

## Original Article

# Neurophysiological assessment of lower-limb voluntary control in incomplete spinal cord injury

HK Lim<sup>1,2</sup>, DC Lee<sup>3</sup>, WB McKay<sup>1,2</sup>, MM Priebe<sup>4</sup>, SA Holmes<sup>1,2</sup> and AM Sherwood<sup>1,2,\*</sup>

<sup>1</sup>Baylor College of Medicine, Houston, TX, USA; <sup>2</sup>Michael E. DeBakey VA Medical Center, Houston, TX, USA; <sup>3</sup>Case Western Reserve University, Cleveland, OH, USA; <sup>4</sup>Edward Hines, Jr. VA Hospital, Hines, IL, USA

**Study design:** Cross-sectional retrospective study of a neurophysiological method of voluntary motor control characterization.

**Objectives:** This study was undertaken to validate the surface electromyography (sEMG)-based voluntary response index (VRI) as an objective, quantitative, laboratory measure of spinal cord injury severity in terms of voluntary motor control disruption.

**Setting:** VA Medical Centers in Houston and Dallas Texas, USA.

**Methods:** A total of 67 subjects with incomplete spinal cord injury (iSCI), American Spinal Injury Association Impairment Scale (AIS)-C ( $n = 32$ ) and -D ( $n = 35$ ) were studied. sEMG recorded during a standardized protocol including eight lower-limb voluntary motor tasks was analyzed using the VRI method that relates multi-muscle activation patterns of SCI persons to those of healthy-subject prototypes ( $n = 15$ ). The VRI is composed of a measure of the amount of the sEMG activity (magnitude) and the distribution of activity across muscle groups compared to that of healthy subjects for each motor task (similarity index, SI). These resulting VRI components, normalized magnitude and SI, were compared to AIS clinical findings in this study. Receiver operating characteristic analysis was performed to determine the SI values best separating AIS-C and AIS-D subjects.

**Results:** Magnitude and SI for AIS-C subjects had mean values of  $0.27 \pm 0.32$  and  $0.65 \pm 0.21$ , respectively. Both parameters were significantly larger in the AIS-D subjects ( $0.78 \pm 0.43$  and  $0.93 \pm 0.06$ ), respectively ( $P < 0.01$ ). An SI value of 0.85 was found to separate AIS-C and AIS-D groups with a sensitivity of 0.89 and a specificity of 0.81. Further, the VRI of each leg strongly correlated with the respective AIS motor score (0.80,  $r < 0.01$ ).

**Conclusions:** In the domains of voluntary motor control, the sEMG-based VRI demonstrated adequate face validity and sensitivity to injury severity as currently measured by the AIS.

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**Keywords:** motor control; quantitative analysis; surface EMG; spinal cord injury; voluntary movement

## Introduction

With widely varying degrees of severity, damage to the spinal cord long-tract descending systems disrupts voluntary control of muscles of the lower limbs. When completely severed, the loss of supraspinal control brings paralysis. However, lesions clinically judged as complete often retain residual supraspinal connectivity not clinically recognizable.<sup>1,2</sup> For motor incomplete spinal cord injured (iSCI) subjects, partially disrupted voluntary control of lower-limb muscles determines

many aspects of their recovery following the acute phase post injury.

For clinical diagnosis and treatment planning purposes, the severity of human iSCI is currently assessed through a carefully developed classification scheme based upon subjective clinical observations. The American Spinal Injury Association (ASIA) impairment scale (AIS) is endorsed by the International Spinal Cord Society (ISCoS) and has been used as the International Standard for Neurological and Functional Classification of Spinal Cord Injury.<sup>3</sup> The AIS is also the measure of spinal cord injury (SCI) severity recommended by Congress of Neurological Surgeons.<sup>4</sup> The AIS is based

\*Correspondence: AM Sherwood, Michael E DeBakey VA Medical Center (153), 2002 Holcombe Blvd., Houston, TX 77030, USA

in part on the palpation and observation of voluntary contraction and the scoring of relative strengths for key lower-limb muscles.<sup>4</sup> The strengths of the AIS are that it structures the observations that characterize visible or palpable movements, provides scores amenable to quantitative analysis, and can be performed without instrumentation in the clinical setting. In its initial form, the AIS exhibited limitations in the form of inter- and intra-rater variability.<sup>5</sup> These problems were lessened but not eliminated by the revised AIS standards and by clarification of criteria through aggressive education of physicians, therapists, and nurses.<sup>3,6-8</sup> However, the subjective nature of assessment of post-SCI motor function using the AIS criteria remains a limitation, resulting in considerable variability.<sup>9</sup> The promise of new treatment approaches and their likely incremental effects on voluntary control demands objective measures with greater sensitivity be employed to assess their effectiveness. The attempted therapeutic manipulation of neuroplasticity<sup>10-12</sup> to modify neural circuitry through neural implantation<sup>13</sup> and molecular manipulation of surviving neural structures<sup>14</sup> will require objective quantification methods to reach clinical practice.

The American Academy of Neurology has determined that surface electromyography (sEMG) is an acceptable diagnostic tool for the kinesiologic analysis of motor control and movement disorders<sup>15,16</sup> and sEMG has been proposed as a measure of CNS motor output.<sup>17,18</sup> One such objective measure of residual motor function is found in the Brain Motor Control Assessment (BMCA) protocol that couples standardized administration and control of instructions, environment, and pace of presentation of elementary voluntary motor tasks with the recording of multi-muscle sEMG.<sup>1,19-22</sup> The BMCA protocol has demonstrated consistency and sensitivity to subclinical motor function.<sup>1,2</sup> Fung and Barbeau<sup>23</sup> found that by applying a 'dynamic EMG profile index' to the repeating cycles of muscle activation they could characterize gait. Similarly, methods of analysis of sEMG recorded during elementary voluntary motor tasks performed in the supine position, were developed to create a voluntary response index (VRI)<sup>22</sup> that has been shown to be sensitive enough to detect motor control differences between healthy subjects and individuals with SCI, across a group of SCI subjects, and within individual SCI subjects across time and following intervention.<sup>24</sup> Further, the VRI has been used to characterize trace voluntary control in complete SCI subjects.<sup>2</sup>

The purpose of this study was to evaluate the VRI for its criterion validity as an objective, quantitative measure of SCI lesion severity as it impacts voluntary motor control severity.

## Methods

### *Subjects*

Data for this study were drawn from three other studies, all using the same recording protocol, of individuals

with SCI in a spasticity study done with approval of the local review board for human research. From these three studies, 67 subjects with iSCI were used for the analysis reported here (four female and 63 male,  $49.5 \pm 15.2$  years of age),  $57.0 \pm 53.5$  months postinjury, 32 for AIS-C, and 35 for AIS-D. In addition, 15 healthy subjects (four female and 11 male,  $36 \pm 10$  years of age) were used to form the prototype response vector (below). The subjects presented primarily with cervical level lesions, with 40 cervical (60%), 18 (27%) between T1 and T9, and 9 (13%) below T10. Partial data from seven of these SCI subjects were previously presented in a report describing the VRI method's sensitivity.<sup>24</sup>

### *Diagnostic evaluation*

All SCI subjects were classified using the AIS. To characterize the motor and sensory levels of each patient, 10 myotomes and 28 dermatomes on each side of the body were graded on a six-point scale.<sup>3</sup> The key lower limb muscles used to calculate the unilateral motor scores that make up the AIS are iliopsoas, quadriceps, tibialis anterior, extensor hallucis longus, and triceps surae. Subjects were classified based on the bilateral motor score as incomplete AIS-D (muscle score greater or equal to 3 for at least half of the key muscles below the neurological level) or AIS-C (muscle score less than 3 for more than half of key muscles below the neurological level).<sup>3</sup>

### *Recording protocol*

sEMG recordings using a SynAmps amplifier (Neuroscan, El Paso, TX, USA) were made from the right and left quadriceps (Q), adductor (A), hamstrings (H), tibialis anterior (TA), and triceps surae (TS) muscle. Pairs of 1-cm diameter sEMG electrodes were placed 3 cm apart and centered on the long axis over muscle bellies. Four elementary voluntary maneuvers performed by both legs independently (unilateral hip-knee flexion and extension, and ankle dorsiflexion and plantar flexion)<sup>17</sup> were chosen for their simplicity, and required little thought and no training for their performance. All maneuvers were repeated three times each, cued by an audible tone. The 10 sEMG channels were recorded with a bandwidth of 30–500 Hz and a gain of 1000. Movement sensors and event cue markers were also recorded and along with the sEMG, were continually digitized at a rate of 2000 samples/s for the duration of the protocol.

### *Data reduction*

To produce sEMG envelopes with an effective sampling rate of 20 samples/s, full bandwidth sEMG data were reduced using a root mean square (RMS) algorithm.<sup>25</sup> These envelope data were the basis for subsequent processing. The sEMG activity for each muscle (channel) was then reduced to a single number by averaging over a 5-s movement window beginning with the initiation of the movement cue, after baseline correction

by subtracting the averaged activity over the 1-s immediately preceding the movement cue.<sup>20</sup> An average of the three repeated trials for the 10 recorded muscles comprised the response vector (RV) used in calculation of the VRI described below. We used the term, vector, as a way of referring to a set of numbers (in our case, 6 or 10) derived from the average muscle activity. Using vector notation has the advantage of being able to summarize this set of numbers or vector in terms of its magnitude (length) and orientation (in the hypothetical 10-dimensional space). Two vectors, for example, one representing the distribution of sEMG activity in healthy subjects (PRV) and the other representing the distribution in a given subject with spinal cord injury (RV), may be easily compared in terms of both magnitude and orientation. We used the inner or dot product to compare the orientations of these two vectors, which is equivalent to the cosine of the angle between them.

*Data analysis*

The multi-muscle sEMG distribution patterns were described using the similarity index (SI) and the magnitude of the response vector (magnitude), |RV|. These two components together comprise the VRI (Equation (1)).<sup>22</sup> The SI is calculated from a comparison of the distribution of activity, that is, RV, in the 10 lower-limb muscles of an SCI subject to the group of healthy subjects' responses, that is, the prototype response vector (PRV), for the same movement.<sup>22</sup> In the previous study,<sup>24</sup> voluntary ankle dorsiflexion was analyzed after an intervention in iSCI subjects and found significant differences. To expand and explore other voluntary movements in the BMCA protocol, in this study, we analyzed unilateral hip and knee flexion and extension, and unilateral ankle dorsi- and plantar flexion. Therefore, four pairs of VRI values were calculated for each subject. A normalized VRI (VRI<sub>n</sub>), normalized magnitude and SI, was defined (Equation (2)) using the SI as in Equation (1), but magnitude normalized to the mean healthy-subject magnitude for each specific motor task (Equation (3)) expressed as normalized magnitude, |RV|<sub>n</sub>. For evaluating asymmetry, the absolute differences of scores (motor score, SI, and normalized magnitude) were used.

$$VRI \equiv (|RV|, SI) \tag{1}$$

where RV = [R<sub>1</sub>, R<sub>2</sub>, R<sub>3</sub>, R<sub>4</sub>, R<sub>5</sub>, R<sub>6</sub>, R<sub>7</sub>, R<sub>8</sub>, R<sub>9</sub>, R<sub>10</sub>], R<sub>1</sub> and R<sub>6</sub> = right and left quadriceps, R<sub>2</sub> and R<sub>7</sub> = right and left adductor, R<sub>3</sub> and R<sub>8</sub> = right and left hamstrings, R<sub>4</sub> and R<sub>9</sub> = right and left tibialis anterior, R<sub>5</sub> and R<sub>10</sub> = right and left triceps surae,

$$SI = \frac{\sum_i (RV_i PRV_i)}{|RV| |PRV|}$$

(i = 10 for ankle movements and i = 6 for hip-knee movements)

$$VRI_n \equiv (|RV|_n, SI) \tag{2}$$

where

$$|RV|_n = \frac{|RV|}{\mu_{|RV_{HS}|}}$$

$$\mu_{|RV_{HS}|} = \frac{\sum_i^n |RV_{HSi}|}{n}, \tag{3}$$

n = number of healthy subjects (HS)

The SI values for hip-knee flexion and extension, and ankle dorsal and plantar flexion motor tasks were averaged for each side. The side with the higher average SI was used to represent the subject for comparison to their AIS values. Unilateral SI and normalized magnitude averages were used for comparison to the unilateral AIS motor scores. Also, the averaged VRI<sub>n</sub> for hip and knee flexion and ankle dorsiflexion was calculated for normalized magnitude and SI values separately.

*Analysis*

*Combined scores* The AIS provides a single value for each subject, largely determined by the side with the highest component unilateral motor score. For comparison to this single AIS value, it was necessary to use the side with the highest average SI value to characterize individual SCI subjects by VRI<sub>n</sub>. Motor scores for right and left lower-limbs were also compared with normalized magnitudes and SIs. A total of 52 SCI subjects for whom unilateral lower limb scores were available were used for the comparison between unilateral VRI<sub>n</sub> and unilateral motor scores (using both left and right side scores together, ie, 104 data points) for the lower limbs. The mean values obtained from the healthy subject group served as the denominators for the normalization of magnitude values, which are listed in Table 1. In the comparison of motor score with normalized magnitude and SI, all possible combinations of normalized magnitude and SI were made to find the highest correlation.

*Comparison of AIS and VRI results* In order to evaluate the degree to which the VRI<sub>n</sub> classification of subjects matched the clinically derived AIS classification, we employed a commonly used pattern recognition method termed the receiver operating characteristic (ROC) curve. This method is used to evaluate the performance of any classification scheme that categorizes cases into one of two groups.<sup>26</sup> The method iteratively computes the number of correctly classified cases (hits) and incorrectly classified cases (false alarms) as a function of the decision threshold for the classification scheme. By plotting these two variables against each other, the ROC curve is derived. Computing the area under the curve provides a measure of 'goodness' of the classification, with an area of 0.5 representing no discrimination ability, to a maximum of

**Table 1** Average magnitude of RV and SI of healthy subjects during volitional movements ( $n = 15$ )

Motion	Magnitude of RV ( $\mu V$ )		SI	
	Average	STD	Average	STD
Right hip-knee flexion	82.1	31.8	0.95	0.04
Right hip-knee extension	27.1	10.0	0.95	0.05
Left hip-knee flexion	71.2	33.3	0.97	0.04
Left hip-knee extension	24.2	9.7	0.97	0.03
Right ankle dorsiflexion	240.2	108.8	1.00	0.01
Right ankle plantar flexion	44.7	23.7	0.94	0.05
Left ankle dorsiflexion	220.1	85.7	0.99	0.02
Left ankle plantar flexion	39.3	13.6	0.96	0.03

1.0, a perfect separation with no overlap. In the current situation, as in most realistic classification problems, some overlap may be anticipated. Thus, to determine the 'best' separation, a decision criterion must be established. In this case, we chose to maximize the function (hits - false alarms), to equally weigh the two kinds of errors that can occur in setting the decision threshold. The method also yields sensitivity and specificity measure for the classification of these data.

*Comparison of motor scores and VRI results* Nonparametric correlations were performed to determine the relation between the  $VRI_n$  and AIS motor scores. All possible combinations of VRIs were tested to find the highest correlation values.

## Results

### *AIS versus $VRI_n$*

Unilateral AIS motor scores were significantly larger for AIS-D ( $18.5 \pm 5.4$ , average  $\pm$  SD) than for AIS-C ( $6.9 \pm 5.3$ ) subjects ( $P < 0.05$ ) among the 52 subjects for whom lower limb motor scores were available. There was also significant asymmetry between sides within these incomplete SCI subjects with a mean side-to-side difference of  $3.5 \pm 4.9$  in AIS motor scores. Furthermore, there was an average difference in unilateral VRI values of  $0.36 \pm 0.57$  in normalized magnitude and  $0.23 \pm 0.26$  in SI ( $P < 0.05$ ).

Figure 1 illustrates the relationship between the multimuscle patterns of sEMG activity and the calculated VRI values for five SCI subjects who had an average unilateral magnitude between 47 and 103% of the healthy-subject prototype presented in the order of decreasing SI. Sequenced from highest to lowest SI, the sEMG patterns in this illustration show decreasing prime mover activation and increasing, inappropriate coactivation of antagonistic and contralateral muscles.

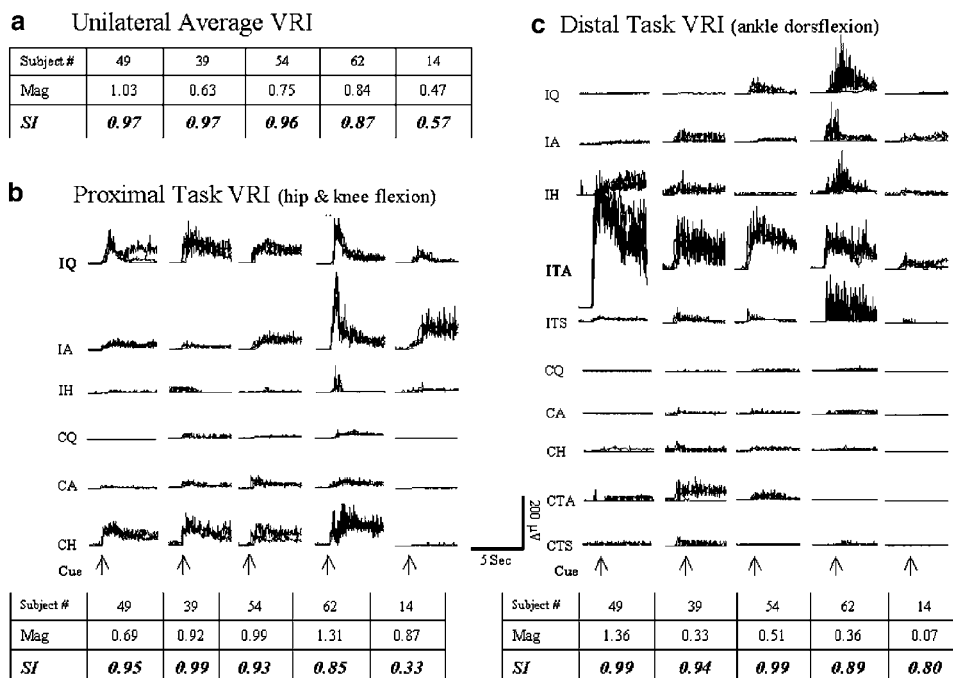
Since the AIS produces a single value to describe each subject and eight  $VRI_n$ s are produced for the eight motor tasks, the average SI was calculated for the two unilateral movements for each side and used to

determine the side for each SCI subject having the highest average SI. With the 'better' side thus defined, averaged normalized magnitude and SI for that best side showed significant differences between SCI subjects and healthy subjects ( $P < 0.01$ ), and between AIS-C and AIS-D SCI subject groups ( $P < 0.05$ ).  $VRI_n$  values averaged across the two maneuvers for AIS-D subjects were significantly larger than those of AIS-C subjects, with normalized magnitude values of  $0.78 \pm 0.43$  and  $0.27 \pm 0.32$  and SI values of  $0.93 \pm 0.06$  and  $0.65 \pm 0.21$ , respectively ( $P < 0.01$ ). In addition, magnitude and SI representing each of eight motor tasks were significantly larger in the AIS-D subjects than that in the AIS-C group ( $P < 0.05$ ).

In the pattern recognition analysis, the area under the ROC curve for averaged SI for unilateral hip-knee flexion and ankle dorsiflexion (Table 2), measured 0.94 (confidence interval from 0.89 to 0.99) and for the corresponding averaged magnitude 0.84 (confidence interval from 0.74 to 0.95). The area under the ROC curve for SI for the eight voluntary motor tasks taken together was 0.76, and eight averaged 0.87. Taking the motor tasks separately, results ranged from a high of 0.87 for ankle dorsiflexion SI to a low of 0.70 for ankle plantarflexion SI. This analysis identified AIS-D subjects using thresholds of 0.85 for the SI and 0.33 for the average normalized magnitude, with a sensitivity of 0.89 and a specificity of 0.81, as shown in Figure 2.

### *Motor score versus VRI*

The AIS unilateral motor scores were correlated to the different SIs representing individual motor tasks or combinations of tasks, for example, proximal movements together or flexion movements together. Correlation coefficients ranged from 0.22 to a high of 0.80 ( $P < 0.01$ ) which was observed for the four unilateral motor tasks taken together (Table 3). Hip-knee flexion, dorsiflexion and plantar flexion showed the strongest correlation coefficients, 0.80 ( $r < 0.01$ ) with unilateral motor scores (Table 3). Figure 3 illustrates the relation between the VRI and the AIS unilateral motor score. It is noteworthy that Figure 3 contains unilateral,



**Figure 1** Five representative SCI subjects, selected to have average unilateral VRI values (two motor tasks) in which magnitude was between 47 and 103% times the healthy-subject prototype presented in the order of decreasing SI (a). sEMG RMS envelope data from the ipsilateral quadriceps (IQ), adductor (IA), and hamstring (IH), contralateral quadriceps (CQ), adductor (CA), and hamstring (CH) for three superimposed trials of the unilateral hip–knee flexion motor task recorded from those subjects and presented in the same order as in (a) with their respective per-task VRI values at the bottom (b). IQ, IA, IH, ipsilateral tibialis anterior (ITA), and triceps surae (ITS), and CQ, CA, CH, contralateral tibialis anterior (CTA) and triceps surae (CTS) sEMG envelopes for three unilateral ankle dorsiflexion motor task trials (c). Note the qualitative deterioration of the sEMG patterns in the form of decreasing prime mover activation, IQ (b) and ITA (c), and increasing coactivation of ipsilateral and contralateral muscles with decreasing SI values, seen especially well in the distal joint control patterns (c)

**Table 2** ROC results from various combinations of the SI

Combined maneuvers	Area	Significance level	Confidence Limits	
			Low	High
Two flexions (H/K Flex + DF)	0.94	0.000	0.89	0.99
Three flexions (H/K Flex + DF + PF)	0.91	0.000	0.84	0.98
Four maneuvers (H/K Flex + H/K Ext + DF + PF)	0.90	0.000	0.83	0.98
Eight maneuvers	0.87	0.000	0.78	0.95
DF	0.87	0.000	0.78	0.96
H/K Flex	0.83	0.000	0.73	0.93
All flexion, left + right	0.88	0.000	0.81	0.96

Note that all areas of magnitudes of each combination were lower than those of SI. Where the abbreviations are the same with the following full names: hip–knee flexion (H/K Flex), hip–knee extension (H/K Ext), dorsiflexion (DF), and plantar flexion (PF)

lower-limb scores. In general, SI values for flexion motor tasks were better correlated with the motor scores than were normalized magnitude values and extension motor task SI values. Also, all correlation coefficients between motor score and combined SI values that included the dorsiflexion task were over 0.75 ( $P < 0.01$ ) (Table 3).

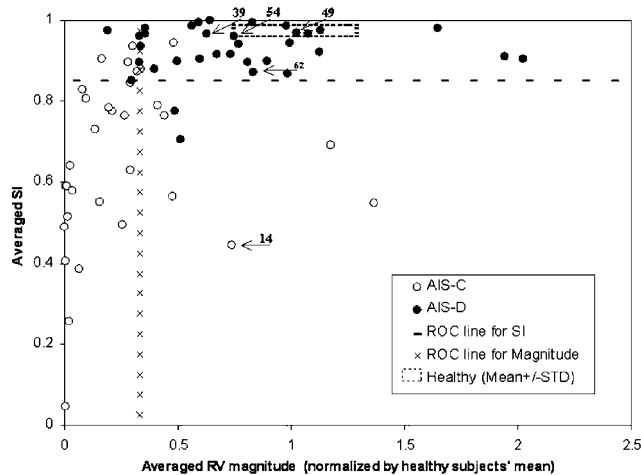
## Discussion

The VRI was designed to be sensitive to the degree of disintegration of motor control that is brought by neurological damage. The data described here show that VRI values were significantly higher for AIS-D than for AIS-C SCI subjects with highest

sensitivity to AIS category being found in the ankle dorsiflexion task VRI.

These results should not be surprising when the two assessment methods are compared because the neurophysiological VRI shares three of the five muscles that are considered to be ‘key’ to the AIS. Further, both assessments measure the ability of the subject to perform similar simple movements using those key muscles.

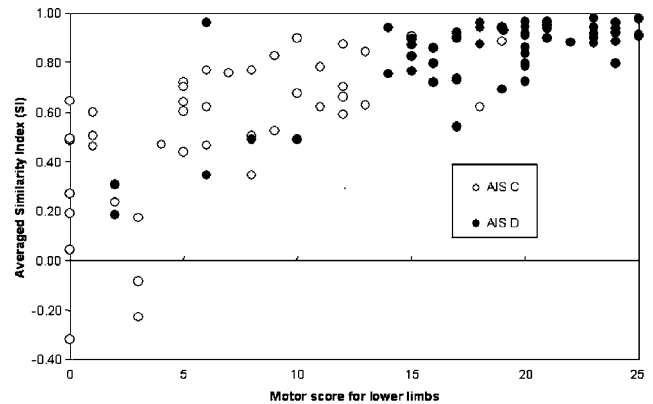
Differences between the clinical and laboratory assessments emerge from their respective purposes.



**Figure 2** Averaged SI plotted versus averaged normalized magnitude for hip–knee flexion and dorsiflexion. The side with the highest average SI from those two movements was plotted for comparison with the AIS. Both normalized magnitude and SI showed significant differences between AIS-C and AIS-D subjects ( $P < 0.01$ ). The decision thresholds were drawn based on the ROC curves computed separately for the averaged normalized magnitude and SI using an error minimization criterion (see Methods) and the dotted box is the mean  $\pm$  SD for the healthy-subject prototype

The AIS standard provides a structure for examining voluntary movement after SCI that can be applied by an individual clinician and requires no instrumentation.<sup>3</sup> In addition, the AIS provides a standard language for use when discussing patients under treatment.<sup>27</sup> However, the AIS is limited by its subjectivity and the resulting intra- and inter-rater variability.<sup>9</sup> The VRI, on the other hand, objectively measures the relative activation of muscles, recorded during integrated control of simple, elementary movements<sup>22,24</sup> and the VRI calculation provides a continuous data value capable of measuring incremental changes in control of those movements.<sup>22</sup>

As currently defined, the VRI would not well-differentiate AIS-D and -E subjects because the distribution of muscle activity is too close to that of healthy subjects, with a resulting clustering of SI values near 1.0, that is, a ceiling effect for SI values. The EMG record has much more information than is incorporated into the VRI, most notably the envelope shape or temporal



**Figure 3** Averaged SI versus motor scores. Average similarity index calculated from three maneuvers (hip–knee flexion, dorsiflexion, and plantar flexion) showed highest correlation with motor score (0.80,  $r < 0.01$ ,  $n = 54$ )

**Table 3** Comparison between motor score and response vector magnitude and similarity index

Maneuver	Normalized magnitude			SI		
	C	D	C+D	C	D	C+D
H/K Flex + DF + PF	0.71**	0.38**	0.66**	0.69**	0.52**	0.80**
H/K Flex + DF	0.71**	0.48**	0.74**	0.69**	0.35**	0.76**
DF + PF	0.67**	0.38**	0.63**	0.60**	0.6**	0.77**
Unilateral (four)	0.73**	0.34**	0.66**	0.64**	0.55**	0.79**
Proximal (two)	0.70**	0.22	0.62**	0.45**	0.41**	0.64**
Distal (two)	0.67**	0.37**	0.63**	0.56**	0.6**	0.75**
H/K Flex	0.66**	0.26**	0.62**	0.50**	0.16	0.62**
H/K Ext	0.71**	0.19	0.60**	0.42**	0.46**	0.60**
Ankle DF	0.70**	0.5**	0.76**	0.57**	0.53**	0.76**
Ankle PF	0.67**	0.30**	0.57**	0.40**	0.54**	0.58**

The highest correlation was found between the unilateral lower extremity motor score and the SI averaged across hip–knee flexion (but not extension), dorsiflexion and plantar flexion maneuvers when AIS-C and -D groups were taken together

\*\*Correlation is significant at the 0.01 level (two-tailed). H/K Flex, H/N Ext, DF and PF were added for unilateral (four). H/K Flex and H/N Ext were added for proximal (two). DF and PF were added for distal (two)

aspects of the waveform. Thus, temporal features including initiation, peak timing, and cessation of activity should be analyzed and incorporated into an expanded index to add more resolution for those with motor control close to that of healthy subjects.

The VRI method is based on an analysis of the distribution of EMG activity. If activity levels are too small, no useful determination of EMG patterns is possible. Thus, for example, differentiation of AIS-A and -B subjects is limited by this floor effect. This was discussed in another publication of our group.<sup>2</sup>

Previous work using sEMG has shown that as motor control deteriorates during a fatiguing voluntary motor task in healthy subjects, muscles not involved in the task begin to coactivate, and coactivation continues to increase during the period of the exercise.<sup>28</sup> Also, using sEMG as an objective measure of coactivation, Thomas *et al*<sup>29</sup> noted that muscles 'weakened by SCI' require near-maximal effort and activation that is accompanied by synergistic activation of other antagonistic muscles that further exacerbates the weakness of the movement. As illustrated in Figure 1, the SI value was sensitive to this deterioration of the integrated motor control for the simple motor tasks tested here and may find use in guiding therapies that train isolated activation of the agonist. Therefore, the laboratory-based VRI might provide a clinically useful extended view of integrated motor control for the selection of treatment modality and to serve as an objective monitor of changes in motor control brought by disease, trauma, or treatment.

Accurate, sensitive assessment tools are needed in the face of new interventions for motor function that are on the horizon that will need to be tested for efficacy. Methods that target incremental augmentation of neuroplastic processes are emerging using technologies that upregulate neurotransmitter systems,<sup>30</sup> increase neurite growth,<sup>14,31</sup> or seek to replace lost neurons through genetic manipulation<sup>32</sup> or neural implantation.<sup>13</sup> Changes induced in motor control by each of these intervention technologies are likely to be modest and incremental, therefore requiring sensitive, objective measurement of effects to reach general application individually and in concert.

The BMCA protocol maneuvers have been used to study CNS motor output changes brought on after SCI<sup>17,19,20</sup> for more than three decades. However, it is not known which motor tasks or in which combinations of the tasks best reflect injury severity. The comparison between motor score and VRI<sub>n</sub> in this study provides some insight into this issue. Even though the protocol tasks were not intended for direct comparison with the AIS or its component motor scores, the correlation between the two was quite strong in this study. Also, averaged SI values for flexion tasks showed a stronger correlation with the AIS motor scores than did those of extension tasks. This could be due to the fact that the BMCA protocol is performed in the supine position leaving hip-knee extension from the flexed position is really an eccentric hip-knee flexion against gravity. Plantar flexion, the other limb extension task in the

protocol, is gravity-neutral as is dorsiflexion but is contaminated by being performed from the dorsiflexed position, complicating both neural control and data analysis with resultant increased variance.

By relating sEMG patterns recorded in incomplete SCI subjects to those seen in healthy subjects, the VRI becomes a standardized measure of motor control to which SCI subjects can be objectively compared. From this comparison, individualized treatment plans that include physical modalities may be designed to train control of a selected ankle or hip flexor. For example, EMG biofeedback or EMG-triggered functional electrical stimulation may be used to improve the control features, primarily improved agonist activation and reduced coactivation of antagonistic muscles,<sup>28,33</sup> that should impact SI values while strength training might be indicated to increase low magnitudes. Of course, this presumes that decreased coactivation and increased strength are related to improved function in the experience of the individual SCI subject.<sup>29,34,35</sup> It remains in the realm of future study to answer questions about the specific VRI-measured effects that can be induced by the wide array of interventions available and on the horizon.

## Conclusion

These findings strongly suggest that the VRI is sensitive to the severity of SCI in a way that is similar to established clinical assessment. They also suggest that the VRI may offer added sensitivity in the form of objective, standardized quantified measure of the severity of a spinal cord lesion and resulting impairment of motor control. Further, the VRI provides the ability to evaluate proximal and/or distal lower-limb joint control independently. However, further study is needed to evaluate the utility of the VRI in treatment planning and effect assessment.

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