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Reliability of surface electromyographic measurements from subjects with spinal cord injury during voluntary motor tasks

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Abstract—In this study, the reliability of surface electromyographic data (root-mean-square) for volitional motor tasks drawn from a standardized protocol was assessed. For each motor task, 5 s epochs of data were analyzed with a new method to generate a measure called the voluntary response index (VRI). The VRI consists of two components, magnitude and similarity index (SI), that were separately analyzed for repeatability. We examined three repetitions of each of 10 volitional motor tasks in 69 subjects with spinal cord injury (American Spinal Injury Association [ASIA] Impairment Scale [AIS], classifications C and D: 34 AIS-C and 35 AIS-D) for short-term (within-day) reliability. In 6 of the 69 subjects (3 each, AIS-C and AIS-D), the entire study was repeated after 1 week and results were assessed for intermediate-term (1 week apart) reliability. The reliability of the method for voluntary motor tasks was assessed by intraclass correlation coefficient (ICC), analysis of variance, coefficient of variance, and Pearson's correlation. Good reliability was found for magnitude (ICC = 0.71–0.99, Pearson's r = 0.77–0.99) and for SI (ICC = 0.65–0.96, Pearson's r = 0.72–0.93) for three repeated tests (within-day). Significant difference was found for studies completed 1 week apart for magnitude (p = 0.02) but not for SI (p = 0.57). In addition, SI showed less variation than magnitude (p < 0.001). No significant difference of magnitude and SI between tasks was observed.

Key words: central nervous system, electromyography, lower limb, muscle (voluntary), quantitative evaluation, rehabilitation, reliability, similarity index, spinal cord injury, surface electromyography.

INTRODUCTION

Reliability is the degree of consistency or stability, i.e., the ability to obtain similar results from the same subject at different times using the same equipment [1]. It is prerequisite to the appropriate use of new equipment or new measurement methods. Because surface electromyography (sEMG) is a well-known method, many prior studies reported its reliability using various methods. The reliability of sEMG has been reported as the variance ratio, paired t-test, a one-way analysis of variance (ANOVA), the coefficient of variation (CV), Pearson's correlation, and intraclass correlation coefficient (ICC) [2–3].

Abbreviations: AIS = ASIA Impairment Scale, ANOVA = analysis of variance, ASIA = American Spinal Injury Association, BMCA = brain motor control assessment, CNS = central nervous system, CV = coefficient of variation, ICC = intraclass correlation coefficient, MVC = maximum voluntary contraction, PRV = prototype response vector, RMS = root-mean-square, RV = response vector, SCI = spinal cord injury, sEMG = surface electromyography, SI = similarity index, VRI = voluntary response index.

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The time frames commonly used are short-, intermediate-, and long-term reliability of sEMG measurements [3]. It would be expressed as within-day and between-day reliability [2,4–7]. The time gap for the repeated measures may be a few seconds to minutes for the short-term reliability, a few hours to a few days for intermediate-reliability, and a few days to a few weeks or months for long-term reliability. In the comparison of within-day (or short-term) measurement and between-day (or intermediate-term) measurement, previous studies show generally higher reliability for within-day measurement.

In prior studies, characteristics of sEMG were variously expressed in terms of its mean frequency, (normalized) root-mean-square (RMS) amplitude, average rectified value, maximum voluntary contraction (MVC) to 10 percent of MVC, and conduction velocity [2–3,7–10].

In spite of muscles tested or methods and task used, many studies showed fairly good reliability (ICC $\geq$ 0.7, Pearson's $r \geq 0.7$). However, we found no studies of the reliability of sEMG studies of upper motor-neuron function in subjects with central nervous system (CNS) lesions, such as spinal cord injury (SCI), even though sEMG is considered an acceptable tool for kinesiologic analysis of movement disorders [11]. Subjects with SCI showing high reliability during volitional motor tasks would provide a good basis for the use of this method in, for example, studies of the response to various interventions. Recently, the voluntary response index (VRI) was introduced as a measure of the quality of voluntary control during motor tasks based on sEMG [12]. One of the main features of this method, differentiating it from previous methods, is the use of the distribution of activity across 10 muscles during particular voluntary motor tasks to evaluate the subjects' volitional motor control ability. The VRI's use as an objective evaluation method has been tested in several studies [13–15]. However, validation of its reliability has not been done. In this study, we assessed the short- and intermediate-term reliability of the VRI recorded during voluntary motor tasks in 69 subjects with incomplete SCI.

METHODS

Subjects

In this retrospective analysis, we studied 69 subjects (4 female and 65 male, aged 48.1 ± 4.6 years) with incomplete SCI (54.8 ± 3.6 months postinjury, American Spinal Injury Association [ASIA] Impairment Scale [AIS], classifications C and D: 34 AIS-C and 35 AIS-D) and 15 healthy subjects (4 female and 11 male, aged 36 ± 10 years). AIS-C and AIS-D are subjects who retain at least some voluntary motor control after SCI, with AIS-C being more severe and AIS-D retaining substantial voluntary muscle control ability. The data analyzed for this paper were a combination of the data from three studies using the same protocol at two Texas Department of Veterans Affairs (VA) medical centers, one in Dallas (study A: 6 AIS-C and 12 AIS-D) and the other two in Houston (study B: 10 AIS-C and 11 AIS-D, and study C: 18 AIS-C and 12 AIS-D). The SCI subject data used for this paper were a convenience sample. Except for two subjects, the data used have been previously presented in a report comparing results of the VRI method with a clinical measurement [15]. Data sets from three repetitions of each voluntary motor task within the same measurement session for each of these 69 patients were used for the short-term reliability assessment. From these 69 subjects, 6 underwent a second test 1 week after the initial test with no change in their clinical status (medication, therapy, etc.), permitting assessment of intermediate repeatability involving removing and replacing electrodes as described in the following.

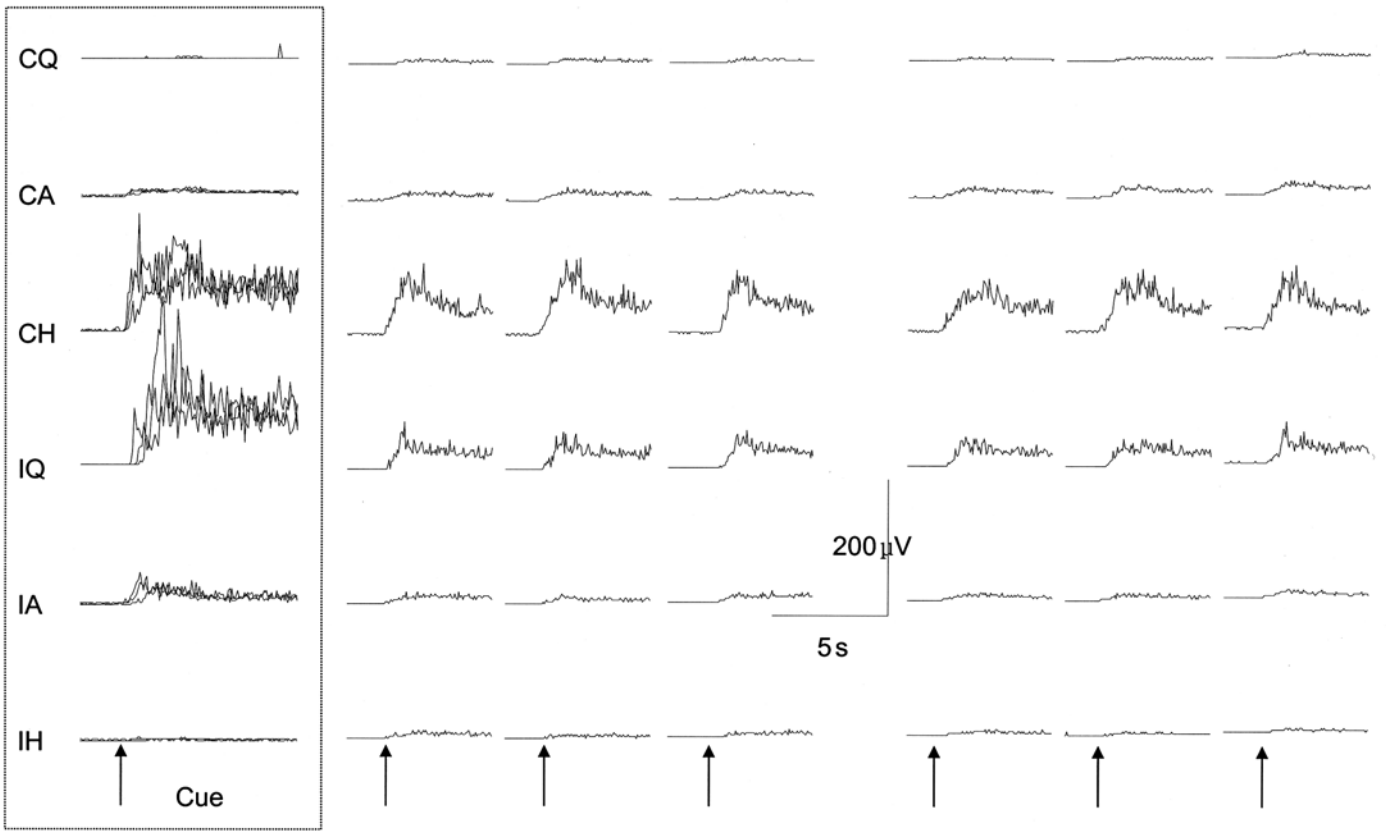
Recording Protocol

sEMG recordings using pairs of 1 cm-diameter silver/silver chloride recessed sEMG electrodes placed over the muscle bellies 3 cm apart were made from the right and left quadriceps (mainly rectus femoris), adductor, hamstrings, tibialis anterior, and triceps surae muscles. Electrodes were centered on the long axis over muscle bellies for recording during 10 voluntary motor tasks that are segments of the brain motor control assessment (BMCA) protocol performed by both lower limbs (bi- and unilateral hip-knee flexion and extension, and ankle dorsiflexion and plantar flexion) [16]. All motor tasks were repeated three times each, cued by an audible tone. The 10 sEMG channels were recorded with a bandwidth of 30 to 500 Hz and a gain of 1,000. Movement sensor and event cue marker outputs were also recorded and, along with the sEMG, were continually digitized at a rate of 2,000 samples/s for the duration of the protocol. Data recorded from movement sensors to monitor pitch movement of thigh and shank segment and pitch and yaw movement of foot segment were not analyzed in the paper but used as references for sEMG data qualification. The value of the high-pass filter (30 Hz)

was originally selected in 1972 (prior to publication of International Society of Electrophysiology and Kinesiology standards, 1980 [17]) for minimizing movement artifacts in this BMCA protocol, which involves a great deal of subject movement. This bandwidth was consistently used for all reported recordings, permitting appropriate comparisons among these recordings. **Figure 1** shows sEMG RMS envelope data from the three ipsilateral muscles and three contralateral muscles for three repeated trials of the unilateral hip-knee flexion motor task recorded from one patient as an example.

Data Reduction

We then used an RMS algorithm to produce sEMG envelopes with an effective sampling rate of 20 samples/s from the full bandwidth sEMG data [18]. These envelope data were the basis for subsequent processing. The average activity for each muscle (channel) over a 5 s window was computed and corrected for any baseline activity by subtraction of the averaged activity over the 1 s immediately preceding the motor task cue [19]. These averaged sEMG responses to the three repeated trials for the 10 recorded muscles were then themselves averaged over



SI	0.92	0.89	0.92	0.91	0.90	0.92
Magnitude (%)	69.3	77.9	61.3	62.3	66.2	57.3

Figure 1.
Surface electromyography root-mean-score envelope data from contralateral quadriceps (CQ), adductor (CA), hamstring (CH), ipsilateral quadriceps (IQ), adductor (IA), and hamstring (IH) of unilateral hip-knee flexion motor task recorded **(a)** from healthy subject, superimposed; **(b)**, **(c)**, and **(d)** for three repeated trials of one spinal cord injury (SCI) subject (American Spinal Injury Association Impairment Scale, classification D); and **(e)**, **(f)**, and **(g)** from same SCI subject 1 week later). These two studies showed similar ranges of magnitude (69.5% ± 8.3% to 61.9% ± 4.5%) and similar muscle control pattern, i.e., similarity index (SI) (0.91 ± 0.02 to 0.91 ± 0.01).

the three repetitions of each motor task to quantify the distribution of activity across the various muscles, and expressed as a response vector (RV), whose elements are these baseline-corrected change activities.

Data Analysis

To objectively characterize the observed voluntary motor control, we employed the recently described VRI [20], which comprises two components, the magnitude of the RV, |RV|, and the similarity index (SI) sEMG (**Equation (1)**). Taken together, these two components of the VRI describe the amount of activity (magnitude of the RV) and its distribution (SI) in comparison with the distribution of activity observed in healthy subjects doing the same motor task. The SI is computed as the cosine or dot product of the normalized RV and the prototype response vector (PRV) obtained from the healthy subjects for the same motor task [20]. As previously defined, PRVs were generated from the average of RVs across the 15 control subjects for each phase of each movement [20]. For this study, we analyzed bilateral and unilateral hip and knee flexion and extension, and unilateral ankle dorsi- and plantar flexion:

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

where RV = [R_1 R_2 R_3 R_4 R_5 R_6 R_7 R_8 R_9 R_{10}], R_1 and R_6 = right and left quadriceps, R_2 and R_7 = right and left adductor, R_3 and R_8 = right and left hamstrings, R_4 and R_9 = right and left tibialis anterior, R_5 and R_{10} = right and left triceps surae, and

$$\mathrm{SI} = \frac{\sum_i (\mathrm{RV}_i \mathrm{PRV}_i)}{|\mathrm{RV}||\mathrm{PRV}|} \qquad (2)$$

(i = 10 for ankle movements and i = 6 for hip-knee movements, i.e., R_4, R_5, R_9, and R_{10} are not included for the variety of possible motor strategy for these movements [12]).

Statistical Analysis

The reliability of magnitude and SI was assessed with ICCs [21], Pearson's correlation coefficients, and CVs calculated from a one-way ANOVA. To compare across tasks, we normalized magnitudes by the average values obtained in healthy subjects for each task [15] to account for the observed differences among these tasks. The short-term reliabilities for magnitude and SI were calculated with ICCs and an ANOVA. An AIS-C and AIS-D group comparison and flexion and extension motor tasks comparison were made with Pearson's correlation coefficients and CVs. To see the difference of magnitude and SI between original data and the data 1 week later, we compared each motor task for six subjects using Pearson's correlation coefficients and an ANOVA. The effect of tasks was also tested with ANOVA. Note that the SIs of 15 healthy subjects were not used for the reliability test because the data were used for the PRV. Instead, their reliability was checked by an alternate method, as described next.

We computed a set of alternate PRVs by excluding each healthy subject in turn; the values we obtained using this set of alternate prototypes did not change substantially (average and standard deviation of coefficient of the variation for 10 motor tasks: 0.4% ± 0.2%); thus, we computed SIs for the 15 healthy subjects using the original (15 subject) PRVs. To show the influence of one subject's absence to PRV, we calculated the norm and coefficient of variance of the PRV. A norm of 1.0 would indicate all responses showed the same proportion of muscle activity during a given motor task.

RESULTS

The average magnitude (expressed as a percentage of that obtained from healthy subjects) of 69 SCI subjects for 10 voluntary motor tasks was 79 ± 92 percent (48% ± 87% for AIS-C and 110% ± 87% for AIS-D), and SI, 0.67 ± 0.33 (0.54 ± 0.35 for AIS-C, 0.81 ± 0.23 for AIS-D). The average magnitude and SI of six SCI subjects who finished two tests 1 week apart for the 10 voluntary motor tasks were 38 ± 45 percent and 0.62 ± 0.30, respectively. The magnitude and SI values for the 15 healthy subjects whose data was used to construct the PRV were 86.5 ± 88.6 μV and 0.97 ± 0.02, respectively [15]. Alternate PRVs computed by excluding each healthy subject in turn for 10 voluntary motor tasks showed less than 1 percent of coefficient of variance for all norms of motor tasks. The norm of these alternate PRVs computed by excluding single healthy subjects ranged from 0.91 (right hip knee flexion) to 0.99 (right ankle dorsiflexion).

Short-Term Reliability

Three repetitions for each of 10 motor tasks were analyzed for repeatability with the use of ICCs (**Table**). Generally, the reliabilities of the two components of VRI,

Table.
Within-day intraclass correlation coefficient (ICC) of 10 voluntary motor tasks.

Motor Task	AIS-C (*n* = 34)		Diff (Mag-SI)	AIS-D (*n* = 35)		Diff (Mag-SI)	Totaled (*n* = 69)	
	Mag	SI		Mag	SI		Mag	SI
Bilateral Hip-Knee Flexion	0.91	0.80	0.11	0.93	0.91	0.02	0.94	0.88
Bilateral Hip-Knee Extension	0.87	0.73	0.14	0.71	0.94	–0.23	0.82	0.84
Right Hip-Knee Flexion	0.97	0.78	0.19	0.98	0.90	0.08	0.98	0.86
Right Hip-Knee Extension	0.95	0.74	0.21	0.90	0.93	–0.03	0.94	0.82
Left Hip-Knee Flexion	0.99	0.65	0.34	0.87	0.96	–0.09	0.94	0.80
Left Hip-Knee Extension	0.93	0.72	0.21	0.81	0.72	0.09	0.89	0.76
Right Ankle Dorsiflexion	0.89	0.78	0.11	0.96	0.93	0.03	0.97	0.87
Right Ankle Plantar Flexion	0.97	0.77	0.20	0.80	0.78	0.02	0.91	0.80
Left Ankle Dorsiflexion	0.77	0.84	–0.07	0.92	0.85	0.07	0.91	0.87
Left Ankle Plantar Flexion	0.98	0.78	0.20	0.91	0.73	0.18	0.95	0.77
Average	0.92	0.76	0.16	0.88	0.87	0.014	0.93	0.83

AIS-C and -D = American Spinal Injury Association Impairment Scale (Classifications C and D), Mag = magnitude, SI = similarity index, Diff = difference.

magnitude, and SI were good (ICC = 0.93 ± 0.05 for magnitude and ICC = 0.83 ± 0.04 for SI) for the 69 SCI subjects. The ICCs of magnitude were slightly larger than those of SI ($p < 0.01$). The magnitude of 15 healthy subjects showed good reliability (ICC = 0.90 ± 0.04).

The average CV for SIs of 10 motor tasks for the AIS-D group was better (CV = 0.11 ± 0.07) than that for AIS-C (CV = 2.25 ± 2.0). The average CV for the magnitude of 10 motor tasks for both groups were 0.32 ± 0.06 for AIS-C and 0.20 ± 0.05 for AIS-D. AIS-D group showed smaller CV values than AIS-C group ($p < 0.01$). Flexion movements (0.23 ± 0.23) showed lower CV values than extension movements (0.28 ± 0.27) for magnitude ($p < 0.05$).

Correlation analysis results showed a moderate to strong correlation for three repeated measures (r = 0.83 to 0.98 for magnitude and r = 0.77 to 0.88 for SI, $p < 0.05$ for both). The magnitude (r = 0.93 ± 0.04) showed stronger correlation than SI (r = 0.83 ± 0.04) overall. No group difference existed for AIS-C (r = 0.80 ± 0.08) and AIS-D (r = 0.87 ± 0.12) in the correlation analysis of SI. Flexion movements (r = 0.95 ± 0.03 for magnitude and r = 0.86 ± 0.03 SI) showed significantly higher correlation than extension movements ($p < 0.05$).

Intermediate-Term Reliability

Data recorded 1 week apart from six subjects for 10 motor tasks also showed fairly strong correlation for magnitude (r = 0.91, $p < 0.01$, **Figure 2**) and SI (r = 0.87, $p < 0.01$, **Figure 3**). Task effects were not significant.

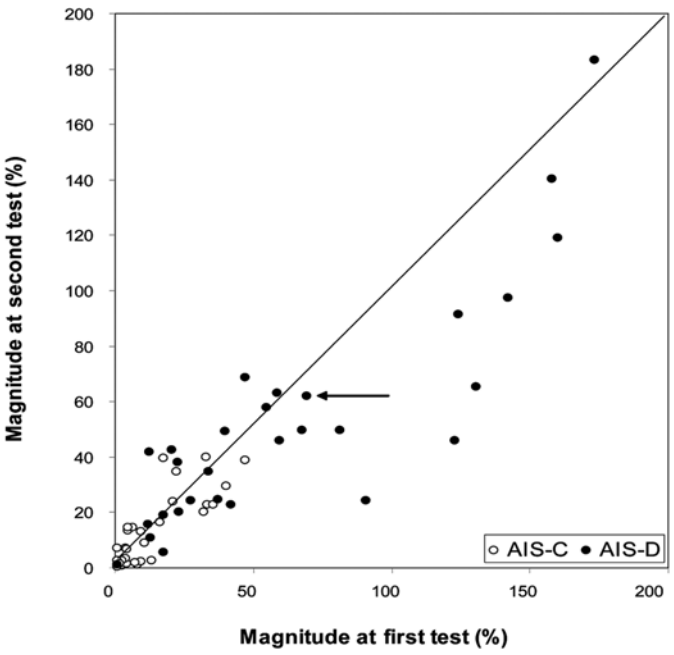


Figure 2.
Magnitude of 10 motor tasks from six patients in test-retest, 1 week apart, data set (n = 60) showed strong correlation (Pearson's correlation r = 0.91). Point identified by arrow is patient demonstrated in **Figure 1** and 45° line is for ease of readers' interpretation. AIS-C and -D = American Spinal Injury Association Impairment Scale, classifications C and D.

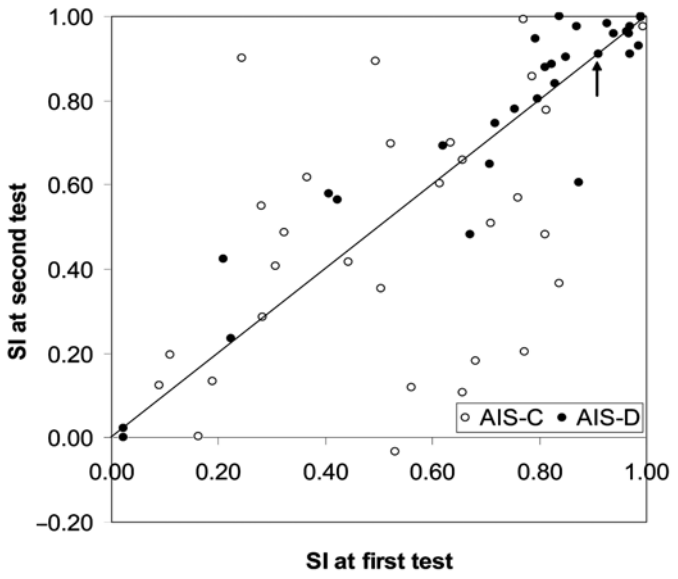


Figure 3.
Similarity index (SI) of 10 motor tasks from six patients in test-retest, 1 week apart, showed good correlation (Pearson's correlation $r = 0.87$). Point identified by arrow is patient demonstrated in **Figure 1** and 45° line is for ease of readers' interpretation. AIS-C and -D = American Spinal Injury Association Impairment Scale, classifications C and D.

DISCUSSION

EMG studies regarding reliability include such terminology as reproducibility, repeatability, and consistency [3], but these terms need to be used separately, and only reliability is used in this study. In this study, sEMG measures of voluntary control in 69 subjects with SCI and 15 healthy subjects were tested for reliability, and results showed good to excellent reliability for both short- and intermediate-term results. The ICC of magnitude was higher than that of SI within the whole patient group and within the ASIA-C group. However, CVs of magnitude and SI for 10 motor tasks were less in the AIS-D group than in the AIS-C group. The fact that the magnitude CV for AIS-C subjects was higher is undoubtedly a "floor" effect of the low magnitudes observed in these subjects, as can be seen in **Figure 2**. The very high reliability of the SI for healthy subjects represents a "ceiling" effect, in that the values all lie above 0.8. This suggests that the method, while well distinguishing subjects with severely compromised motor function from those with less severe loss, would not be appropriate for assessing small changes in persons with intact CNSs. In the future, those small changes will be elucidated by the addition of dimensions examining the temporal elements of motor control (activation sequence, rise time, etc.), thereby building on the foundation provided by the VRI.

Although the number of subjects was small, a similar pattern of reliability among these subjects was also observed over intermediate times. This observation is consistent with the results obtained for the voluntary and involuntary portions of the BMCA protocol [19]. In that study, responses in 52 subjects evaluated 1 week to 2 weeks apart were compared and found to be quite repeatable. Thus, one can reasonably assume that the small number of subjects reported here represent what could be expected in general.

Two primary factors may account for the excellent reliability seen in this study: one is the method used in the data analysis, i.e., VRI, and the other one is the protocol, BMCA, that is strictly controlled and standardized. The reliability of the RMS sEMG is not a new method. However, the main difference here is that VRI considers activity in 10 muscles that are involved for a certain task, and other studies considered only one muscle at a time. A given motion may be achieved using only one or two muscles, but other muscles surrounding the joint or segment of the body must be appropriately controlled even though their activity levels are comparatively low. The relative activity among muscles used for the activity might be changed by the strategies selected and competing human performance resources like speed and accuracy [22]. Showing reliability even over the short-term for subjects with an SCI is important because their motor control ability is limited, is easily fatigued, and may include involuntary control. Thus, the reported high reliability suggests that the subjects used consistent strategies that were not substantively affected by fatigue or other confounds.

Functional Coordination and Reliability

To date, we found no studies that reported the reliability of muscles' coordination during specific tasks. This is not surprising, considering that we found only two papers regarding quantitative evaluation of the coordinating ability of subjects, including patients with damaged CNS [12,23]. This is likely because most research has focused on a specific muscle or muscles that are well controlled by an intact CNS. However, some fundamental studies regarding the coordination have been initiated already for the cocontraction evaluation of muscles between agonist and antagonist [8,24–26] and for functional electrical

stimulation [27–28]. In addition, the role of the spinal cord pattern generator [29] is now being considered in humans as well [30–31]. However, patterns that are designed to control the terminal muscles to achieve a certain motor task have not yet been quantitatively studied, and the excellent reliability in this study suggests that it is time to initiate such studies for the various patterns generated by the CNS, including the spinal cord.

Test-Retest Reliability

Test-retest reliability has traditionally been analyzed with Pearson's product-moment coefficient of correlation [32]. However, as Pearson's correlation coefficients have the limitation of dealing with the strength of the association only [2,33], the ICC has become the preferred index [2–4,6–7,9–10,34–37]. Reliability measures are often obtained only for healthy subjects. Our search of the literature did not reveal any papers dealing with reliability of sEMG tests in patients. In healthy subjects, the quantities being measured are often narrowly distributed. This is thus a "worst-case test" of reliability for a given measure, because comparatively smaller between-subjects mean square of healthy subjects may result in smaller reliability coefficient. In patient populations, the same parameters are generally more broadly distributed (e.g., large CVs, as reported here). In such cases, getting "excellent reliability" results is generally easier, since intraindividual variability is generally much less than interindividual variability. This is important to note so that a particular measure is not rejected as being "not reliable" when it is tested only with healthy subjects—a worst-case test—when, in fact, the measure is intended to be used (clinically or in research) with subjects exhibiting a wide range of the parameter in question.

Limitation of This Study

Regardless of the current results showing good to excellent reliability for these studies conducted by well-trained technologists using a protocol (BMCA) with demonstrated reliability [19] and sensitivity to clinical condition [20], two things could affect the reliability of sEMG. We retested a subject 1 week later and a small scar caused by the skin preparation was still present, so the electrode might have been placed anywhere from a few millimeters to a centimeter from the original site. Other investigators have reported a marked change in the level of recorded muscle activity could occur with even small changes in location of bar electrodes, 1 mm wide [38], particularly if they are located near the innervation zone [39]. The fact that the prior studies showed satisfactory repeatability [19] suggests that these factors have not played a major role in the results of this protocol. Electrode location factors do not impact the short-term reliability, since the electrodes were not removed; rather, we sought to understand only the "biological variability" in the system.

CONCLUSION

The current study found good to excellent short- and intermediate-term reliability of sEMG from SCI subjects during 10 voluntary motor tasks. This result provides further evidence of the potential use of sEMG and VRI for the evaluation of CNS motor control in those situations in which an objective repeatable measure is needed, such as in treatments intended to improve such control.

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