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Chapter 12

Emerging Techniques for Assessment of Sensorimotor Impairments after Spinal Cord Injury

Filipe Barroso, Diego Torricelli and Juan C. Moreno

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Abstract

Gait function can be altered after incomplete spinal cord (iSCI) lesions. Muscular weakness, co-activation of antagonist muscles, and altered muscle mechanics are likely to provoke abnormal gait and postural movements. Functional scales are available for assessment of functional walking in SCI patients, such as walking index for spinal cord injury (WISCI II), timed up and go (TUG) test, 10-meter walk test (10MWT), and 6-minute walk test (6MWT). Novel metrics for a more detailed comprehension of neuromuscular control in terms of degree of voluntary motor control have been recently proposed. This section describes novel techniques based on muscle synergy and frequency domain analysis of electromyographic signals. Such techniques are illustrated as potential tools for assessment of motor function after SCI with experimental data and a case study describing a diagnostic scenario. This chapter presents a discussion of the current status of the emerging metrics for assessment of sensorimotor impairments. Conclusions are given with respect to the availability of enriched information about neuromuscular behavior between functional tasks (walking and pedalling) and the potential relevance of these new techniques to improve the efficacy of treatment to improve locomotion after iSCI.

Keywords: Rehabilitation, spinal cord injury, walking, functional scales

1. Introduction

Gait function can be altered after incomplete spinal cord (iSCI) lesions. Muscular weakness, co-activation of antagonist muscles, and altered muscle mechanics are likely to provoke abnormal gait and postural movements. Human walking involves the coordination of several muscles and its correct activation. One of the main goals of treatment after SCI is to recover the ability

to walk again. The assessment of the neurorehabilitation process has traditionally been done based on the qualitative methods (classic clinical scales) or subjective assessment from physiotherapists (based on clinical gaze) [1]. Traditional techniques are prone to low reliability and, as a consequence, may result in inadequate or costly interventions. More importantly, clinical tests focused on behavioral outcomes provide little information about the underlying differences between healthy and impaired nervous system [1]. It is becoming more and more clear that a more profound understanding of impairments may be crucial not only to prescribe effective treatments to individual patients but also to gather comparative results and evidence that are needed to develop novel therapies. Thus, motor neurorehabilitation should be informed by more reliable and repeatable metrics that allow a quantitative assessment of motor control performance and recovery.

Gait analysis is broadly known as means to adequately assess and follow-up patients and supports a clinical decision on the best treatment [2]. Clinical gait analysis involves a variety of techniques including kinematic or joint motion measurements; kinetic or joint torque assessment, electromyographic (EMG) measurements, and video analysis. Measures derived from gait analysis provide a detailed and quantitative description. This might further be used to extract important information to select a task-oriented approach that might enhance therapeutic response, which cannot be provided by clinical evaluation alone [2]. Instrumented clinical gait analysis, despite its objectivity, is not straightforward in practice. Thus, more concise indexes of gait function are to be developed to assess the changes in gait function over time and evaluate interventions.

Most widely used functional scales for gait rehabilitation in SCI patients are walking index for spinal cord injury (WISCI II), timed up and go (TUG) test, 10-meter walk test (10MWT), and 6-minute walk test (6MWT). As mentioned above, to achieve adequate treatment, it is crucial to investigate not only the functional effect but also the mechanisms underlying the impaired function. Recently, the use of quantitative metrics based on electromyography and biomechanical features is bringing a new insight into the motor recovery mechanisms and performance outcomes after neural damage. EMG features provide useful information concerning brain motor control strategies [3]. Muscle activation patterns and muscle synergies have been proposed as a potential technique to measure motor recovery following therapeutic interventions [4]. Muscle synergies, understood as groups of co-activated muscles that are responsible for task execution in different conditions, can explain the way that central nervous system (CNS) solves control of multiple muscles and degrees of freedom by means of a smaller number of neural parameters [5]. This brings a more comprehensive understanding of the underlying motor strategies responsible for impaired locomotion.

The aim of this chapter is to present the emerging indexes based on EMG and biomechanical data to support therapeutic interventions in SCI patients who are commonly affected with spastic paresis and require targeted relearning and activation of a residual motor function. Novel metrics based on computational methods, such as muscle coherence and muscle synergy analysis, are presented as tools for a more detailed comprehension of neuromuscular control in terms of degree of voluntary motor control. Conclusions are given with respect to the availability of enriched information about neuromuscular behavior between functional tasks

(walking and pedalling) and the potential relevance of these new techniques to improve the efficacy of treatment to improve locomotion after iSCI.

2. Sensorimotor impairments after SCI

The spinal lesion leads to sensorimotor impairments in both upper and lower extremities. Ambulation results limited due to the sensory and proprioceptive impairments and muscle spasticity, commonly found even in subjects that reach a sufficient level of ambulation. The mechanisms involved in muscle spasticity are related to the lesion in the CNS that leads to changes in the excitability of spinal reflexes and loss of supraspinal drive. This results in abnormal muscle function and leads to altered mechanical muscle properties. In addition to this, proprioceptive and sensory impairment lead to altered or loss afferent feedback to the CNS, which in turn progressively affects motor control and leads to unstable, non-physiological gait. In particular, symptoms such as muscular weakness, co-activation of antagonist muscles, and altered muscle mechanics provoke abnormal gait and postural movements.

The relationship between hypertonia and gait function is still not clear controversial [6]. The difficulty to classify iSCI subjects as spastic or not is a well-known problem [7]. Spasticity in SCI patients is mostly associated (clinically) with the presence of flexor and extensor spasms triggered by cutaneous stimulation. In practice, it is important to determine whether an impaired gait is mainly caused by disabling paresis but also altered afferent feedback to the CNS. Novel metrics to assess motor control based on detailed EMG analysis are required to complement and optimize interventions that focus on the clinical signs of spasticity, such as exaggerated reflexes and muscle tone (e.g., medication).

3. Clinical assessment of walking ability after SCI

The main goal of clinical assessments is to quantify the motor recovery by observing and measuring the functional changes that occur in the patient after the injury. This is normally done by scales, which quantify the patient's residual functions under a wide spectrum, and therefore support scientifically the clinical practice in making effective choice on the treatment, studying cost-benefit of the rehabilitation process and quantifying objectively the degree of incapacity or handicap. Nevertheless, the sensitivity and reliability of current scales are still limited. For instance, the score assignment still relies on a strong subjective component, which causes high intra and inter-rater variability, even when the scale is carried out by experienced examiners [8]. In addition, scales often have similar content and purpose, which makes difficult to decide which of the available tests are superior and should be used as outcome measures. Therefore, there is a need to incorporate new and more objective methods to assess of motor recovery into the existing panorama. In the following, we present and briefly describe the main measures used in clinical settings to evaluate the functional recovery after SCI.

3.1. ASIA impairment scale (AIS)

This scale [9] provides a correct assessment of the severity of the SCI and can assess the developmental stage of the lesion. The evaluation is mainly based on motor exploration and includes complementary tests for sensory and muscle assessment. Ten muscles are evaluated (covering upper and lower limbs) to get muscle balance score between 0 and 5. The sensory examination measures superficial and deep sensitivity on a scale of 0–2 in 28 sensitive key points (for example, the big toe to C6 or armpit for L2). The sum of the motor and sensory scores reflects the global degree of impairment. According to international standards established by the American Association of SCI AIS, this can be classified into five levels, ranging between complete lesion (A, sensory but not motor function is preserved below the neurological level and includes the sacral segments S4–S5) and normality (E, the sensorimotor functions are completely preserved).

3.2. Walking index for spinal cord injury (WISCI II)

This index [10] specifically measures the functionality of walking and aims to quantify the secondary physical limitations in SCI. A recent study on functional measures of gait in people with SCI [11] showed how previous scales (e.g., 10 m and timed up and go, TUG) were unable to discriminate the improvement in function of patients who needed assistive devices during walking, such as walker or crutches. These data suggest that the WISCII scale serves as a valid tool for measuring changes in locomotion and effectiveness of treatment after SCI when technical help or the assistance of an external person is required to realize gait function. The scoring method is based on visual observation of the patient's ability during walking over at least 10 m. Walking ability is classified in this index, from the level with the most severe disabilities (0), to less severe disability (20). Within this range, the patient is classified according to the use of devices, braces, and physical assistance of one or two people.

3.3. Timed up and go (TUG) test

Originally developed to study the balance in senior age [12], this test demonstrated its validity as a measure of walking performance in neurologically injured subjects [13]. This tool measures the time (in seconds) that patients take to get up from a chair, walk 3 m, and sit back. Walk 3 m is the traditional test TUG, but there are adaptations in which the patient has to walk 10 or 7 m. The score ranges from one (normal) to five points (very abnormal). Times above 20 s are predictors of falls. This test captures the complex interaction between balance and movement, including planning, initiation, and implementation, and completes a series of linked movements that are common in activities of daily living. The validity of the TUG has been studied in different works and found to have a sensitivity and specificity of 87%.

3.4. 10-meter walk test (10MWT)

This test quantifies the walking speed by measuring the time (in seconds) that the patient takes to travel a distance of 10 m [13]. This scale was firstly proposed to assess gait in patients with stroke and Parkinson's disease, and then transferred as an alternative to evaluate patients with

SCI. A study [14] comparing several clinical scales of motion concluded that 10MWT is a more reliable and easier handling tool than the test of 6-minute walk test (see next section). As a drawback, this test requires additional information on technical aids needed during walking.

3.5. 6-minute walk test (6MWT)

This test calculates the distance (in meters) that patients are able to walk in six minutes [15]. Initially, it was used to measure cardiovascular exercise capacity in elderly patients with heart or lung disease, as a submaximal test of the aerobic capacity of the individual. It is one of the most widely used tests to evaluate gait motor recovery in neurologically injured subjects [16].

3.6. Spinal cord (functional) independence measures (FIM and SCIM)

The functional independence measure (FIM) scale was originally developed to assess disability of individuals with stroke [17]. This tool has been then widely applied for the evaluation of the functionality in the SCI. It is a standard and validated scale studying the state of functional recovery of patients from hospital admission to discharge. It is also used globally to monitor the progress of the functionality of patients throughout the rehabilitation treatment. It measures 18 activities, of which 13 items refer to the motor area and five to the cognitive status. These 18 items are grouped into six blocks: self-care, sphincter control, transfers, locomotion, communication, and awareness of the external world. It includes seven levels ranging from total dependence to full independence [18,19].

The SCIM scale was developed specifically to improve some aspects of the FIM scale [13]. This scale consists of 16 items (score range 0–100) and includes three levels of activity: (1) self-care (feeding, grooming, bathing, and dressing), (2) respiration and sphincter management, and (3) mobility (bed and transfers and indoor/outdoor). Scores are obtained by adding up the individual items. The item scores are weighted related to the assumed clinical relevance.

4. Scales to assess clinical conditions of spasticity

The correct measurement of spasticity is of vital importance in SCI for three main reasons: (i) evaluating the effectiveness of anti-spasticity treatments, (ii) optimizing individually the amount of antispastic medication to patients, and (iii) understanding the pathophysiological mechanisms underlying this disorder [20]. However, although spasticity is usually easy to recognize, its quantification is a much more complex process [21]. A unique scale that can provide a general and objective assessment of spasticity is still not available in the literature; therefore, the various tests and clinical measures are usually combined in order to evaluate different aspects of spasticity. The existing clinical measurements include scales that measure muscle hypertonia (modified Ashworth scale (MAS), EAM) [22], the spasms often suffered by patients (frequency spasms scale Penn) [23], and the reflected hyperexcitability after SCI (scale of severity of spasms (SCATS) [24]. In the following sections, these three methods will be briefly described.

4.1. Modified Ashworth scale (MAS)

This scale measures the resistance of muscle to passive stretching [22]. The resistance value is scored between 0 and 4, being "0" the absence of any increase in tone during movement; "1" slight increase in tone and muscle response at the start of movement or increased resistance at the end of the movement; "1+" slight increase in muscle resistance movement followed by minimal resistance throughout the remainder of the range of motion; "2" significant increase in muscle endurance during most arc joint movement, but the joint moves easily; "3" marked increase in muscle strength or passive movement is difficult in flexion or extension; and "4" the affected joints are rigid in flexion or extension. Two physiotherapists should perform this test independently.

4.2. Penn spasm frequency scale (PSFS)

The PENN scale is a tool to quantify spasm frequency suffered by the patient during the 24 h prior to the test [25]. The scores on this scale are between 0 and 4, where "0" is the total absence of spasms, "1" spasms caused only by stimulation, "2" spasms that occur less than once every hour, "3" spasms occur more than once every hour, and "4" spasms that occur more than 10 times an hour. As for the MAS scale, two physiotherapists should perform this test independently.

4.3. Spinal cord assessment tool for spastic reflexes (SCATS)

This scale is a physiologically based measure for spastic reflexes for use in individuals with SCI. It measures the reflected hyperexcitability, which includes clonus, flexor spasms, and cramps in the extensors. This scale is developed to provide a measure of primary spastic reaction, addressing categories of spasms as follows: (1) clonus, (2) flexor spasms, and (3) extensor spasms. The spasm is triggered and rated with a score ranging from 0 to 3. The SCATS does not provide information on patient perspective, which is an important aspect since spasms are sometimes perceived beneficial to the patient. This tool is simple and quick (<5 s) to administer but despite its simplicity it has not been widely accepted yet. The measure could be conducted during a home visit or at a clinic/hospital. A study [24] evaluated the validity of this scale, demonstrating that it correlated significantly with kinematic and electromyographic measures, and with Ashworth scores.

5. Emerging metrics to assess sensorimotor impairments after spinal cord injury

Despite its ability to assess and provide information about underlying mechanisms and changes in motor control, electromyography (EMG) is still rarely employed in the clinical setting to assess SCI patients [26]. Thus, novel approaches using EMG should be explored, as EMG can be very valuable to understand compensatory strategies and for further rehabilitation processes.

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This section describes novel techniques based on muscle synergies and frequency-domain analysis of EMG signals (muscle coherence). Such techniques are illustrated as potential tools for assessment of motor function after SCI with experimental data and a case study describing a diagnostic scenario.

5.1. EMG coherence

Neurophysiological studies demonstrate only limited spontaneous recovery of voluntary motor function after incomplete SCI diagnosed with the American Spinal Injury Association (ASIA) Impairment Scale (AIS) [9,27]. Thus, there is a clinical need to identify new comprehensive outcome measures that may be used to assess sensorimotor impairments after incomplete SCI (iSCI). Effective neurophysiological measures should have clinical relevance, reflecting the recovery of volunteer motor force and gait function, as well as the development of maladaptive motor plasticity, such as the spasticity syndrome, which is known to limit the recovery of voluntary motor strength, gait, and daily life activities following SCI [28–34]. These measures may facilitate clinical diagnosis and guidance of individualized neurorehabilitation programs.

5.1.1. Muscle coherence

Lower limb EMG coherence analysis has been used as an indirect measure of voluntary motor control, gait function [35], and spasticity [27] after iSCI. This is a frequency-domain measure of the similarity between two independent EMG signals, having the potential to assess the descending motor drive [36]. The fact that it just needs EMG recording to be calculated makes it suitable for clinical applications. On the other hand, muscle coherence activity estimation can be obtained from the same muscle (intramuscular coherence) [37,38], as well as between two different muscles (intermuscular coherence) [38–40].

Smith et al. [41] have shown that the synchronization of motoneuron discharges (coherence) was reduced after spinal cord injury and also that it could be better recorded during isometric muscle contractions. The analysis of muscle coherence has been used to diagnose lesions in voluntary motor control mechanisms and functionality of SCI patients, for example, gait control [37,38]. Several studies support the use of muscle coherence analysis as an indirect measure of the common descending tracts during the execution of specific motor tasks. For instance, it has been suggested the existence of an association between the force of a maximum isometric contraction and corticospinal activity, based on the evidence of a reduction of intracortical inhibition modulated by training muscle strength [42–45]. Despite the potential of this technique, few studies have investigated which type of movement would be optimal for the use of muscle coherence calculation as a greater diagnostic measure.

Measuring the residual activity of tibialis anterior may represent an interesting diagnostic measure of functionality after SCI, mainly because this muscle receives increased innervation from the corticospinal system [45]. In fact, ankle dorsiflexion movement has been used as an indirect measure of adaptive neuroplasticity during the rehabilitation phase [46], while the

recording of tibialis anterior co-activation during plantarflexion may be also used as indicator of maladaptive mechanisms after SCI, such as spasticity or its associated symptoms [47].

5.1.2. An emerging methodology to assess muscle coherence

This section sums up the methodology and main results presented by [27], who analyzed intramuscular TA coherence within specific frequency bands between 10–60 Hz from subjects who suffered an iSCI, while they performed different movement tasks.

Muscle coherence between two TA EMG signals (intramuscular coherence) was calculated during the periods of activation of this muscle during controlled ankle dorsiflexion movements. Specifically, EMG was recorded during the following ankle dorsiflexion tasks: (I) isometric activation at 50, 75, and 100% of maximal voluntary torque (MVT), (II) isokinetic activation at 60 and 120°/s and III) isotonic dorsiflexion at 50% MVT. Periods of activation were visually determined after processing EMG signals. This analysis of EMGs started with demeaning of raw signals, followed by band-pass filtering (3–700 Hz) and rectification.

Muscle coherence was computed using the function "mscohere" of Matlab (Version 7.11). The output of this function is the magnitude-squared coherence estimate of the input signals (both TA signals), using Welch's averaged modified periodogram method [48]. Finally, four bandwidths were analyzed: 10–16, 15–30, 24–40, and 40–60 Hz. For each band, it was computed the mean magnitude squared coherence estimate. A non-significant higher level of coherence activity was identified within the 10–16 Hz band in the iSCI spasticity group, when comparing the isometric activation at 100% of MVT for subjects diagnosed without or with spasticity. For the other bands of frequency, no differences were identified for TA intramuscular coherence [27].

There was also a negative correlation between the TA muscle coherence measured during isometric activation at 100% of MVT and specific symptoms of SCI spasticity muscle hypertonia, passive resistive torque, and involuntary muscle contractions. The modified Ashworth scores correlated negatively with TA coherence within the 24–60 Hz frequency band. The severity spasms measured with the SCATS scale also presented a negative correlation the 40–60 Hz band. On the other hand, a positive correlation was found between the Penn score and the TA coherence for the 15–30 Hz band. A positive correlation was also identified between the degree of clonus activity and TA coherence within the 10–16 Hz bandwidth [27].

TA coherence calculated as the ratio of 120/60°/s isokinetic activation was higher in the iSCI spastic subgroup, when compared with the non-spastic group [27]. In summary, the results presented by Bravo-Esteban et al. [27] suggest that TA muscle coherence activity estimation during the execution of controlled ankle dorsiflexion movements may be used to assess the level of spasticity in iSCI patients.

5.2. Analysis of muscle synergies during cycling

Given the redundancy of the musculoskeletal system, a long-stand idea is that the central nervous system (CNS) controls muscle activation through the use of a synergistic organiza-

tion constituted by basic control elements called synergies (or motor modules) [49–51]. In 1967, Nikolai Bernstein [52] proposed the existence of muscle synergies as a simplified strategy of motor control. Muscle synergies are functional sets of muscles, co-activated by varying their timing and/or neural drive. This synergistic control is thought to underlie the execution of different biomechanical tasks [53].

Muscle synergies may offer new insight into the underlying motor strategies responsible for impaired locomotion [1]. Thus, muscle synergies have been proposed as a potential technique to measure motor recovery [4]. Nevertheless, it is still difficult to assess or predict motor performance in those patients who lack the required muscle strength to walk during the early stage of the rehabilitation, even with some body weight supports. Given the similarities in kinematics and muscle control with walking [54], cycling may be explored as a novel framework to assess motor performance in iSCI patients.

5.2.1. Comparison of two iSCI patients

Based on the findings presented in our previous research [3], confirming the hypothesis that similar synergistic features are shared between walking and cycling, we further performed a research testing the hypothesis that muscle synergies outcomes extracted during cycling can be used as indicators of gait performance in iSCI patients. Preliminary results of two patients are presented in this section.

5.2.1.1. Subjects

Two iSCI patients gave their written consent to participate in this study and for data publication, after being informed about the procedures and possible discomfort associated with the experiments, in accordance with the Declaration of Helsinki. The local Toledo Paraplegics Hospital (Spain) Clinical Ethical Committee approved this study (07/05/2013 N°47).

Patient ID	Age (years)	Gender	Time post-SCI (months)	Level of lesion	Most affected side	AIS	WISCI II	TUG (s)	10-meter (s)
01	25	M	5	T4	Left	D	15	29.3	27.7
02	77	M	13	C7	Right	D	19	25.1	10.2

M, male; F, female; Level of lesion: C—Cervical, T—Thoracic; AIS, American Spinal Injury Association (ASIA) Impairment Scale. WISCI II, walking index for spinal cord injury; TUG, timed up and go.

Table 1. Individual iSCI patients' description, as well as the amount of physical assistance needed and gait performance.

Detailed information of the patients is presented in **Table 1**. Both patients received the standard rehabilitation program of the hospital. Inclusion criteria were as follows: aged between 18 and 80 years; motor incomplete spinal lesion (AIS C-D) of traumatic and non-traumatic etiology, with a prognosis of recovery of the walking function; evolution of at least 1.5 months. Exclusion criteria were as follows: supraspinal or peripheral neurological involvement; history

of epilepsy; musculoskeletal involvement of lower limbs or spasticity higher than 3 (measured with the Modified Ashworth Scale) for each joint, either for extension or flexion.

5.2.1.2. Experimental protocol

Prior to the experiment, a trained physiotherapist performed a set of clinical evaluations in order to inform about the functional status of the patients. The gait performance was evaluated using the timed up and go (TUG) test [55] and the 10-meter test [56]. In order to quantify the amount of assistance required by the subjects (10 m walk), the walking index for spinal cord injury (WISCI II) was applied. This is a 21-point scale that ranges from 0 (patient unable to stand and/or participate in assisted walking) to 20 (patient ambulates 10 m with no devices, no braces and no physical assistance) [10].

On the day of the experiment, patients received their standard rehabilitation therapy in the morning. In the afternoon, each iSCI patient performed four cycling trials (at 30, 42, 50, and 60 rpm, revolutions per minute) of 30 s duration each, with 60 s resting between trials. These trials were performed on an electronically braked cycle ergometer (MOTOmed viva2, Reck, Betzenweiler, Germany) in the passive mode. For each patient, the order of the trials was randomized to avoid biased results. Patients were asked to perform the experiment while sat on a regular chair.

An auditory metronome was used in order to synchronize patients' cycling frequency with the desired cadence. An EMG amplifier (EMG-USB, OT Bioelettronica, Torino, Italy) with recording bandwidth of 10–750 Hz, overall gain of 1000 V/V, and acquisition frequency of 2048 Hz was used to record surface electromyography (sEMG) of 13 muscles of the most affected leg of patients. The recorded muscles were as follows: Gluteus Medius, Adductor Longus, Sartorius, Tibialis Anterior, Rectus Femoris, Tensor Fascia Latae, Vastus Lateralis, Vastus Medialis, Biceps Femoris, Semitendinosus, Soleus, Gastrocnemius Lateralis, and Gastrocnemius Medialis. The most affected side was determined based on the muscle score [57] of quadriceps, hamstrings, TA, and gastrocnemius for both limbs.

Bipolar sEMG electrodes (Ag-AgCl, Ambur Neuroline 720, Ambu, Ballerup, Denmark) were fastened with a 2-cm inter-electrode distance on each recorded muscle, following SENIAM recommendations for sEMG recording procedures [58]. One angular sensor (Vishay, Malvern, PA) was applied to estimate the crank angle at a sampling frequency of 100 Hz. Segmentation of pedaling cycles was then performed based on the bottom dead center (BDC) position of the pedal.

5.2.1.3. Muscle synergies analysis

For each patient and trial, 10 continuous pedaling cycles were selected for analysis. The selected raw EMG signals were pre-processed using high-pass filtering at 20 Hz, demeaning, rectification, and low-pass filtering at 5 Hz, resulting in the EMG envelopes [49,59]. Muscle synergies were extracted using a Non-Negative Matrix Factorization (NNMF) algorithm [60]. A detailed explanation of the procedure to extract muscles synergies is presented in [49] and [3]. For each trial, the NNMF algorithm was run four times, considering as input two to five

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synergies. In order to avoid local minima, for each run, the NNMF was repeated 40 times and the repetition with the lowest reconstruction error was selected.

To assess whether the recorded EMGs were well described as a combination of the identified synergies, two indicators of the quality of reconstruction of the EMG data were used: the *variability accounted for* (VAF_{total}) [49] and the *coefficient of determination* (r^2) [61]. Both VAF_{total} and r^2 have been adopted in most studies on muscle synergies [49,61]. VAF_{total} has been suggested to be more stringent than r^2, since it is sensitive to both shape and amplitude of the signals, whereas r^2 only addresses similarity in shape.

5.2.1.4. Results

Patient 02 presented better motor performance than patient 01. In the case of WISCI II, patient 01 scored 15 points, whereas patient 02 score 19 points. Patient 01 needed 19.3 s to perform TUG test, whereas patient 02 needed 25.1 s to perform the same test. Patient 01 needed 27.7 to perform the 10-meter test, whereas patient 02 just needed 10.2 s to perform the same test.

As a general trend, patient 02 presented higher values of VAF_{total} and r^2 than patient 01, for all speeds and number of synergies. Also, the higher the number of synergies used to reconstruct EMG data, the better the data were reconstructed (higher VAF_{total} and r^2 values). Both patients reached their minimum values of VAF_{total} at 50 rpm, using two synergies to reconstruct EMG data. VAF_{total} values in such condition were 79% (**Figure 1A**) for patient 01 and 76% (**Figure 1B**) for patient 02. Patient 01 reached 92% as maximum VAF_{total} value. This value was observed when using five synergies at 60 rpm. For patient 02, a maximum VAF_{total} of 95% was reached when using five synergies at 42 rpm.

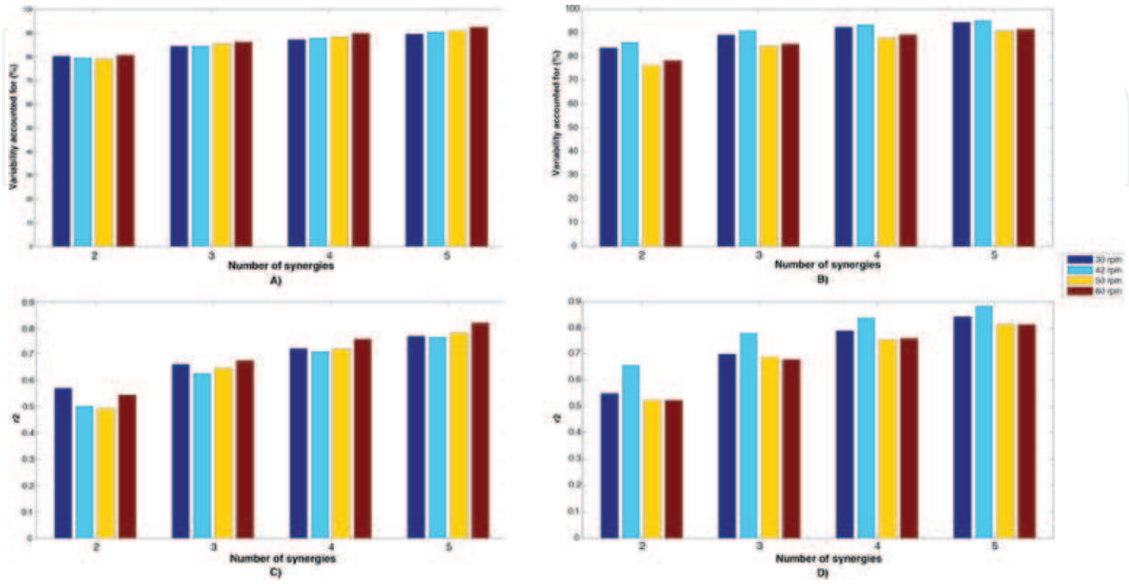

Figure 1. Variability accounted for (VAF_{total}) for patient 01 (A) and patient 02 (B), as well as coefficient of determination (r^2) for patient 01 (C) and patient 02 (D), according to the number of synergies, for each of the four speeds (30, 42, 50, and 60 rpm).

In the case of r^2 values, a minimum of 0.49 (**Figure 1C**) and 0.52 (**Figure 1D**) were obtained for patient 01 (at 50 rpm) and patient 02 (at 60 rpm), respectively. Both values were obtained using two synergies. On the other hand, maximum r^2 values of 0.82 and 0.89 were obtained for patient 01 (at 60 rpm) and patient 02 (at 42 rpm), respectively. Both values were obtained using five synergies. The quality of reconstruction indicators seems to correlate positively with WISCI II scores, that is, patient 02 presented higher values of VAF_{total} and r^2 and also higher values of WISCI II. On the other hand, quality of reconstruction indicators seem to correlate negatively with TUG and 10-meter tests, that is, patient 02 presented higher values of VAF_{total} and r^2 and also needed less time to perform these two gait performance tests.

5.2.1.5. Discussion

Based on the observed common muscle synergies between cycling and walking [3], this preliminary study tested the hypothesis that the analysis of muscle synergies during cycling correlates with gait performance scales in iSCI patients. These preliminary results corroborate this hypothesis.

Results showed positive correlations between WISCI II and EMG reconstruction goodness scores (VAFtotal and r^2) when recording a set of 13 muscles of the most affected leg. In the case of gait speed tests, reconstruction goodness scores correlated negatively with TUG and 10-meter tests. Our results are in agreement with the fact that patients with lower amount of required assistance and good walking performance present higher signal-to-noise ratio in EMG signals than patients with poor walking performance, as severely impaired subjects usually present reduced signal-to-noise ratio in the EMG signals due to reduced signal strength [60]. As a consequence of lower signal-to-noise, lower VAF_{total}, and r^2 values are expected [5].

6. Conclusions

Recovery after SCI is greatly dependent on the severity of the injury as well as the treatment provided in each phase of the lesion, being the subacute phase (up to approximately 6 months) the best phase to promote plastic changes in the CNS. Functional Improvements such as the increase of gait speed increased recovered distance or better WISCI II scores have been observed in acute SCI patients if compared to chronic SCI patients [62].

The application of simple diagnostic measures that might provide comprehensive information regarding the state of adaptive and maladaptive motor control mechanisms after SCI could play a crucial role in guiding rehabilitation strategies in the clinic. Neurophysiological measures should be preferred over qualitative clinical measures, as they are more independent, provide objective data and can be performed in less cooperative patients [63]. However,

standardization and clinical validation should be achieved to allow for wide use in the clinical setting.

The analysis of muscle synergies during cycling can be explored as a novel approach for the quantitative assessment of gait performance. This analysis can complement current assessment procedures. On the other hand, the analysis of intramuscular coherence of tibialis anterior can also be explored as a measure of spasticity during the subacute phase of recovery in SCI patients, as it provides information on the mechanisms of maladaptive plasticity (specifically spasticity) [27].

In the future, additional researches are needed in order to validate TA muscle coherence analysis and use it in the clinical setting for the assessment of sensorimotor impairments in SCI patients. Specifically, longitudinal studies have to be performed since the initial stage of recovery, comparing muscle coherence with clinical and functional scales. This will be also useful to provide new information on the neurophysiological mechanisms present during the recovery stage in SCI patients.This work has been partially funded by grant from the European Commission, within the Seventh Framework Programme (IFP7-ICT-2013-10-611695: BioMot - Smart Wearable Robots with Bioinspired Sensory-Motor Skills).

Author details

Filipe Barroso[1,2], Diego Torricelli[2] and Juan C. Moreno[2*]

*Address all correspondence to: jc.moreno@csic.es

1 Department of Physiology, Feinberg School of Medicine – Northwestern University, Chicago, IL, USA

2 Neural Rehabilitation Group, Cajal Institute, Spanish National Research Council (CSIC), Madrid, Spain

References

[1] SAFAVYNIA, S. A.; TORRES-OVIEDO, G.; TING, L. H. Muscle synergies: implications for clinical evaluation and rehabilitation of movement. Top Spinal Cord Inj Rehabil, v. 17, n. 1, p. 16-24, 2011.

[2] NADEAU, S. et al. Guiding task-oriented gait training after stroke or spinal cord injury by means of a biomechanical gait analysis. Progress in Brain Research, v. 192, p. 161-180, 2011.

[3] BARROSO, F. O. et al. Shared muscle synergies in human walking and cycling. Journal of Neurophysiology, v. 112, n. 8, p. 1984-1998, 2014.

[4] ROUTSON, R. L. et al. The influence of locomotor rehabilitation on module quality and post-stroke hemiparetic walking performance. Gait Posture, v. 38, n. 3, p. 511-517, 2013.

[5] STEELE, K. M.; TRESCH, M.; PERREAULT, E. The number and choice of muscles impact the results of muscle synergy analyses. Front Comput Neurosci, v. 7, 2013.

[6] DUFFELL, L. D.; BROWN, G. L.; MIRBAGHERI, M. M. Facilitatory effects of anti-spastic medication on robotic locomotor training in people with chronic incomplete spinal cord injury. J Neuroeng Rehabil, v. 12, n. 29.

[7] REICHENFELSER, W. et al. Monitoring of spasticity and functional ability in individuals with incomplete spinal cord injury with a functional electrical stimulation cycling system. J Rehabil Med, v. 44, n. 5, p. 444-449, 2012.

[8] SAVIC, G. et al. Inter-rater reliability of motor and sensory examinations performed according to American Spinal Injury Association standards. Spinal Cord, v. 45, p. 444-451, 2007.

[9] MAYNARD, F. M. J. et al. International standards for neurological and functional classification of spinal cord injury. American Spinal Injury Association. Spinal Cord, v. 35, n. 5, p. 266-274, 1997.

[10] DITTUNO, P. L.; DITUNNO, J. F. Walking index for spinal cord injury (WISCI II): scale revision. Spinal Cord, v. 39, n. 12, p. 654-656, 2001.

[11] SAENSOOK, W. et al. Discriminative ability of the three functional tests in independent ambulatory patients with spinal cord injury who walked with and without ambulatory assistive devices. J Spinal Cord Med, v. 37, n. 2, p. 212-217, 2014.

[12] PODSIADLO, D.; RICHARDSON, S. The timed "Up & Go": a test of basic functional mobility for frail elderly persons. J Am Geriatr Soc, v. 39, n. 2, p. 142-148, 1991.

[13] FURLAN, J. C. et al. Assessment of disability in patients with acute traumatic spinal cord injury: a systematic review of the literature. J Neurotrauma, v. 28, p. 1413-1430, 2011.

[14] VAN HEDEL, H. J.; WIRZ, M.; DIETZ, V. Assessing walking ability in subjects with spinal cord injury: validity and reliability of 3 walking tests. Arch Phys Med Rehabil., v. 86, n. 2, p. 190-196, 2005.

[15] GUYATT, G. H. et al. The 6-miunte walk: a new measure of exercise capacity in patients with chronic heart failure. Can Med Assoc J, v. 8, n. 919-923, p. 132, 1985.

[16] MAANUM, G. et al. Walking ability and predictors of performance on the 6-minute walk test in adults with spastic cerebral palsy. Dev Med Child Neurol, v. 6, n. e126-e132, p. 52, 2010.

[17] HAMILTON, B. B.; GRANGER, C. V. Disability outcomes following inpatient rehabilitation for stroke. Physical Therapy, v. 74, n. 5, p. 494-503, 1994.

[18] KIRSHBLUM, S. et al. Late neurologic recovery after traumatic spinal cord injury. Arch Phys Med Rehabil, v. 85, p. 1811-1817, 2004.

[19] CATZ, A. et al. A multicenter international study on the spinal cord independence measure, version III: Rasch psychometric validation. Spinal Cord, v. 4, n. 275-291, p. 45, 2007.

[20] BURRIDGE, J. H. et al. Theoretical and methodological considerations in the measurement of spasticity. Disabil Rehabil, v. 27, n. 1-2, p. 69-80, 2005.

[21] BIERING-SORENSEN, F.; NIELSEN, J. B.; KLINGE, K. Spasticity-assessment: a review. Spinal Cord, v. 12, n. 708-722, p. 44, 2006.

[22] BOHANNON, R. W.; SMITH, M. B. Interrater reliability of a modified Ashworth scale of muscle spasticity. Phys Ther, v. 67, n. 2, p. 206-207, 1987.

[23] PENN, R. D. Intrathecal baclofen for severe spasticity. Ann N Y Acad Sci, v. 531, p. 157-166, 1988.

[24] BENZ, E. N.; HORNBY, T. G. A physiologically based clinical measure for spastic reflexes in spinal cord injury. Arch Phys Med Rehabil, v. 86, n. 1, p. 52-59, 2005.

[25] Development and Use of a Knowledge Translation Tool: The Rehabilitation Measures Database Moore, Jennifer L. et al. Archives of Physical Medicine and Rehabilitation, Volume 95, Issue 1, 197–202 January 2014.

[26] WANG, P. et al. Detection of abnormal muscle activations during walking following spinal cord injury (SCI). Res Dev Disabil, v. 34, n. 4, p. 1226-1235, 2013.

[27] BRAVO-ESTEBAN, E. et al. Tibialis anterior muscle coherence during controlled voluntary activation in patients with spinal cord injury: diagnostic potential for muscle strength, gait and spasticity. J Neuroeng Rehabil, v. 11, n. 23, 2014.

[28] BEAUPARLANT, J. et al. Undirected compensatory plasticity contributes to neuronal dysfunction after severe spinal cord injury. Brain, v. 136, n. Pt 11, p. 3347-3361, 2013.

[29] D'Amico, J. M., Condliffe, E. G., Martins, K. J. B., Bennett, D. J., & Gorassini, M. A. (2014). Recovery of neuronal and network excitability after spinal cord injury and implications for spasticity. Frontiers in Integrative Neuroscience, 8, 36. http://doi.org/10.3389/fnint.2014.00036

[30] ZORNER, B. et al. Clinical algorithm for improved prediction of ambulation and patient stratification after incomplete spinal cord injury. J Neurotrauma., v. 27, n. 1, p. 241-252, 2010.

[31] BOAKYE, M. et al. Quantitative testing in spinal cord injury: overview of reliability and predictive validity. J Neurosurg Spine., v. 17, n. 1, p. 141-150, 2012.

[32] PETERSEN, J. A. et al. Spinal cord injury: one-year evolution of motor-evoked potentials and recovery of leg motor function in 255 patients. Neurorehabil Neural Repair, v. 26, n. 8, p. 939-948, 2012.

[33] CURT, A.; KECK, M. E.; DIETZ, V. Functional outcome following spinal cord injury: significance of motor-evoked potentials and ASIA scores. Arch Phys Med Rehabil, v. 79, p. 81-86, 1998.

[34] YANG, J. F. et al. Volitional muscle strength in the legs predicts changes in walking speed following locomotor training in people with chronic Spinal Cord Injury. Phys Ther, v. 91, n. 6, p. 931-943, 2011.

[35] HANSEN, N. L. et al. Reduction of common synaptic drive to ankle dorsiflexormotoneurons during walking in patients with spinal cord lesion. J Neurophysiol, v. 94, p. 934-942, 2005.

[36] Boonstra, T. W. (2013). The potential of corticomuscular and intermuscular coherence for research on human motor control. Frontiers in Human Neuroscience, 7, 855. http://doi.org/10.3389/fnhum.2013.00855

[37] HALLIDAY, D. M. et al. Functional coupling of motor units is modulated during walking in human subjects. J Neurophysiol, v. 89, p. 960–968, 2003.

[38] BARTHELEMY, D. et al. Impaired transmission in the corticospinal tract and gait disability in spinal cord injured persons. J Neurophysiol, v. 104, p. 1167–1176, 2010.

[39] HANSEN, N. L. et al. Synchronization of lower limb motor unit activity during walking in human subjects. J Neurophysiol, v. 86, p. 1266–1276, 2001.

[40] NORTON, J. A.; GORASSINI, M. A. Changes in cortically related intermuscular coherence accompanying improvements in locomotor skills in incomplete spinal cord injury. J Neurophysiol, v. 95, p. 2580–2589, 2006.

[41] SMITH, H. C. et al. Motor unit discharge characteristics during voluntary contraction in patients with incomplete spinal cord injury. Exp Physiol, v. 84, p. 1151–1160, 1999.

[42] CROS, D.; SOTO, O.; CHIAPPA, K. H. Transcranial magnetic stimulation during voluntary action: directional facilitation of outputs and relationships to force generation. Brain Res, v. 1185, p. 103–116, 2007.

[43] ZOGHI, M.; NORDSTROM, M. A. Progressive suppression of intracortical inhibition during graded isometric contraction of a hand muscle is not influenced by hand preference. Exp Brain Res, v. 177, n. 2, p. 266–274, 2007.

[44] WEIER, A. T.; PEARCE, A. J.; KIDGELL, D. J. Strength training reduces intracortical inhibition. Acta Physiol (Oxf), v. 206, n. 2, p. 109–119, 2012.

[45] BROUWER, B.; ASHBY, P. Corticospinal projections to lower limb motoneurons in man. Exp Brain Res, v. 89, p. 649–654, 1992.

[46] WIRTH, B.; VAN HEDEL, H. J.; CURT, A. Changes in corticospinal function and ankle motor control during recovery from incomplete spinal cord injury. J Neurotrauma, v. 25, p. 467–478, 2008.

[47] GOMEZ-SORIANO, J. et al. Voluntary ankle flexor activity and adaptive coactivation gain is decreased by spasticity during subacute spinal cord injury. Exp Neurol, v. 224, p. 507–516, 2010.

[48] WELCH, P. The use of fast Fourier transform for the estimation of power spectra: a method based on time averaging over short, modified periodograms. IEEE Transactions on Audio and Electroacoustics, v. 15, p. 70–73, 1967.

[49] CLARK, D. J. et al. Merging of healthy motor modules predicts reduced locomotor performance and muscle coordination complexity post-stroke. J Neurophysiol, v. 103, n. 2, p. 844-857, 2010.

[50] NEPTUNE, R. R.; MCGOWAN, C. P. Muscle contributions to whole-body sagittal plane angular momentum during walking. J Biomech, v. 44, n. 1, p. 6-12, 2011.

[51] Ilngle, D. (1968). The Co-ordination and Regulation of Movements. Papers translated from Russian and German. N. Bernstein. Pergamon, New York, 1967. xii + 196., illus. $8. Science, 159(3813), 415–416. Retrieved from http://science.sciencemag.org/content/159/3813/415.2.abstract.

[52] Santello M, Bianchi M, Gabiccini M, Ricciardi E, Salvietti G, Prattichizzo D, Ernst M, Moscatelli A, Jörntell H, Kappers AM, Kyriakopoulos K, Albu-Schäffer A, Castellini C, Bicchi A. Hand synergies: Integration of robotics and neuroscience for understanding the control of biological and artificial hands. Phys Life Rev. 2016 Feb 3. pii: S1571-0645(16)00026-9. doi: 10.1016/j.plrev.2016.02.001. [Epub ahead of print] Review. PubMed PMID: 26923030.

[53] ZEHR, E. P. et al. Neural regulation of rhythmic arm and leg movement is conserved across human locomotor tasks. J Physiol, v. 582, p. 209-227, 2007.

[54] WALL, J. C. et al. The timed get-up-and-go test revisited: measurement of the component tasks. J Rehabil Res Dev, v. 37, n. 1, p. 109-113, 2000.

[55] FORREST, G. F. et al. Are the 10 meter and 6 minute walk tests redundant in patients with spinal cord injury? PLoS One, v. 9, n. 5, 2014.

[56] SEDDON, H. W. J. Medical Research Council: Aids to the Exam of the Peripheral Nervous System. [S.l.]: London: Her Majesty's Stationery Office, 1976.

[57] HERMENS, H. J.; FRERIKS, B.; MERLETTI, R. European Recommendations for Surface ElectroMyoGraphy: Results of the SENIAM Project. Enschede, The Netherlands: Roessingh Research and Development, 1999.

[58] HUG, F. et al. Is interindividual variability of EMG patterns in trained cyclists related to different muscle synergies? J Appl Physiol, v. 108, n. 6, p. 1727-1736, 2010.

[59] LEE, D. D.; SEUNG, S. Learning the parts of objects by non-negative matrix factorization. Nature, v. 401, p. 788-791, 1999.

[60] TORRES-OVIEDO, G.; MACPHERSON, J. M.; TING, L. H. Muscle synergy organization is robust across a variety of postural perturbations. J Neurophysiol, v. 96, n. 3, p. 1530-1546, 2006.

[61] DOBKIN, B. et al. Weight-supported treadmill vs over-ground training for walking after acute incomplete SCI. Neurology, v. 66, n. 4, p. 484–493, 2006.

[62] XIE, J.; BOAKYE, M. Electrophysiological outcomes after spinal cord injury. Neurosurg Focus, v. 25, n. 5, p. E11, 2008.

[63] YANG, J. F.; MUSSELMAN, K. E. Training to achieve over ground walking after spinal cord injury: a review of who, what, when, and how. J Spinal Cord Med, v. 35, n. 5, p. 293-304, 2012.