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Research Article

Upper Limb Electromyographic Analysis Synchronized with Kinematics in Cervical Spinal Cord Injured Patients during the Activity of Daily Living of Drinking

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Keywords

- Surface electromyography
- Kinematics
- Upper limb
- Functional assessment
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- Spinal cord injury

Abstract

Background: Analytical descriptive study to describe the surface electromyographic (sEMG) patterns in healthy and cervical SCI patients and to classify these findings within the reaching and forward transport phases within the activity of daily living (ADL) of drinking

Methods: Eighteen subjects divided into three groups participated in the study: a healthy group (n=7) and two groups of patients with cervical SCI with metameric level C6 (n=7) and C7 (n=4). On each subject, sEMG data were recorded from 9 muscles and synchronized with trunk and right arm kinematic data, while performing five complete cycles of the ADL of drinking. The EMG activity was expressed as root mean square (RMS) values. The kinematic variables analyzed were the range of motion of shoulder, elbow and wrist joints. The Kruskal-Wallis test was applied to find possible differences between the three groups analyzed.

Results: The analysis of the EMG activity revealed differences in the distal muscles (triceps brachii and wrist flexors and extensors) between the healthy people and SCI patients, and in proximal muscles (biceps brachii between C6 and C7 SCI patients and in posterior deltoid between healthy people and C7 SCI patients). In relation to kinematics, the more important differences were found in the wrist joint.

Conclusion: This study provides new evidences about the neuromuscular mechanisms underlying the execution of the ADL of drinking in SCI patients. This tool could be useful to determine the response to therapeutic interventions.

INTRODUCTION

Approximately 66% of human spinal cord injuries (SCI) affect the cervical segments and 70% of them are clinically incomplete [1]. In all these cases, the upper limb (UL) function is completely or partially compromised, causing a loss of independence in the activities of daily living (ADL) as well as in the use of the UL as a source of weight support in bipedal posture or locomotion. The type and degree of functional impairment of the arm after SCI depend on the level at which the lesion occurs and its transverse and longitudinal extension throughout the spinal cord. A very consistent anatomo-functional spinal cord correlation has been extensively reported [2], which relates the specific control of one muscle with one particular spinal segment. This fine topographical organization predicts the degree of dependence in SCI patients according to the level of injury and its severity. Segmental interneurons (INs) and motoneurons (MNs) death contributes to the chronic UL deficits [3,4]. However, disruption of the supraspinal synaptic information on all segments below the lesion site is more clinically relevant. The muscles whose MNs are above the lesion site may have fewer motor units than normal function, but otherwise normal strength. Muscles with MNs in the injury level are partially affected, whereas muscles with MNs below the injury level exhibit augmented stretch reflexes and involuntary contractions or spasms, and lack of a normal pattern of voluntary contraction [5].

The human UL motor behavior relies on a balanced combination of force, skill and accuracy to achieve the required complex coordination between the different joints and their corresponding muscles. Although the arm movements have been more dependent on cortical control in mammals, the human spinal cord retains a complex intrinsic circuitry. Electrophysiological data have demonstrated the existence of a propriospinal system in humans [6], which play an important role in normal UL functions and appear to facilitate the recovery of hand function after central nervous system damage [7].

While performing ADL, UL muscles do not act as simple isolated elements, but as an integrated system capable to adjust in response to external perturbations. Coordination is then required and is usually impaired in tetraplegic patients [8], so these patients must learn new motor strategies in order to perform ADL, but the way in which the new strategies are developed is unclear [9].

The understanding of intra-limb coordination patterns may provide insight into mechanisms of recovery after a spinal cord injury. Kinematics, kinetics and specially electromyography have yielded consistent information onto the mechanisms underlying normal and pathological motor control in cats [10,11], humans [11-14] and to a lesser extent, in rodents [15-18]. Kinematic and electrophysiological data synchronously acquired allow elucidating the neuromuscular networks and their activation patterns [13,19-21]. UL clinical assessment is usually conducted by functional scales. However, after the spinal damage these approaches are unable to accurately measure the arm motor behaviour, and can only grasp gross functional changes. Furthermore, these scores scarcely allow extracting any conclusion at a physiological level [9,22].

Until now, the kinematic studies performed within clinical settings have provided important findings in relation to movement compensations [23-26]. However, there is no evidence of UL studies that include EMG and kinematic analysis simultaneously. Including electromyographic registration in combination with kinematic analysis may help generating new knowledge on the development of these new strategies and skills [9].

In a previous study, we found significant differences in the kinematics of the ADL of drinking between healthy and cervical SCI patients, throughout the observation of an augmented range of motion in the wrist joint in the patients [23]. The complete ADL of drinking is divided in five consecutive phases by means of the kinematic data: reaching, forward transport, drinking, distal transport and returning to the initial point [25]. UL muscles are implicated in a different way along the drinking cycle depending on the phase within the complete ADL. The objective of the present study is to extend the previous findings, including evidences on the electromygraphic patterns classified into two specific phases of the ADL of drinking i.e. the reaching and forward transport, due to their implication in the activity as different flexor and extensor muscle patterns.

MATERIALS AND METHODS

Subjects

A total of 18 subjects divided into three groups participated in the study: a healthy group (n=7) and two groups of patients with cervical SCI with metameric level C6 (n=7) and C7 (n=4). All participants were right handed and performed the activity with the right arm. Background data of participants are provided in (Table 1). All patients fulfilled the following inclusion criteria: age 16 to 65 years, at least 6 months from the injury onset, and level of injury C6 or C7 classified according to the American Spinal Injury Association (ASIA) scale into grades A or B [27]. Patients who presented any vertebral deformity, joint constraint, surgery on any of the UL, balance disorders, dysmetria due to associated neurologic disorders, visual acuity defects, cognitive deficit, or head injury associated with the SCI were excluded. Patients were classified into C6 and C7 SCI by a physical examination. The UL Motor Index was obtained through the assessment of the strength of five muscles groups of the right UL, performed by a physiotherapist [27]. Each muscle group can be assessed between 0 (no function) to 5 (normal function) with a total of 25 points. The guidelines of the declaration of Helsinki were followed in every case. Informed consent was obtained from all individual participants included in the study, which was approved by the Local Ethics Committee, Toledo, Spain.

Experimental protocol and data collection

Surface electromyography (EMG) was recorded using an EMG recording system (Noraxon, Scottdale, Arizona, USA) at a sample frequency of 1500Hz, synchronized online with the photogrammetry system. Bipolar-type, self-adhesive and disposable Ag/AgCl surface electrodes were used. The distance between the each pair of electrodes was 20 mm. Surface electrodes were positioned as described in Cram et al. [28] on the following nine muscles (Figure 1): upper trapezius (UT), posterior deltoid (PD), middle deltoid (MD), anterior deltoid (AD), pectoralis major (PM), biceps brachium (BB), triceps brachium (TB), wrist extensor (WE) and wrist flexor (WF). The reference electrode was placed on the C7 spinous process. Previous to electrode placement, the subjects' skin surface was prepared following the SENIAM recommendations [29].

UL movement analysis was carried out using the Codamotion

Table 1: Demographic and clinical characteristics of the sample analyzed (n=18).

Variables	Healthy subjects	C6 SCI	C7 SCI
	(n=7)	(n=7)	(n=4)
Sex (Male)[a]	3 (42.8)	4 (57.4)	4 (100)
Age (years)[b]	28.0 (5.0)	34.0 (5.0)	30.5 (10.0)
Height (cm)[b]	168.0 (20.0)	175.0 (10.0)	184.0 (10.0)
Weight (Kg)[b]	65.0 (21.1)	90.2 (7.1)	79.0 (9.1)
SCI evolution (months)[b]	-	8.5 (2.2)	7.5 (1.8)
ASIA (grade A)[a]	-	3 (42.8)	2 (50)
ASIA (grade B)[a]	-	4 (57.2)	2 (50)
Motor Index[b]	25.0 (0.0)	13.0 (3.0)	14.5 (2.0)

[a] Frequency and percentage for categorical variables; [b] mean and standard deviation for continuous variables

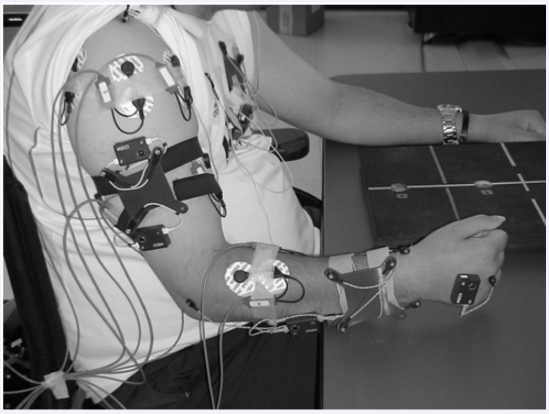

Figure 1 A cervical SCI patient instrumented with Codamotion markers and EMG electrodes.

photogrammetry system (Charnwood Dynamics, Ltd, UK). This system is based on active markers that emit infrared light captured by two scanner units. Eighteen markers were placed on the trunk and the right arm (Figure 1): eight markers were placed on superficial bony prominences (right iliac crest, right and left acromion, lateral and medial epicondyles of the elbow, radial and ulnar styloid processes of the wrist and the third metacarpal head); nine markers were placed in three clusters, of three markers each, placed on the chest, the arm and the forearm. An additional marker was placed on the chest. Marker clusters were used to minimize the estimation error due to marker displacements on the skin during the movement. Marker data were recorded at a sample frequency of 200Hz.

After performing a maximum voluntary contraction (MVC) test, each participant completed five cycles of the ADL of drinking from a glass, consisting of the following actions: starting from an initial position, reaching and grasping a glass, transporting it to the mouth, taking a swallow, transporting back and releasing it on the table, and returning to the initial point. Patients were seated in their own wheelchairs, whereas healthy participants were seated in a conventional wheelchair Action3 Invacare (Invacare Corp, Elyria OH, USA) with a similar configuration to that of the patients' wheelchair. The chair was placed before a table measuring 120x60 cm. The height was adjustable to each patient, until to reach the hand palm on the table with an elbow flexion of 90º. In every case, the subject-to-table distance was 18-20 cm and the angle between the seat and back was 90-100º. The starting position for all patients was defined as a position in which the patient's trunk rested firmly against the back of the chair. A hard plastic glass measuring 6.5 cm in diameter by 17.5 cm high was used. The glass was placed at the 75% of the maximum upper limb reaching distance of the patient.

The experimental set up was explained in detail in a previous study [23].

Data analysis

Kinematic data of marker positions were processed by means of a biomechanical model developed in Visual3D, involving the trunk, arm, forearm and hand segments [23]. Joint kinematic variables were computed for shoulder, elbow and wrist. The variables analyzed were the range of motion (ROM) of the shoulder joint in the flexion-extension, abduction-adduction and external-internal rotation movements; the ROM in the elbow joint in flexion-extension and pronation-supination movements; and the wrist ROM in flexion-extension movement. Moreover, we analyzed the movement of the distal segment, the hand. Moreover, we calculated the maximal and the mean distance between trajectories, obtained during the complete cycle of the drinking task, the real one performed by the patient and the reference one corresponding to the healthy pattern [30]; the maximal and the mean velocities during the movement and the numbers of peaks in the velocity profile were also computed.

The EMG signal was processing in amplitude. There are several methods of EMG processing, as for example, smoothed, low pass filtered, full-wave rectified and RMS envelope [31].

In this study, EMG signal was filtered by a high pass filter at 20 Hz, and a low pass filter at 450 Hz to minimize, respectively, the interferences with low frequency noise originating from undesired movement of cables and electrodes, and the high-frequency electromagnetic noise. A notch filter was applied to remove noise at 50 Hz. The filtered EMG signals were full-wave rectified and the root mean square (RMS) envelope of the EMG signal has been calculated across the five movement recordings. The RMS is calculated using a moving window, by squaring each value of the rectified EMG signal x(n) within the window, finding the arithmetic mean of those squared values, and taking the square root of the result (Eq.1), as expressed by the following equation:

$$\mathrm{RMS}\{x[n]\} = \sqrt{\frac{1}{N}\sum_{n} x^2[n]} \qquad \text{(Eq.1)}$$

where N equals the window length (150ms) and x[n] equals the data within the window.

The RMS value is frequently used for processing EMG, because this value reflects the level of the physiological activity in the motor unit during a contraction [32]. Moreover, the RMS calculation is considered to provide the most insight on the amplitude of the EMG signal since it gives a measure of the power of the signal, while producing a waveform that easily analyzable.

With the aim of comparing between the subjects and obtaining the averaged RMS curves for healthy group and both groups of patients, the curves for each subject were interpolated to a uniform length. Then the results are expressed as a percentage in the horizontal axis, corresponding 0 and 100% to the initial and ending points, respectively, within the drinking task.

The recordings were analyzed with Matlab 2011 (Mathworks, Natick, MA, USA). To facilitate the analysis, the complete ADL was broken down into 5 consecutive phases limited by events: the reaching phase (includes grasping the glass); the forward transport phase; the drinking phase consisting on limiting to take a swallow, distal transport (includes releasing the glass on the table) and returning to the initial point phases.

Statistical analysis

Statistical analysis was performed with SPSS (Statistical Packages for Social Sciences, release 12.0 for Windows, SPSS Inc, Chicago, IL) and Sigma Plot 11.0. In the analysis of kinematic and EMG variables, the mean value of the five trials was used.

A descriptive analysis of the clinical and functional variables was made by calculating the mean and standard deviation of the quantitative variable and the frequencies and percentages of the qualitative variables.

To check the discriminative capability of the kinematic and EMG variables analyzed, a comparison between healthy and SCI patients, and between patients with different spinal injury level was made. The Kruskal-Wallis test was applied to find possible differences in each variable between the three groups analyzed; the Kruskal-Wallis test is $p < 0.05$, the equivalence of behavior between groups can be rejected and a pairwise comparison can be made using the U Mann-Whitney test. The Bonferroni correction was applied, which takes into account randomness due to multiple comparisons.

RESULTS

The sample analyzed was broken down into three groups that were matched in age, weight and height.

Kinematics

The kinematic study provided information in relation to the ROM of the joints involved for each movement analyzed: flexion-extension, abduction-adduction and external-internal rotation for shoulder joint; flexion-extension and pronation-supination for the elbow joint; and, flexion-extension movement for the wrist. Moreover, in terms of the kinematic chain segments, the movement of the distal segment, i.e. the hand, was analyzed.

The more important differences in the kinematic patterns were obtained in the UL distal segment, the hand and the wrist joint (Table 2). The flexion-extension movement in the wrist joint was greater in C6 and C7 SCI patients than in healthy subjects ($p<0.05$).

In relation to the hand kinematics, the deviations between trajectories was greater in C6 SCI patients (20.69 ± 5.52 cm) when compared to healthy subjects (10.52 ± 2.77 cm) ($p<0.01$) and C7 SCI patients (14.03 ± 3.01 cm) ($p<0.05$). The movement during the complete cycle of the drinking task was more fragmented in SCI patients compared to healthy subjects ($p<0.01$). The number of peaks in the velocity profile was 6.83 in healthy subjects and practically twice this amount for C6 and C7 SCI patients (12.53 and 13.82, respectively). Statistically significant differences were found between healthy and SCI patients but not between C6 and C7 SCI patients (Figure 2).

EMG

Statistically significant differences were found in the muscle activation levels during the complete cycle of the ADL of drinking (Table 3). Differences were observed in the distal muscles (triceps brachium and wrist flexors and extensors) between the healthy and both groups of SCI patients (Figure 3). The curves showed in Figure 3 could be in accordance with kinematic results in the wrist joint. The amplitude of the RMS envelope for the C6 SCI patients (dashed line) is greater than for the healthy group (solid line) in (Figure 3A) corresponding to extensors muscles. In (Figure 3B), the dashed line presents a peak at the time 10% and another one at 60%. These peaks in the curve corresponding to the C6 SCI patients could be due to the compensation strategies for manipulating the glass during the movement execution. It's necessary taking into account that these peaks are not present in the solid curve corresponding to the healthy group. This result

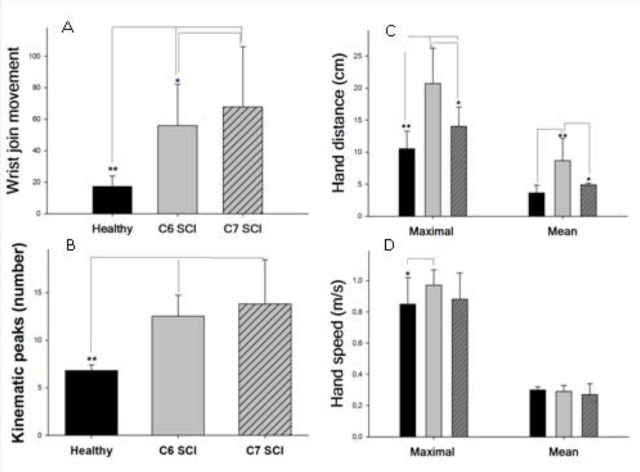

Figure 2 Kinematic changes during the ADL of drinking in the three studied samples. A) Wrist joint displacement. B) Number of peaks during the complete cycle. C) and D) Hand distance and speed respectively. Black, gray and crosswise lined rows: healthy subjects, C6 and C7 SCI respectively. *p<0.05. ** p<0.01.

matches with the kinematic results in healthy people, in which the range of motion of the wrist joint was smaller than in both groups of patients (Table 2).

Differences were observed in proximal muscles between C6 and C7 SCI patients for the biceps brachium muscle and between healthy and C7 SCI patients for posterior deltoid muscle ($p<0.05$). The segregated analysis data obtained during the reaching and forward transport phases are shown in (Table 3 and Figure 4).

Reaching phase

During this phase, at the proximal level, differences were found in the posterior deltoids muscle between the healthy and both groups of patients. This muscle presented a higher activation in both groups of patients. The same behavior was found in wrist flexors muscles (a mean value of 1.77mV in healthy people; 9.99 mV in C6 SCI patients and 6.42 mV in C7 SCI patients in the RMS variable) (Table 3 and Figure 4).

However, the biceps brachium activation was greater in C7 SCI patients than in healthy and C6 SCI patients ($p<0.05$). For the triceps brachium and wrist extensors muscles the differences in the patterns were found between healthy and C6 SCI patients, being greater in C6 SCI patients when compared to the healthy group ($p<0.01$) (Table 3).

Forward transport phase

During this movement phase, no significant differences were found in the proximal muscles upper trapezius, deltoid and pectoralis major. However, as a difference between the reaching phase, healthy people showed a greater biceps brachium activation compared to C6 SCI patients ($p<0.05$).Moreover, the triceps activation was significantly different and lower in healthy compared to both groups of SCI patients ($p<0.01$). No differences were found in the wrist flexor muscles activation between the three groups analyzed, but the wrist extensor muscles activity was greater in C6 SCI patients when compared to healthy subjets ($p<0.05$) (Table 3 and Figure 4).

DISCUSSION

Table 2: Kinematic data during the complete cycle of the ADL of drinking in the three populations analyzed.			
KINEMATIC VARIABLES	**Healthy (n=7)**	**C6 SCI (n=7)**	**C7 SCI (n=4)**
Shoulder joint movement (º)			
Flexion-extension	68.16 ± 19.27	78.00 ± 17.41	68.85 ± 15.32
Abduction-adduction	24.08 ± 2.24	23.04 ± 8.16	23.83 ± 12.21
External-internalrotation	26.78 ± 9.57	34.40 ± 22.72	33.48 ± 6.37
Elbow joint movement (º)			
Flexion-extension	85.90 ± 25.12	71.00 ± 40.86	91.87 ± 75.22
Pronation-supination	36.43 ± 9.81	52.29 ± 26.49	38.87 ± 47.57
Wrist joint movement (º)			
Flexion-extension	17.32 ± 6.70^{a,b}	55.92 ± 26.38^{a}	67.68 ± 38.43^{b}
Hand movement			
Maximal distance (cm)	10.52 ± 2.77^{c}	20.69 ± 5.52^{a,c}	14.03 ± 3.01^{a}
Mean distance (cm)	3.62 ± 1.25^{c}	8.65 ± 3.52^{a,c}	4.89 ± 0.26^{a}
Maximal velocity (m/s)	0.85 ± 0.17^{a}	0.97 ± 0.10^{a}	0.88 ± 0.17
Mean velocity (Vmean) (m/s)	0.30 ± 0.02	0.29 ± 0.04	0.27 ± 0.07
Peaks number (units)	6.83 ± 0.58^{c,d}	12.53 ± 2.21^{c}	13.82 ± 4.63^{d}
Data are expressed as mean and standard deviation a,b (p<0.05) and c,d (p<0.01)			

Table 3: Mean RMS value (mV) during the complete cycle of the ADL of drinking and the reaching and forward transport phases separately									
	Healthy	**C6 SCI**	**C7 SCI**	**Healthy**	**C6 SCI**	**C7 SCI**	**Healthy**	**C6 SCI**	**C7 SCI**
Upper trapezius	14.93 ± 4.40	12.86 ± 5.37	8.39 ± 2.83	10.81 ±0.78	10.52 ± 5.71	9.71 (4.71)	16.07 ± 9.00	19.37 ± 17.32	9.85 ± 2.96
Posterior deltoid	**2.98 ± 0.85^{a}**	4.54 ± 0.98	**3.64 ± 0.98^{a}**	**1.66 ± 0.78^{a,c}**	**4.49 ± 2.54^{c}**	**3.62 (1.52)^{a}**	3.01 ± 0.78	4.31 ± 1.05	3.89 ± 0.91
Middle deltoid	12.01 ± 4.41	7.02 ± 2.19	4.75 ± 1.80	4.77 ± 2.02	7.39 ± 5.04	5.00 (3.67)	6.84 ± 2.78	6.02 ± 2.74	6.29 ± 0.47
Anterior deltoid	22.69 ± 10.35	22.71 ± 11.04	15.96 ±9.31	14.98 ±9.72	25.73 ± 15.71	25.72 (21.36)	27.17 ± 9.80	32.14 ± 13.95	25.32 ± 8.38
Pectoralis major	8.86 ± 3.84	9.64 ± 4.47	10.62 ± 5.51	5.65 ± 3.46	12.25 ± 6.08	14.35 (7.81)	11.58 ± 5.32	14.40 ± 6.23	14.12 ±5.96
Biceps brachium	9.94 ± 4.94	**7.12 ± 2.51^{a}**	**10.19 ± 4.36^{a}**	**5.37 ± 4.12^{a}**	**8.85 ± 3.51^{b}**	**13.88 (2.77)^{a,b}**	**15.31 ± 3.99^{a}**	**8.69 ± 4.30^{a}**	11.74 ± 2.01
Triceps brachium	**1.91 ± 0.54^{c,d}**	**3.51 ± 1.10^{c}**	**5.54 ± 2.41^{d}**	**1.21 ± 0.49^{c}**	**4.60 ± 2.10^{c}**	5.88 (2.30)	**2.24 ± 0.32^{b,c}**	**3.88 ± 1.51^{b}**	**3.89 ± 1.10^{c}**
Wrist extensors	**5.05 ± 2.24^{a,c}**	**11.40 ± 5.85^{c}**	**7.21 ± 3.71^{a}**	**3.40 ± 2.30^{c}**	**12.41 ± 4.66^{c}**	8.19 (6.27)	**7.36 ± 2.13^{a}**	**18.78 ± 10.27^{a}**	11.69 ± 3.70
Wrist flexors	**2.65 ± 0.95 ^{a,b}**	**8.48 ± 3.09^{a}**	**4.92 ± 1.72^{b}**	**1.77 ± 0.80^{a,c}**	**9.99 ± 8.34^{c}**	**6.42 (2.50)^{a}**	4.29 ± 3.50	6.31 ±1.45	5.24 ± 3.07
Data are expressed as mean and standard deviation. a,b (p<0.05) and c,d (p<0.01)									

In the present study, we made a combined analysis of the EMG and kinematic patterns involved in the ADL of drinking. The ADL of drinking is particularly suitable for analyzing pathological patterns because it requires UL coordination and control but its execution doesn't require maximal forces. In particular we focused the analysis on the reaching and transport phases, because they imply the activation of different flexor and extensor neuromuscular patterns differently disrupted depending on the spinal cord injury level.

The differences observed in EMG patterns between healthy and patients with cervical SCI were matched with the differences in kinematic results during the complete cycle of this ADL. As we only included C6 and C7 complete tetraplegic patients, that lack of the ability to grasp but remains different degrees of reaching, we focused our biomechanical measures on shoulder, elbow and wrist joints. Statistical significant differences were found between healthy and C6 and C7 SCI patients in relation to EMG patterns during the reaching and transport phases.

Janssen-Potten et al., performed an exhaustive study for assessing the UL muscle function in tetraplegic people. To reach this purpose, they analyzed 21 UL and trunk muscles [33]. However, the main contribution of this research is that kinematic and EMG data were recorded simultaneously to improve the understanding and interpretation of EMG results, and for that it was necessary to lessen the number of muscles analyzed for space reasons, keeping only those relevant to arm stability in the selected task.

In relation to kinematic analysis, the more important differences between the three populations analyzed were found at the wrist joint. Significant differences were also found in the hand trajectories (variables related to distance) and in the velocity profiles of the hand movement during the complete cycle of the ADL analyzed.

The differences observed in relation to EMG patterns were supported by the kinematic results. We found an increase in the distal flexor – extensor ROM together with an increase of the

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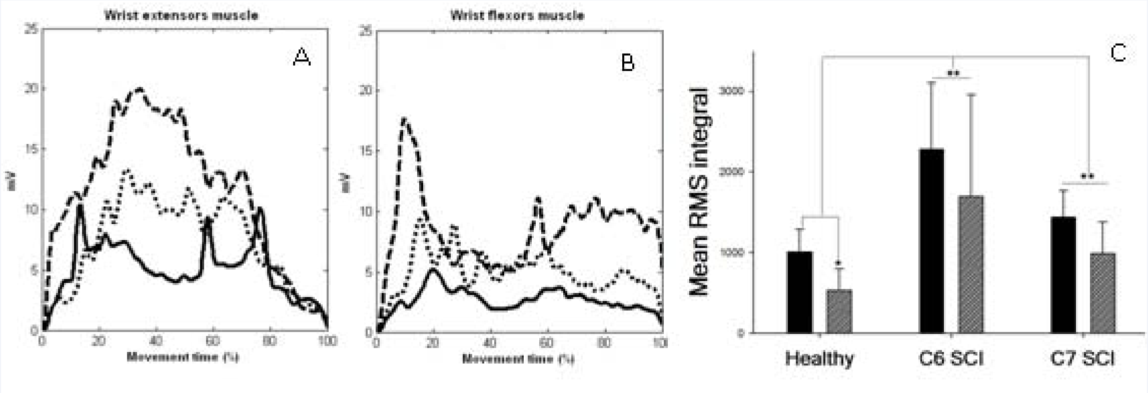

Figure 3 Mean rms EMG signal for the wrist extensors (A) and flexors (B) muscles during the complete cycle of the drinking task. The curves show the mean rms for the healthy group (solid line); the C6 SCI people (dash line) and the C7 SCI people (dotted line). (C) Mean rms EMG integral for the wrist extensors (black columns) and flexors (gray crosswise lined columns) muscles during the complete cycle of the drinking task. *p<0,05. **p<0,01.

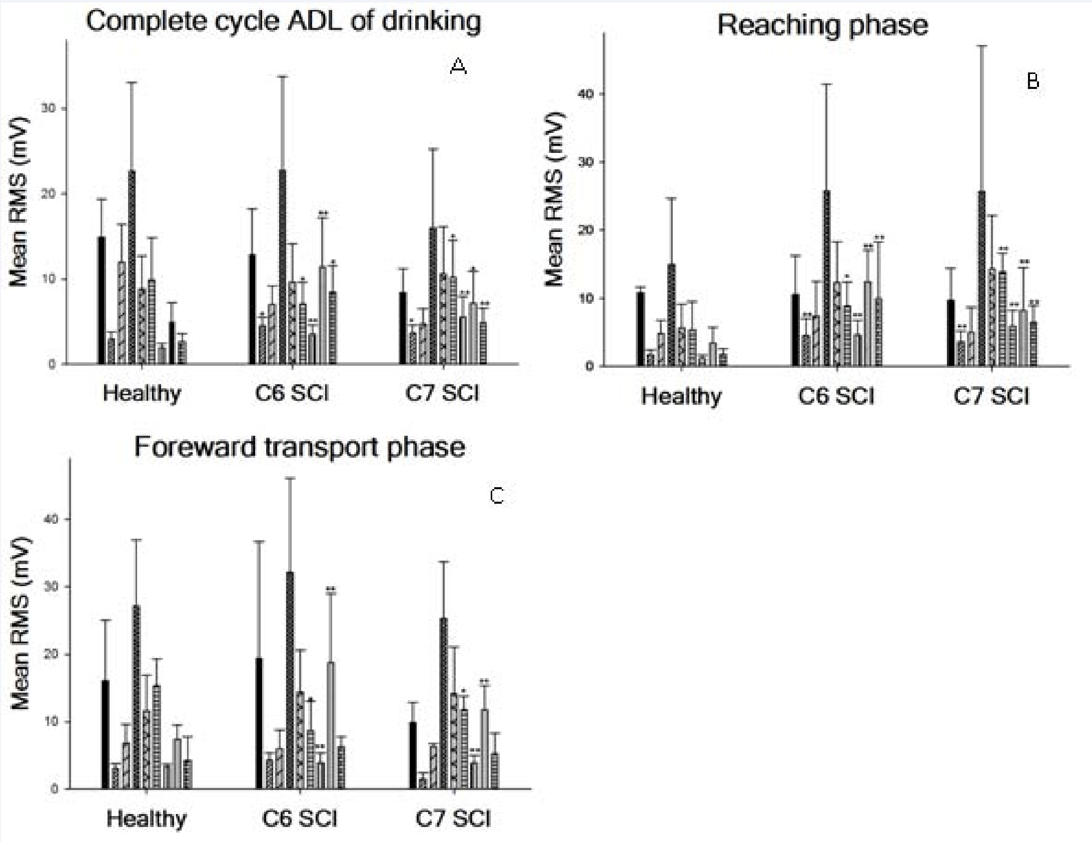

Figure 4 Mean RMS of upper limb muscles during the ADL of drinking. A) Complete cycle of drinking. B) Reaching phase. C) Forward transport phase. Black columns: upper trapezius. Gray fine oblique lines columns: posterior deltoid. Gray coarse oblique line columns: Middle deltoid. Gray fine cross line columns: anterior deltoid. Gray coarse cross line columns: pectoralis major. Gray horizontal line columns: biceps brachium. Gray vertical line columns: triceps brachium. Gray dotted columns: forearm extensors. Gray bricks columns: forearm flexors. *p<0.05, **p<0.01.

number of peaks in the velocity profile in C6 and C7 tetraplegic patients with respect to healthy controls. Interestingly, the forearm flexors sEMG activity increased in C6 and C7 patients compared to normal subjects but only the C6 subgroup incremented triceps braquii and forearm extensor muscles activity during the two phases of the drinking task. Fukuda et al. demonstrated in a previous work that the RMS value maintained a linear relationship with the imposed load and provides insight about the muscle activation and co-activation patterns during the performance of a task [32]. These sEMG increments are in agreement with the kinematic ones observed in the wrist ROM and implies that tetraplegic patients were exerting more force than healthy subject with muscles whose intraspinal circuitries are located below the lesion site, that is only possible if the force would be improving thanks to mono or dysinaptic stretching reflex in triceps and finger flexor muscle contribution. This mechanism has been extensively reported in triceps surae flexor reflexes during normal and pathological bipedalism and locomotion [34], and also observed in the rat triceps braquii after a C6 SCI hemisection too as the way of optimizing the antigravitatory force with a desinervated muscle [35]. A similar behavior has been observed in the biceps brachium activity in C7 patients during de reaching phase. The biceps brachium contraction compels to the triceps brachium to lengthen, triggering an eccentric contraction – the Lombard's paradox - that in case of a denervated triceps brachiicould only be carried out with its stretching reflex circuitry [35,36]. An interesting question to be investigated in future works is whether the neuromuscular substrate of that force improvement could be explained as reactive synaptogenesis inside the biceps brachium muscle -a muscle normally innervated because its MNs column is located above de lesion site- as the development of new intraspinal circuitry after de SCI or a combination of both. In humans, after the spinal damage neural and axonal sprouting phenomena take place from the first month and throughout the first year. Functional recovery is sustained not only from the undamaged spinal tissue but also from the behavioral neuromuscular compensation that improve the final performance [37]. Since deficiencies and compensatory mechanisms are presented together in the residual motor function, careful UL functional studies as kinematics and sEMG analysis are needed to differentiate real functional recovery from compensations and to provide comprehensive tools to unbiased quantify the residual sensory-motor through the time of evolution and facilitate neural plasticity.

Some limitations must be taken into account to correctly understand the present work. First of all, the relatively small size of the sample of SCI patients, especially the C7 subpopulation. To mitigate this, and provide a sufficiently extended dataset, we acquired five records of each subject. Nevertheless, it is necessary to remark that the selected SCI patients had clinically homogeneous lesions, resulting in very similar pattern of behaviour when performing the ADL of drinking. Another limitation is related to the fact that part of the rising in RMS activity registered in desinervated muscles such us triceps brachium or wrist flexors may be due to the crosstalk phenomenon and not to a reflex response improvement as we hypothesize. To minimize this risk, future works should focus on the size, shape and adhesion optimization of the surface electrodes, and may include other more selective electrophysiological measures as needle EMG or somatosensorial and motor evoked potential, in order to further elucidate the reflex contribution to the total strength and the physiological and pathological coactivations during upper limb movements.

The last limitation is in relation to the EMG results as absolute values. In other published studies, where the force/torque is correlated to the EMG it is common to normalize the force/ torque and its respective EMG, relative to the values at maximal voluntary contraction (MVC). 31 However, the measurement of EMG signal in SCI injured patients, who have some upper extremity denervated muscles, represents a challenge. This is the case of the triceps braquii muscle in C6 SCI patients in this study. These patients don't retain a voluntary activity of this muscle. So, for this muscle, a MVC should be near to 0. In this situation, normalization by the MVC would obtain a very high activation of this muscle, and as consequence, the activation level due to not voluntary activity of the muscle wouldn't be detected.

If the same voltage is found in two people within the control group, we could think that the same activation level was reached. However, this reasoned isn't complete and an analysis of the shape of averaged RMS curves should be made, as the curves showed in Figure 3. The analysis of the shape of RMS averaged curves could be addressed in a future research.

CONCLUSION

This paper presented study on UL muscle activity, synchronized with kinematic analysis during the ADL of drinking. This study allows generating knowledge about underlying mechanisms which that are reflected in biomechanical findings.

An increase of muscular activity and joints displacements have been detected in C6 and C7 SCI patients in the UL distal segments in comparison with proximal ones. The significance of these findings is yet uncertain. Synchronized kinematic and sEMG analysis is a feasible and accurate method to measure the long-term changes in the UL motor patterns during the time of recovery after a SCI.

This tool could be useful to determine the recovery plateau and the response to the therapeutic interventions.

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CONFLICT OF INTEREST

Authors disclose any competing financial interests and personal relationships with other people or organizations that could inappropriately influence their work.

ETHICAL APPROVAL

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and local research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

REFERENCES

1. National Spinal Cord Injury Statistical Center, Facts and Figures at a Glance. Birmingham, AL: University of Alabama at Birmingham, 2015.

2. REXED B. A cytoarchitectonic atlas of the spinal cord in the cat. J Comp Neurol. 1954; 100: 297-379.

3. Curt A, Dietz V. Neurographic assessment of intramedullary motoneurone lesions in cervical spinal cord injury: consequences for hand function. Spinal Cord. 1996; 34: 326-332.

4. Thomas CK, Zaidner EY, Calancie B, Broton JG, Bigland-Ritchie BR. Muscle weakness, paralysis, and atrophy after human cervical spinal cord injury. Exp Neurol. 1997; 148: 414-423.

5. Hentz VR, Leclercq C. The management of the upper limb in incomplete

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lesions of the cervical spinal cord. Hand Clin. 2008; 24: 175-184.

6. Pierrot-Deseilligny E, Burke D. The circuitry of the human spinal cord: its role in motor control and movement disorders, 2005. Cambridge University Press. 2005.

7. Burke D. Clinical relevance of the putative C-3-4 propriospinal system in humans. Muscle Nerve. 2001; 24: 1437-1439.

8. Garrison B, Wade E. Relative accuracy of time and frequency domain features to quantify upper extremity coordination. Conf Proc IEEE Eng Med Biol Soc. 2015; 2015: 4958-4961.

9. van Tuijl JH, Janssen-Potten YJ, Seelen HA. Evaluation of upper extremity motor function tests in tetraplegics. Spinal Cord. 2002; 40: 51-64.

10. Orlovskii GN, Deliagina TG, Grillner S. Neuronal control of locomotion: from mollusc to man. Oxford University Press, 1999.

11. Rossignol S, Barrière G, Alluin O, Frigon A. Re-expression of locomotor function after partial spinal cord injury. Physiology (Bethesda). 2009; 127-139.

12. Alexander RM. Simple models of human movement. Applied Mechanics Reviews 1995: 48: 461-470.

13. Gil-Agudo A, Prez-Rizo E, Del Ama-Espinosa A, Crespo-Ruiz B, Prez-Nombela S, Snchez-Ramos A, et al. Comparative biomechanical gait analysis of patients with central cord syndrome walking with one crutch and two crutches. Clinical Biomechanics. 2009; 24: 551-557.

14. Gil-Agudo A, Del Ama-Espinosa A, P rez-Rizo E, Prez-Nombela S, Rodrguez-Rodrguez LP. Upper limb joint kinetics during manual wheelchair propulsion in patients with different levels of spinal cord injury. Journal of biomechanics 2010; 43: 2508-2515.

15. Collazos-Castro JE, López-Dolado E, Nieto-Sampedro M. Locomotor deficits and adaptive mechanisms after thoracic spinal cord contusion in the adult rat. J Neurotrauma. 2006; 23: 1-17.

16. Webb AA1, Muir GD. Compensatory locomotor adjustments of rats with cervical or thoracic spinal cord hemisections. J Neurotrauma. 2002; 19: 239-256.

17. Filli L, Z rner B, Weinmann O, Schwab ME. Motor deficits and recovery in rats with unilateral spinal cord hemisection mimic the Brown-Sequard syndrome. Brain 2011; 134: 2261-2273.

18. López-Dolado E, Lucas-Osma AM, Collazos-Castro JE. Dynamic motor compensations with permanent, focal loss of forelimb force after cervical spinal cord injury. J Neurotrauma. 2013; 30: 191-210.

19. Grillner S, Rossignol S. On the initiation of the swing phase of locomotion in chronic spinal cats. Brain Res. 1978; 146: 269-277.

20. Duysens J, Pearson KG. Inhibition of flexor burst generation by loading ankle extensor muscles in walking cats. Brain Res. 1980; 187: 321-332.

21. Lovely RG, Gregor RJ, Roy RR, Edgerton VR. Effects of training on the recovery of full-weight-bearing stepping in the adult spinal cat. Exp Neurol. 1986; 92: 421-435.

22. Cacho EWA, de Oliveira R, Ortolan RL, Varoto R, Cliquet A. Upper limb assessment in tetraplegia: clinical, functional and kinematic correlations. Int J Rehabil Res. 2011; 34: 65-72.

23. de los Reyes-Guzm n A, Gil-Agudo A, Peasco-Mart n B, Sol s-Mozos M, del Ama-Espinosa A, P rez-Rizo E. Kinematic analysis of the daily activity of drinking from a glass in a population with cervical spinal cord injury. J Neuroeng Rehabil. 2010; 7: 41.

24. Jaspers E, Desloovere K, Bruyninckx H, Klingels K, Molenaers G, Aertbelin E, et al . Three-dimensional upper limb movement characteristics in children with hemiplegic cerebral palsy and typically developing children. Res Dev Disabil. 2011; 32: 2283-2294.

25. Murphy MA, Sunnerhagen KS, Johnels B, Willn C. Three-dimensional kinematic motion analysis of a daily activity drinking from a glass: a pilot study. J Neuroengineering Rehabil. 2006; 3: 18.

26. Murphy MA, Willn C, Sunnerhagen KS. Kinematic variables quantifying upper-extremity performance after stroke during reaching and drinking from a glass. Neurorehabil Neural Repair. 2011; 25: 71-80.

27. Kirshblum SC, Burns SP, Biering-Sorensen F, Donovan W, Graves DE, Jha A, et al. International standards for neurological classification of spinal cord injury (revised 2011). J Spinal Cord Med. 2011; 34: 535-546.

28. Cram JR. Electrodes Placements. In: Criswell E, editor. Cram s introduction to surface electromyography. 2nd ed. Boston, USA: Jones & Bartlett Publishers; 2011; 257-383.

29. Stegeman DF, Hermens HJ. Standards for surface electromyography: the European project. Surface emg for non-invasive assessment of muscles (seniam), 2007.

30. De los Reyes-Guzm n A, Dimbwadyo-Terrer I, P rez-Nombela S, Trincado F, Torricelli D, Gil-Agudo A, et al. Objective metrics for functional evaluation of upper limb during the ADL of drinking: application in SCI. In XIII Mediterranean Conference on Medical and Biological Engineering and Computing. 2013 1751-1754.

31. Merletti R, Di Torino P. Standards for reporting EMG data. J Electromyogr Kinesiol, 1999; 9: 3-4.

32. Fukuda TY, Oliveira J, Pompeu JE, Garcia-Lucareli PR, Garbelotti S, Okano R, et al. Root Mean Square Value of the electromyograpnic signal in the isometric torque of the quadriceps, hamstrings and brachial biceps muscles in female subjects. The Journal of Applied Research. 2010; 10: 1.

33. Janssen-Potten YJ, Seelen HA, Bongers-Janssen HM, van der Woude LH. Assessment of upper extremity muscle function in persons with tetraplegia. J Electromyogr Kinesiol. 2008; 18: 516-526.

34. Dietz V, Duysens J. Significance of load receptor input during locomotion: a review. Gait Posture. 2000; 11: 102-110.

35. Broton JG, Nikolic Z, Suys S, Calancie B. Kinematic analysis of limb position during quadrupedal locomotion in rats. J Neurotrauma. 1996; 13: 409-416.

36. Ghosh A, Sydekum E, Haiss F, Peduzzi S, Zrner B, Schneider R, et al. Functional and anatomical reorganization of the sensory-motor cortex after incomplete spinal cord injury in adult rats. The Journal of Neuroscience 2009; 29: 12210-12219.

37. Hayes KC, Davies AL, Ashki N, Kramer JK, Close TE. Re: Ditunno JF, et al. Spinal shock revisited: a four-phase model. Spinal Cord 2004; 42: 383-395. Spinal Cord. 2007; 45: 395-396.

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