing, and assisted stepping after motor complete paraplegia. **Lancet 377:** 1938–1947, 2011
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 14:**379–388, 2004
7. Lim HK, Lee DC, McKay WB, Priebe MM, Holmes SA, Sherwood AM: Neurophysiological assessment of lower-limb voluntary control in incomplete spinal cord injury. **Spinal Cord 43:**283–290, 2005
8. Lorenz DJ, Datta S, Harkema SJ: Marginal association measures for clustered data. **Stat Med 30:**3181–3191, 2011
9. McKay WB, Lee DC, Lim HK, Holmes SA, Sherwood AM: Neurophysiological examination of the corticospinal system and voluntary motor control in motor-incomplete human spinal cord injury. **Exp Brain Res 163:**379–387, 2005
10. McKay WB, Lim HK, Priebe MM, Stokic DS, Sherwood AM: Clinical neurophysiological assessment of residual motor control in post-spinal cord injury paralysis. **Neurorehabil Neural Repair 18:**144–153, 2004
11. McKay WB, Ovechkin AV, Vitaz TW, Terson de Paleville DG, Harkema SJ: Long-lasting involuntary motor activity after spinal cord injury. **Spinal Cord 49:**87–93, 2011
12. McKay WB, Ovechkin AV, Vitaz TW, Terson de Paleville DG, Harkema SJ: Neurophysiological characterization of motor recovery in acute spinal cord injury. **Spinal Cord 49:**421–429, 2011
13. Samilson RL, Morris JM: Surgical improvement of the cerebral-palsied upper limb. Electromyographic studies and results of 128 operations. **J Bone Joint Surg Am 46:**1203–1216, 1964
14. Sherwood AM, McKay WB, Dimitrijević MR: Motor control after spinal cord injury: assessment using surface EMG. **Muscle Nerve 19:**966–979, 1996
15. Spiess MR, Muller RM, Rupp R, Schuld C, van Hedel HJ: Conversion in ASIA impairment scale during the first year after traumatic spinal cord injury. **J Neurotrauma 26:**2027–2036, 2009
16. Steeves JD, Lammertse D, Curt A, Fawcett JW, Tuszynski MH, Ditunno JF, et al: Guidelines for the conduct of clinical trials for spinal cord injury (SCI) as developed by the ICCP panel: clinical trial outcome measures. **Spinal Cord 45:**206–221, 2007
17. Waring WP III, Biering-Sorensen F, Burns S, Donovan W, Graves D, Jha A, et al: 2009 review and revisions of the international standards for the neurological classification of spinal cord injury. **J Spinal Cord Med 33:**346–352, 2010
18. Wiesendanger M, Rüegg DG: Electromyographic assessment of central motor disorders. **Muscle Nerve 1:**407–412, 1978

Manuscript submitted January 31, 2012.
Accepted June 5, 2012.
Please include this information when citing this paper: DOI: 10.3171/2012.6.AOSPINE12117.

Address correspondence to: Susan J. Harkema, Ph.D., Frazier Rehab Institute, 220 Abraham Flexner Way, Suite 1506, Louisville, Kentucky 40202. email: susan.harkema@jhsmh.org.