Clinical, Kinematic and Muscle Assessment of Bilateral Coordinated Upper-Limb Movements Following Cervical Spinal Cord Injury

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***Abstract*— Cervical spinal cord injury (cSCI) often results in bilateral impairment of the arms, leading to difficulties in performing daily activities. However, little is known about the neuromotor alterations that affect the ability of individuals with cSCI to perform coordinated movements with both arms. To address this issue, we developed and tested a functional assessment that integrates clinical, kinematic, and muscle activity measures, including the evaluation of bilateral arm movements. Twelve subjects with a C5-C7 spinal lesion and six unimpaired subjects underwent an evaluation that included three tests: the Manual Muscle Test, Range Of Motion test and Arm stabilisation test, a subsection of the "Van Lieshout arm/hand function test". During the latter, we recorded kinematic and muscle activity data from the upper-body during the execution of a set of movements that required participants to stabilize both arms against gravity at different configurations. Analytical methods, including muscle synergies, spinal maps, and Principal Component Analysis, were used to analyse the data. Clinical tests detected limitations in shoulder abduction-flexion of cSCI participants and alterations in elbows-wrists motor function. The instrumented assessment provided insight into how these limitations impacted the ability of cSCI participants to perform bilateral movements. They exhibited severe difficulty in performing movements involving over-the-shoulder motion and shoulder internal rotation due to altered patterns of activity of the scapular stabilizer muscles, latissimus dorsi, pectoralis, and triceps. Our findings shed light on the bilateral neuromotor changes that occur post-cSCI addressing not only motor deficits, but also the underlying abnormal, weak, or silent muscle activations.**

***Index Terms*— Spinal cord injury, bilateral arm movement, surface electromyography, muscle synergies, spinal maps.**

I. INTRODUCTION

CERVICAL spinal cord injury (cSCI) results in partial or total loss of motor and sensory functions below the level of the injury, often leading to bilateral impairment of arms and hands. The ability to coordinate the movement of both arms is essential to perform several activities of daily living [1], [2]. Despite this and the recent increase of interest in bilateral training programs [3], there is still limited information regarding the impact of a cSCI on bilateral upper limb neuromotor strategies [4], [5].

Clinical assessments of upper limb motor functions typically rely on traditional tests, such as the Manual Muscle Test (MMT [6]) and Range of Motion (ROM [7]) test. These tests are widely accepted and validated in clinical practice and address various levels of motor evaluation, from muscle strength to articular motions. However, their utility is limited by the presence of inter and intra-rater variability [8], [9], as well as a lack of sensitivity [10]. Moreover, these tests only evaluate a limited range of movements or muscle groups and are typically performed in isolation, without considering the dynamic movement patterns that are critical to perform daily activities.

Several technological solutions, such as motion capture and electromyography (sEMG) systems, allow for a quantitative

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Manuscript received 17 April 2023; revised 1 August 2023; accepted 14 August 2023. Date of publication 28 August 2023; date of current version 14 September 2023. This work was supported by the European Union–NextGenerationEU within the framework of the project "Robotics and AI for Socio-Economic Empowerment (RAISE)." *(Maura Casadio and Camilla Pierella are co-last authors.) (Corresponding author: Maura Casadio.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Comitato Etico Regione Liguria, under Application No. CER Liguria 585/2021.

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This article has supplementary downloadable material available at https://doi.org/10.1109/TNSRE.2023.3309539, provided by the authors.

Digital Object Identifier 10.1109/TNSRE.2023.3309539

assessment of neuromotor functions during movement, overcoming the limitations of clinical tests [11], [12]. Kinematic data analysis from motion capture systems provides information on movement performance, while sEMG data analysis offers insights into muscle activation patterns.

In the last decade, these systems have been extensively used to evaluate motor functions in various neurological diseases, such as stroke and multiple sclerosis [11], [12], [13]. As for cSCI, a number of studies have adopted these techniques to objectively assess unilateral upper limb motor functions after the lesion [14], but little attention has been paid in using these technologies to comprehensively assess how cSCI affects the neuromotor abilities to perform coordinated bilateral movements. Studies by Britten et al. [5], [15] have investigated the kinematic strategies adopted by cSCI individuals with incomplete lesions during coordinated reach-to-grasp actions using a motion capture system. These studies found that these individuals retain a level of bilateral control. However, to the best of our knowledge, few studies have investigated the muscle activity of cSCI survivors when performing coordinated movements with both arms [4], [5], and no studies have adopted the most recent and advanced muscle analysis techniques, i.e. muscle synergies [16] and spinal maps [17], to investigate the effects that a cervical lesion has on the muscle coordination patterns and the overall muscle spatio-temporal organization during these types of movements.

The purpose of this study is to address the need for a comprehensive assessment of bilateral upper-limb neuromotor abilities after cSCI by testing the usability and efficacy of a functional assessment that combines the strengths of traditional clinical outcome measures with the latest technological and analytical methods. The functional assessment integrates a clinical evaluation, based on MMT and ROM test, with an instrumented evaluation of the kinematic and muscle activity data from the upper body - trunk and both arms - during the execution of coordinate bilateral movements required for completing the Stabilisation sub-section of the "Van Lieshout arm/hand function test" (VLT, [18]). The main hypothesis of this work is that the clinical evaluation would provide relevant information on the motor-muscle deficits associated with cSCI, whereas the instrumented evaluation would provide insight into how the combination of these deficits affects complex bilateral movements. We also premised that the outcomes of our analysis would be able to depict modifications in the neuromotor functions of shoulders and elbows as a result of partial denervation of the primary muscles that operate these joints. Specifically, we expected to unveil changes in the kinematics performance of these two joints due to an alteration in the patterns of activity of the pectoralis muscles, of the main scapular stabilizers muscles, and of the triceps [19], [20].

Since the instrumented test consists of a set of coordinated bilateral movements of increasing difficulty, that require subjects to stabilize both arms at different heights and configurations without gravity compensation, we anticipate that the neuromotor deficits associated with cSCI will become more pronounced as the gravitational demand increases.

To verify our hypothesis and provide a preliminary description of how cervical lesions affect bilateral neuromotor abilities, we tested a cohort of twelve cSCI subjects with lesions between C5 and C7 and six unimpaired subjects. We expect that the assessment proposed in the study will provide clinicians with a more reliable and comprehensive method for evaluating bilateral neuromotor deficits after a cervical injury. The adoption of this assessment in the clinical setting will help clinicians establishing realistic rehabilitation goals and monitor the effects of these treatments over time.

II. MATERIALS AND METHODS

A. Participants

We retrospectively analysed the data of cSCI subjects who underwent a functional evaluation protocol at the Spinal Cord Unit of the Santa Corona Hospital in Pietra Ligure, Italy.

The inclusion criteria were: cervical spinal cord injury between C3 - C6 (complete lesion American Spinal Injury Association (ASIA) grade A or incomplete lesion ASIA grade B or C); more than 6 months elapsed since the injury; the ability to perform shoulder and arm movements. The exclusion criteria were: neurological impairments not related to the injury; a cognitive and/or a psychiatric disorder (Mini Mental test score below 27); inability to provide consent.

Twelve cSCI subjects (lesion level between C5 and C7, age 34.7 ± 13.5, 4 females, see Table I in Supplementary Materials) matched these criteria and were included in the study.

While for the ROM and MMT tests the optimal performance values, i.e., the performance of unimpaired young adults, are reported in the literature [8], [21], to obtain a set of reference values for the instrumented evaluation, we analysed the data related to the performance of six unimpaired subjects (UNI) with no history of neurological or muscular disorders (age 25 ± 4.9, 2 females).

The study was conducted in accordance with the national guidelines and the ethical standards of the Declaration of Helsinki (2013 revision) and the retrospective study was approved by the local ethical review board (Comitato Etico Regione Liguria, protocol n. CER Liguria: 585/2021). All participants signed an informed consent, which included the consent for the analysis of the data for scientific purposes and the publication of the results.

B. Experimental Setup and Protocol

All cSCI participants underwent a functional evaluation protocol that included:

- *MMT*, a method to assess muscle strength through manual evaluation. It involves testing muscles against resistance. In our assessment, we evaluated the scapulae, shoulders and arms muscles (see Table II in the Supplementary Materials). A physical therapist graded each muscle with a number from 0 (no visible or palpable contraction) to 5 (normal strength).
- *ROM*, a method to assess upper-body mobility. A trained physical therapist measured the active ROM of both arms using a goniometer (see Table III in the Supplementary Materials) while participants were seated in their wheelchairs.

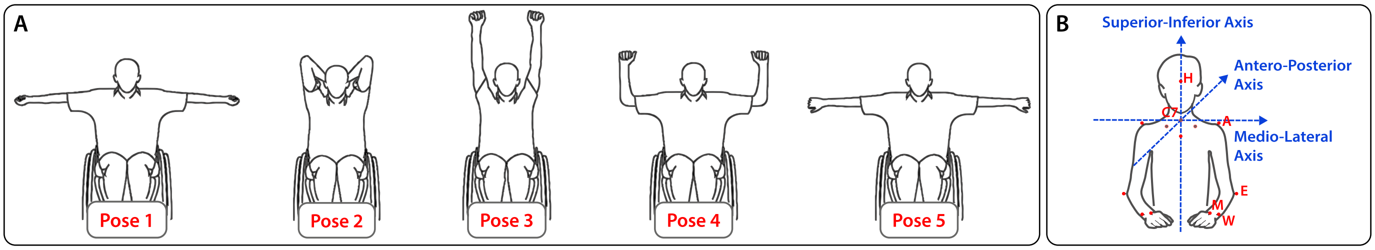

Fig. 1. Panel A: The five poses of the arm stabilisation task of the VLT manual [18]. Panel B: An illustration displaying the markers' placement on the upper body (red dots, H: head, C7: spinal process of C7, A: acromion, E: elbow, W: wrist and M: metacarpus) and the three axes of the body (medio-lateral, superior-inferior and antero-posterior axis) indicated by blue dotted arrows.

- *Arm stabilisation task* of the VLT manual, selected as a method to evaluate bilateral coordinated arm movements. The VLT manual is clinically used to assess the function of the arm and hand with tasks representing the level of activity in accordance with the International Classification of Functioning, Disability, and Health [22]. In our assessment, we adopted the task designed to evaluate bilateral arm function. This task requires participants to stabilize both arms in space against gravity for at least 5 seconds. It consists of 5 different poses, each progressively more challenging. In the VLT manual, pose 1 is identified as the least demanding movement, while pose 5 represents the most difficult movement. Participants were instructed to assume each pose at their preferred speed.

Detail descriptions of each pose (see Fig. 1A) are as follows: *Pose 1*, arms positioned horizontally (parallel to the floor) in the lateral direction, i.e., along the medio-lateral axis (see Fig. 1B), with the elbows fully extended. Thumbs are pointed posteriorly; *Pose 2*, elbows pointing upward while completely flexed, with the hands touching the neck and the forearms touching the head; *Pose 3*, arms positioned over the head with the elbows completely extended along the superior-inferior axis (see Fig. 1B) and the upper arm in outward rotation; *Pose 4*, arms positioned horizontally along the medio-lateral axis, with the elbows flexed 90° in outward rotation; *Pose 5*, arms positioned horizontally (parallel to the floor) in the lateral direction, with the elbows fully extended, i.e., with the arms along the frontal axis. Thumbs are pointed downward.

Each participant performed 6 repetitions for each pose.

C. Data Recording

Muscle activity and kinematic data from the upper trunk and arms were recorded during the arm stabilisation task. The kinematic data were collected using a motion capture system (SMART DX, BTS Bioengineering, Milan, Italy) which consisted of 8 infrared cameras, 2 video cameras and reflective spherical passive markers of 1.5 cm in diameter. During the test we recorded, at a sampling frequency of 100 Hz, the position of 13 markers positioned on the head, the spinal process of C7, sternum and bilaterally on the scapulae, acromions, elbows, wrists and metacarpi ([23], Fig. 1B). The myoelectrical activity of the upper body was recorded bilaterally and simultaneously from 12 muscles: biceps brachii caput brevis (BB-Brevis), biceps brachii caput longus (BB-Long), triceps brachii caput longus (TB-Long), triceps brachii caput lateralis (TB-Lat), pectoralis major (PECT), deltoideus anterior (DELT-Ant), deltoideus medius (DELT-Med), deltoideus posterior (DELT-Post), trapezius pars transversa (TRAP), latissimus dorsi (LAT), infraspinatus (INFR) and rhomboideus major (RHOM). The muscles were recorded with a sampling frequency of 1 kHz using two synchronized systems: the MINI WAVE wireless EMG (Cometa systems, Milan, Italy) and the BTS POCKETEMG (BTS Bioengineering, Milan, Italy). The surface electrodes were placed in accordance with the recommendations of the "Surface Electromyography for the Non-Invasive Assessment of Muscles" [24]. Instrumented data were processed using Matlab (MathWorks, Natick, MA, USA).

D. Data Analysis

1) Kinematic Signals Analysis:

a) Kinematic Data Pre-processing: The markers' trajectories were sampled at 100 Hz and smoothed with a fourth-order Shavitz–Golay filter with a cut-off frequency of 15 Hz [23], which was also used to obtain the subsequent derivative terms (velocity and acceleration). For each pose of the arm stabilisation task, the onset and end of the movement were detected considering the speed of the marker placed on the metacarpus of each arm. The onset of the movement was defined as the first time instant at which the speed of the marker exceeded 10% of the maximum peak speed, while the end of the movement was defined as the time instant corresponding to the first local minimum after the peak speed [25].

b) Kinematic Parameters: To quantify the time required to assume each pose, we computed the "Movement Duration" (seconds) as the elapsed time from the onset to the completion (end) of each movement. As for pose performance, since the arm stabilisation task required participants to assume 5 bilateral upper limb positions mainly distributed along the medio-lateral axis with their elbows, wrists and hands at various heights, we focused on analysing: (a) the planarity of poses; (b) the position along the superior-inferior axis of the arms and head.

For (a), we applied the Principal Component Analysis (PCA) to the entire data set (390 × 3), which included the coordinates of the 13 markers at the end of the 6 repetitions of the 5 poses. From this analysis, we identified the principal components (PCs) and then computed the Variance Accounted For (VAF) by each PC. The greater the % of variance associated with the first two PCs, i.e., the lower the % of variance of the third PC, the higher the planarity of the poses. In other words, we used PCA as a simple method to find the plane explaining most of the variance of the dataset. We also investigated how each pose contributes to the VAF by each PC.

For (b), we considered the relative positions of the markers on acromion, elbow, wrist, metacarpus and of the markers on the head and C7 at the end of each movement. For each pair of markers (i, j) we computed the "Normalized Height" (nH, see Fig. 1 in Supplementary Materials for a schematic representation) as in:

$$\mathrm{nH_{i,j}} = \frac{|\mathrm{y_i} - \mathrm{y_j}|}{\mathrm{d(P_i, P_j)}} \tag{1}$$

with $\mathrm{y_i}$ and $\mathrm{y_j}$ the y-coordinates (i.e. the coordinate along the superior-inferior axis) of each marker and $\mathrm{d(P_i,P_j)}$ the Euclidean distance between the position of the 2 markers in the 3D space. According to (1), if the segment connecting the two markers is parallel to the superior-inferior axis $\mathrm{nH_{i,j}} = 1$, while if it is perpendicular to the superior-inferior axis $\mathrm{nH_{i,j}} = 0$. The nH was computed for the head-spinal process of C7 ($\mathrm{nH_{H,C7}}$), as well as bilaterally for the acromion-elbow ($\mathrm{nH_{A,E}}$), elbow-wrist ($\mathrm{nH_{E,W}}$) and wrist-metacarpus ($\mathrm{nH_{W,M}}$).

2) Muscle Signals Analysis:

a) sEMG Pre-processing: The recorded sEMG data were band-pass filtered between 20-450 Hz, rectified and low-pass filtered (4th order Butterworth filter, cut-off frequency 4 Hz) to obtain the muscles envelope [25]. The envelopes were then segmented considering a window starting 200 ms prior to the onset of the movement and finishing in correspondence with the end of the movement. The segmented envelopes were interpolated over a time base with 101 points to compare them over time [26]. During the assessment, the position of the electrodes did not change, allowing direct comparisons of muscle activation amplitudes for all the poses performed by the same participant. To compare the envelopes of different participants and of the two sides of the body of the same participant, we normalized the sEMG envelopes for their mean value computed over all the data collected from each participant [27].

b) Muscle synergies: According to the "muscle synergy theory", the CNS generates movements by coordinating specific patterns of muscle activations [28]. In recent years, researchers have developed several muscle synergies extraction algorithms based on this theory. These algorithms have proven to be effective in representing the coordination and underlying muscle strategies involved in movement control [13], [29].

In our study, we referred to the existing literature, and we extracted, for each participant, a set of spatial muscle synergies using the non-negative matrix factorization (NNMF, [27], [30], [31], [32]) algorithm. In line with previous studies investigating different movements [33] and tasks performed at various speeds [34], [35], the algorithm was applied to the amplitude and time-normalized sEMG envelopes. Specifically, we utilized the algorithm on a matrix generated by concatenating, for each muscle, the normalized sEMG envelopes of the 5 poses. The peculiarity of the NNMF algorithm is its ability to decompose sEMG envelopes in a defined number of positive components, or muscle synergies, each composed of weight coefficients (W), a discrete representation of how each muscle participates in the muscle synergy, and activation profiles (H), a representation of the temporal activity of each muscle synergy [30], [31], [32]. The implementation of the NNMF algorithm was based on the minimization of the difference between the muscle synergies and the combination of W and H. To avoid convergence to local minima, the extraction was repeated 50 times with random initializations, and we selected the solution explaining the highest overall amount of sEMG variance [32], [36], [37], [38], [39]. For each participant, we extracted 24 sets of muscle synergies.

To determine the minimum number of muscle synergies needed to reconstruct the data set, we considered for each participant the common or the higher value obtained from 2 methods based on the inspection of the fraction of total variation explained by the synergy model (R^2) [12], [13], [40]. The 1st method selected the minimum number of synergies (N) needed to attain a R^2 higher than 90% and the 2nd method was based on the detection of a change in the slope of the R^2 profile. By performing a series of linear regressions on the fractions of curve included between the n-synergy, with $n = 1{:}24$, and its last point, the 24th synergy, the minimum number of synergies was selected as the smallest value for which the mean squared error (MSE) of the linear regression was less than 10^{-4}. To allow easy comparison, the same number of muscle synergies was retained for all participants. The number was established as the rounded average across participants [41]. Since the order of muscle synergies extracted might differ among participants, we matched the muscle synergies among participants according to their similarity, determined using normalized scalar products, with a set of reference synergies. These reference synergies were obtained by grouping the muscle synergies of the unimpaired participants with a hierarchical clustering procedure based on the minimization of the Minkowski distance between weighting coefficient vectors [29], [36].

Following the reordering of muscle synergies, we conducted both qualitative and quantitative analyses to compare the W of each synergy between populations. The 1st analysis involved identifying the primary muscles of each synergy by examining the amplitudes of the W extracted from the unimpaired population, which served as a reference. The primary muscles were determined based on the largest W and compared to those of the cSCI population. The 2nd analysis involved using normalized scalar products to measure the similarity of W amplitudes: (i) within ($\mathrm{DOT_{UNI}}$, $\mathrm{DOT_{cSCI}}$) and (ii) between populations ($\mathrm{DOT_{BTW}}$). The latter was obtained by comparing each cSCI participant with all unimpaired participants.

c) Spinal maps activity: Spinal maps represent the spatiotemporal motoneuronal (MN) activity along the rostrocaudal axis of the spinal cord and are a valuable tool for examining the organization of the MN activity and identifying specific alterations related to neurological lesions [42].

In accordance with the literature [13], [29], for each spinal segment, we computed the indirect measure of the MN activity during task performance as the weighted summation of all sEMG signals innervated by such segment. The weight coefficients were selected in relation to the set of muscles recorded and the value of each weight was set in accordance with Kendall's reference segmental charts (see Table IV in the Supplementary Materials, [42]).

To assess the similarity between spinal maps, we used the 2D Pearson's correlation coefficient (ρ) [13], [29] to compare maps (i) within the unimpaired population (ρ_{UNI}) and (ii) between the two populations (ρ_{SCI}). The latter measure was computed by averaging the values obtained by comparing each cSCI participant with all unimpaired participants.

E. Statistical Analysis

To determine whether there were significant differences in clinical test outcomes between the left and right upper body of cSCI participants, we conducted a Wilcoxon signed-rank test.

To test the hypothesis that the cSCI and unimpaired attained significantly different values of VAF by each PC, we utilized, on both the values extracted from the entire dataset and the ones extracted for each pose, an Independent Samples t-test.

To test the hypothesis that cSCI participants attained significantly different values of movement durations, $\mathrm{nH}_{\mathrm{A,E}}$, $\mathrm{nH}_{\mathrm{E,W}}$ and $\mathrm{nH}_{\mathrm{W,M}}$, than those expected for this task (i.e. those of unimpaired participants) and to examine if there were any lateral asymmetries, we conducted a mixed-design ANOVA for each pose. The ANOVA included one within-subjects factor "arm" (left and right) and one between-subjects factor "population" (unimpaired and cSCI). Since $\mathrm{nH}_{\mathrm{H,C7}}$ is not computed bilaterally, to test the hypothesis that cSCI participants attained significantly different values of $\mathrm{nH}_{\mathrm{H,C7}}$compared unimpaired participants, we conducted, for each pose, an Independent Samples t-test.

To investigate if there was a significant difference in terms of muscle synergies W similarity within each population and between populations, we conducted two Independent Samples t-tests. Specifically, we compared $\mathrm{DOT}_{\mathrm{cSCI}}$ vs $\mathrm{DOT}_{\mathrm{UNI}}$ and $\mathrm{DOT}_{\mathrm{UNI}}$ vs $\mathrm{DOT}_{\mathrm{BTW}}$, for each extracted muscle synergy.

Finally, to examine whether there were significant differences in spinal maps' activity between populations and to assess any potential lateral asymmetries, we conducted, for each pose, a mixed-design ANOVA on the spinal maps 2D Pearson's correlation coefficients (ρ), considering one within-subjects factor "arm" (left and right) and one between-subjects factor "population" (unimpaired and cSCI).

Prior to each statistical analysis, parameters were tested with the Shapiro-Wilk test, to verify the normality assumption. The parameters identified as not normally distributed were reshaped using the Box-Cox transformation.

The statistical analyses were performed within Jamovi environment (Jamovi software 0.9.2.8). In all tests, statistical significance was set at $p < 0.05$. In the figures, p-values smaller than 0.001 are denoted with "$**$", while p-values smaller than 0.05 are denoted with "$*$". A Bonferroni correction for multiple comparisons was applied to the mixed-design ANOVA post hoc analysis.

III. RESULTS

A. Clinical Evaluation

Participants with cSCI attained lower MMT scores in all body districts (scapula: 3.65 mean ± 0.37 std; shoulder: 3.62 ± 0.20; elbow: 3.05 ± 1.84 and wrist: 2.85 ± 0.88) compared to the maximum score of 5 expected for unimpaired individuals. Specifically, cSCI participants displayed particularly low MMT scores in elbow extension, wrist flexion, and wrist pronation (see Fig. 2 in Supplementary Materials). No differences were observed between the left and right body sides.

TABLE I

ROM VALUES (DEG) OF cSCI PARTICIPANTS (MEAN ± STD)

	cSCI Right arm	**cSCI Left arm**	**Reference Values** [21]
Shoulder			
Flexion	127.5 ± 22.4	132.5 ± 25.1	180
Abduction	95.5 ± 52.3	99 ± 51.1	180
Hor. Adduction	27.5 ± 12.5	25 ± 13.7	45
Hor. Abduction	120 ± 18.2	113.5 ± 14.1	135
Elbow			
Flexion	136.9 ± 14.3	137.2 ± 12.3	150
Extension	9.5 ± 15.7	5 ± 6.7	0
Wrist			
Flexion	43.5 ± 20.7	41 ± 19.8	80
Extension	64.5 ± 13.0	60.5 ± 10.9	70
Supination	82 ± 11.8	85.5 ± 9.2	80

Regarding the ROM test outcomes (see Table I), there were no significant differences in ROM values between the right and left arms of the cSCI population. The ROM values for shoulder flexion, abduction, horizontal adduction and abduction, elbow flexion and extension, and wrist flexion of cSCI participants were particularly lower compared to the reference values [21].

B. Kinematic Performance

Except for pose 1, cSCI participants exhibited significantly higher, yet variable, movement durations (pose 2: $F(1,16) = 5.73$, $p = 0.03$; pose 3: $F(1,16) = 10.4$, $p = 0.005$; pose 4: $F(1,16) = 11.5$, $p = 0.004$; pose 5: $F(1,14) = 18.9$; $p < 0.001$) for each pose, with no significant difference between arms (see Fig.2A).

As for the % of VAF explained by the PCs extracted from the entire dataset (Fig. 3A), the first two PCs explained more than 96% of the variance of the entire dataset, and no significant differences were observed in terms of planarity between cSCI and unimpaired participants, with both populations exhibiting low % of VAF explained by PC3. However, significant differences between populations were observed in the VAF explained by the first two PCs. cSCI participants obtained significantly higher values of VAF% for PC1 (and consequently significantly lower values of VAF explained by PC2) compared to the unimpaired participants (PC1: $p = 0.009$; PC2 $= p = 0.007$).

The reason behind these differences is evident from the analysis of the pose's contribution to the VAF explained by each PC reported in Fig. 3B.

The variance explained by PC1 was mainly attributed to poses 1 and 5 for both populations, with a minor additional contribution from pose 4. These poses required participants to perform complete or partial arm extensions, suggesting that PC1 predominantly captured the variability associated with arm extension along the medio-lateral axis. The significantly

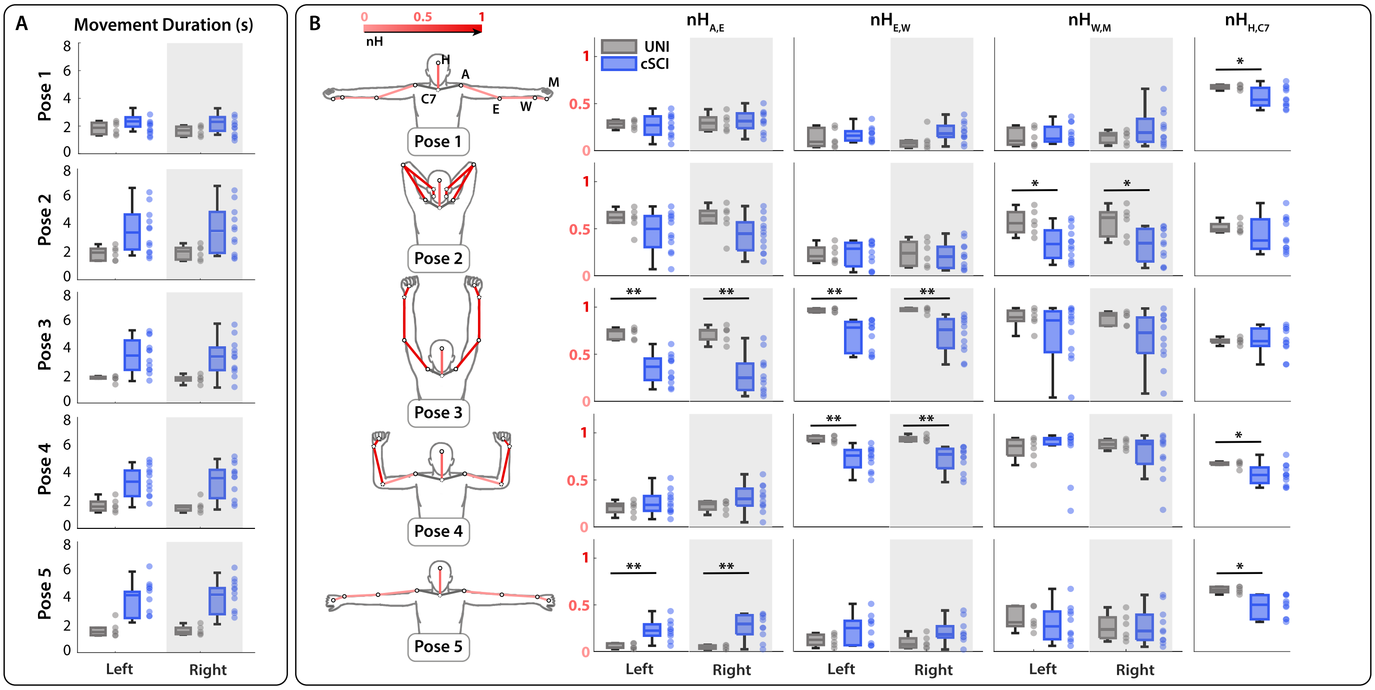

Fig. 2. Panel A: Movement duration (seconds) of cSCI and unimpaired (UNI) populations for each pose and arm. Panel B: Normalized Height (nH) values for each pose between acromion (A), elbow (E), wrist (W), metacarpus (M), head (H) and the spinal process of C7 (C7). Boxplots display median and 25th - 75th percentiles for cSCI (blue) and UNI (grey) populations.

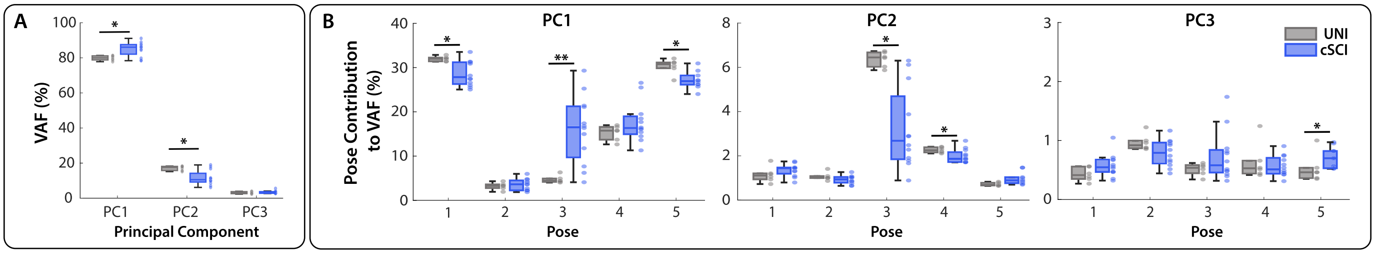

Fig. 3. Panel A: VAF explained by PCs extracted from the entire data set, expressed as the percentage (%) of the total variance. Panel B: Contribution of each pose to the VAF by each PC. Boxplots display median and 25th - 75th percentiles for cSCI (blue) and unimpaired (grey) populations.

lower values of variance explained by PC1 for poses 1 ($p = 0.01$) and 5 ($p = 0.007$) in the cSCI population compared to the unimpaired population reveal the difficulty of cSCI participants in completely extending their arms against gravity.

PC2 predominantly resulted from pose 3, where participants were required to extend their arms upward. However, cSCI participants encountered considerable challenges in executing this pose, resulting in their hands being positioned at a lower height with respect to unimpaired participants. Consequently, the cSCI population exhibited reduced variability along PC2 ($p = 0.003$) and increased variability along PC1 ($p < 0.001$) compared to the unimpaired population. Smaller, but still significant, differences were also observed in PC2's VAF for pose 4, indicating partial difficulty for cSCI participants in performing this pose as well.

As for PC3, this component exhibited lower variance across all poses, with the highest variance observed in pose 2 for both populations. In this pose, both unimpaired and cSCI participants positioned their hands behind their neck with their elbows facing upward, leading to a forward shift of both the elbows and the head. This suggests that PC3 mainly captured the variability associated with the antero-posterior axis. The significant difference between populations in VAF explained by this PC for pose 5 reveals that cSCI participants tended to shift their upper-body forward when performing this pose.

As for the analysis of the arms and head position along the vertical axis, the nH values are reported in Fig. 2B.

In pose 1, no significant differences were observed between populations in terms of $nH_{A,E}$, $nH_{E,W}$ and $nH_{W,M}$. This pose was the least demanding pose of the 5, and participants of both populations were able to fully extend the arms horizontally in the lateral direction. This is confirmed by the lower values of $nH_{A,E}$, $nH_{E,W}$ and $nH_{W,M}$. Moreover, cSCI participants tended to flex their head in the forward direction, as indicated by the lower values of $nH_{H,C7}$. In pose 2, cSCI participants exhibited a tendency to flex both wrists, as indicated by the lower values of $nH_{W,M}$ (Population: $F(1,16) = 9.98$, $p = 0.006$). In pose 3, cSCI participants were not able to fully flex the shoulders and completely extend the elbows. This is evidenced by the lower values of $nH_{A,E}$ ($F(1,16) = 26.5$, $p < 0.001$) and $nH_{E,W}$ ($F(1,16) = 22.4$, $p < 0.001$). In pose 4, cSCI participants exhibited difficulty maintaining a 90° angle of flexion in

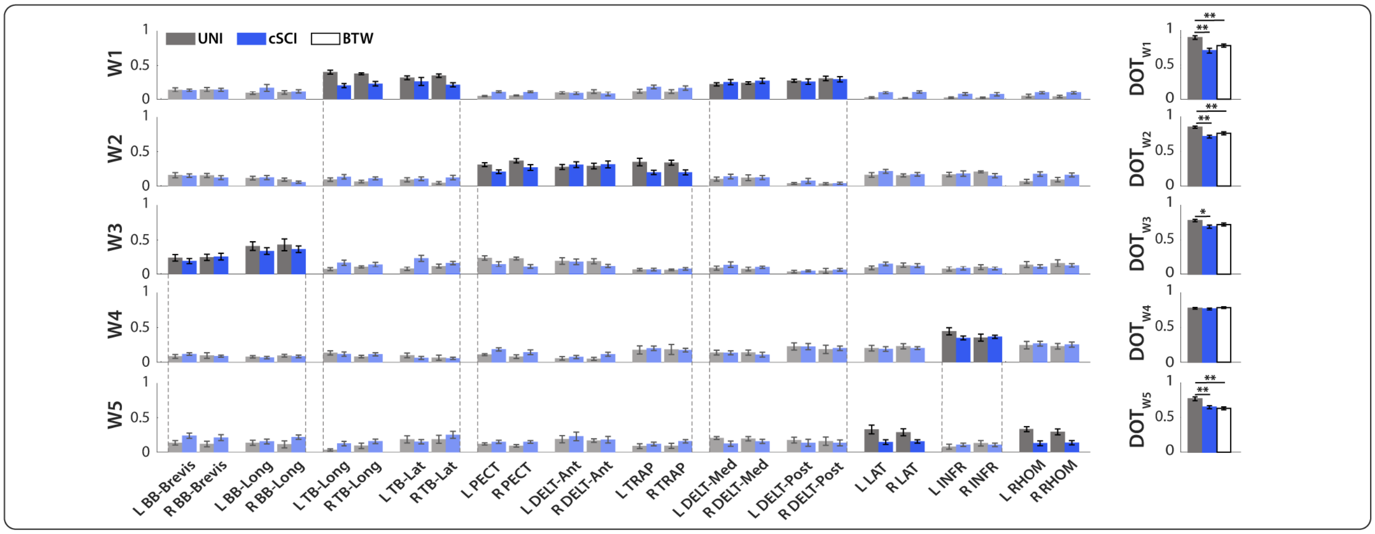

Fig. 4. Weight coefficients (W, mean ± se) of the 5 muscle synergies for unimpaired (grey bars) and cSCI (blue bars) populations and the scalar products (DOTs, mean ± se) computed within populations (DOT_{UNI} in grey, DOT_{cSCI} in blue) and between populations (DOT_{BTW}, white bars, black outline). The muscle clusters that mainly describe each synergy are represented in sharper colours. The name of the muscles from the left side of the body is preceded by the letter "L", while the ones from the right side of the upper body are preceded by the letter "R".

both elbows, as indicated by significant differences in $nH_{E,W}$ between populations ($F(1,16) = 30.5$, $p < 0.001$). They also experienced difficulty in maintaining their head straight upward, as evidenced by the lower values of $nH_{H,C7}$($p = 0.025$). In pose 5, significant differences were observed in $nH_{H,C7}$ ($p < 0.001$) and $nH_{A,E}$ ($F(1,16) = 22.3$, $p < 0.001$). The cSCI population was unable to fully extend their forearms against gravity, resulting in higher $nH_{A,E}$ values. Furthermore, they were unable to maintain their head upward, as indicated by the lower values of $nH_{H,C7}$.

C. Muscle Synergies

1) Number of Extracted Muscle Synergies: No differences were observed in the number of muscle synergies for the unimpaired and cSCI participants (see Fig. 3 in Supplementary Materials): 5 muscle synergies were identified for both populations (unimpaired: 4.5 mean ± 0.55 std and cSCI: 4.83 ± 1.19).

2) Muscle Synergies Organization - Weight Coefficients: The weight coefficients (W, Fig. 4) of the 5 muscle synergies of both populations were characterized by equal values for each pair of bilateral muscles.

W1 principally involved the TB-Long and TB-Lat, elbow extensors, and the DELT-Post and DELT-Med, usually recruited to abduct and extend the shoulder. In the cSCI population, the contribution of both triceps was lower than in the unimpaired population.

W2 principally involved the PECT and DELT-Ant, which usually cooperate in shoulder flexion and horizontal adduction, and the TRAP, whose main function is to stabilize and adduct (retract) the scapula, maintaining it firmly attached to the chest wall. In synergy 2 the cSCI population has a lower contribution of both the PECT and the TRAP.

W3 principally involved the BB-Brevis and BB-Long, typically recruited for the flexion and supination of the elbow and flexion of the shoulder. BB-Long has also a role in the shoulder adduction. In the cSCI population, the contribution of the latter muscle is lower compared to the unimpaired population, while the weight coefficients of the triceps, both TB-Long and TB-Lat, are slightly higher. In W3, the Biceps and Triceps muscles of cSCI participants appear to be co-activated.

W4 principally involved the INFR, which is mostly recruited to externally rotate the arm and stabilize the shoulder joint.

W5 principally involved the LAT, one of the main stabilizers of the spine/torso during its various movements, and the RHOM, one of the main stabilizers of the upper-body when performing arm movements. In W5, the cSCI population has a lower contribution of LAT and RHOM.

The difference observed by visual inspection between the populations in W1, W2 and W5 was confirmed by the statistical analysis (DOT_{BTW} vs DOT_{UNI} – W1: $p < 0.001$, W2: $p < 0.001$, W5: $p < 0.001$). The weights coefficients were similar among unimpaired participants, as confirmed by the high values of DOT_{UNI}. In contrast, the weights' coefficients similarity among cSCI (DOT_{cSCI}) was moderate but lower than the unimpaired. A significant difference between populations was observed in the inter DOTs of all synergies except W4 (DOT_{cSCI} vs DOT_{UNI} - W1: $p < 0.001$, W2: $p < 0.001$, W3: $p < 0.001$, W5: $p = 0.009$).

3) Muscle Synergies Temporal Activities - Activation Profiles: The activation profiles (H) of the 5 muscle synergies extracted are illustrated in Fig. 5.

H1 mainly contributed to the execution of pose 5, the most challenging pose among the 5, partially to pose 3 and, to a lower extent to pose 1. Indeed, these 3 poses required a higher activation of the triceps to maintain against gravity both arms extended parallel to the floor. In the cSCI population, due to the weakness of both triceps' muscles, the activation profiles of poses 1, 3 and 5 are characterized by anticipated activation timings. The cSCI population activation profile of pose 5 is also characterized by a significantly lower amplitude.

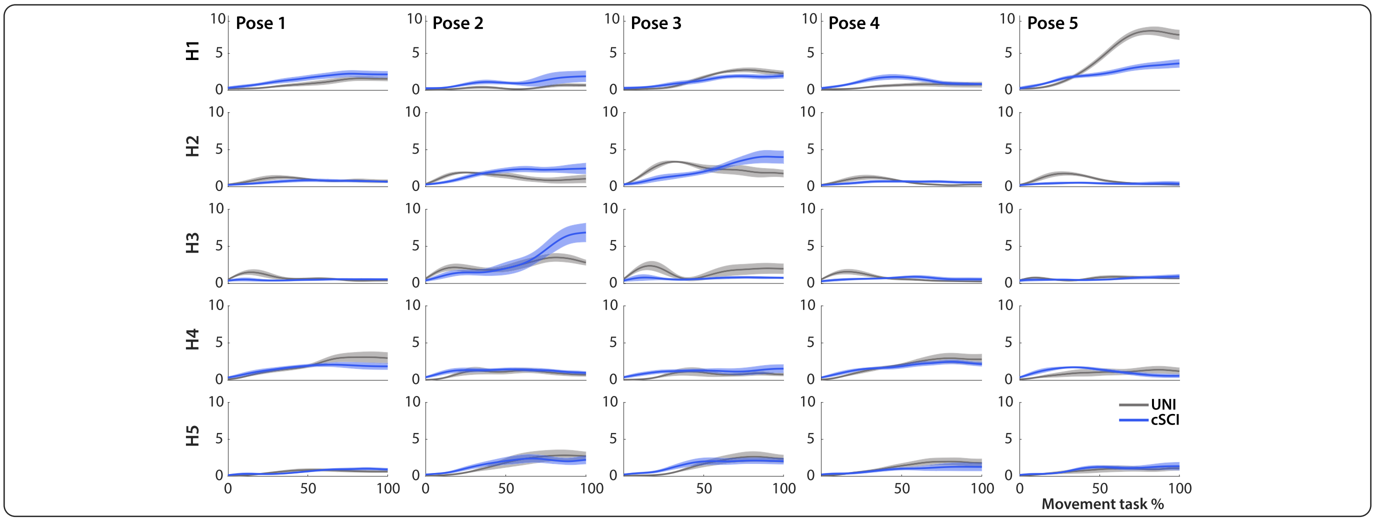

Fig. 5. Muscle synergies activations profiles (H, mean ± se) for each pose. Grey and blue lines respectively represent the unimpaired and cSCI populations.

H2 was mainly active in pose 2 and pose 3, i.e., the two poses that requested participants to raise the elbows above the shoulder level. Due to the smaller contribution of the TRAP and PECT muscles, the timing of this activation for the cSCI population was different compared to the unimpaired participants. While the activation profiles of both poses of the unimpaired participants are characterized by a peak in amplitude in the initial part of the movement (pose 2 at ∼20% and pose 3 at ∼30%), for the cSCI population they are characterized by a delayed and gradual increasing trend with a peak in pose 3 at ∼80% of the movement execution and in pose 2 at ∼60% of the movement execution.

H3 in the unimpaired population was mainly active in (i) the initial part of the movement of all poses and (ii) the second part of the movement of poses 2 and 3. This synergy, indeed, represents how, in the first part of the movement, unimpaired participants recruited muscles that mainly contributed to the flexion of the forearm (BB-Brevis and BB-Long) and arm (PECT). Moreover, in poses 2 and 3, the two poses that required participants to move more against gravity, H3 was active also in the second part of the movement when participants had to gradually reach a complete flexion of the arms and, in pose 2, also maximally flex the forearms. In the cSCI population, instead, H3 was predominantly active in pose 2, describing the strategy adopted by the cSCI participants to complete such pose. During 60% to 100% of the movement execution of pose 2, cSCI participants simultaneously activated the Biceps muscles (H3) and the PECT, DELT-Ant muscles and TRAP (H2).

H4 mainly contributed to pose 1 and pose 4, i.e., the only two poses that requested participants to rotate their arms externally. No significant differences were observed in the activation timing and amplitude of poses 1 and 4 between populations.

H5 was mainly active in the second part of the movement execution of poses 2 and 3, once again the only poses that requested participants to raise the elbows above the shoulder level. In H5, the activation profiles of pose 2 and 3 in the cSCI population are characterized by a small anticipation in the activation timing, with no difference in amplitude.

Most poses exhibited low variability in their activation profiles (low standard errors), except for pose 2 in synergy 3.

D. Spinal Maps Activity

Spinal maps activities for each pose are reported in Fig. 6A.

In poses 1, 3 and 4 no significant differences were observed in the amplitude and timing of the spinal maps activity of the cSCI and unimpaired participants (Fig. 6B). Both populations had an activity in the segments that innervate the TRAP muscles (C2-C3) for almost the entire duration of the movement and an activity in C5-C6 (the segments that innervate the muscles involved in shoulder flexion-abduction) and C8-T1 (segments that innervate the elbow extensors and the INFRA, an external rotator of the shoulder) starting from about 40-50% of the movement until its completion (Fig. 6A). Pose 3 appears to have higher activation amplitudes than poses 1 and 4. This was expected as pose 3 required participants to perform greater shoulder flexion and abduction.

In poses 2 and 5, the spinal maps activity organization appeared to be different between populations, both in amplitude and timing (Fig. 6B, 2nd and 5thpanels).

In pose 2, one of the poses that requested participants to raise the elbows above the shoulder level, the unimpaired population displayed an activity of the C2-C3 segments, principally involved in the innervation of the TRAP muscles, in the first part of the movement execution (10-40%) that diminished in the remaining part of the movement. Conversely, the cSCI population appeared to have a stable activity of the C2-C3 segments between 30-100% of the movement task (Fig. 6A). As for the lower segments of the cervical section of the spine, in both unimpaired and cSCI participants the C5-T1 segments appeared to be active from ∼20% to 100% of the movement task. For the unimpaired participants, the C5-T1 segments had a higher activation between 60% and 100% of the movement task, while the C5-T1 segments of the cSCI population had an anticipated activation (40-100% of

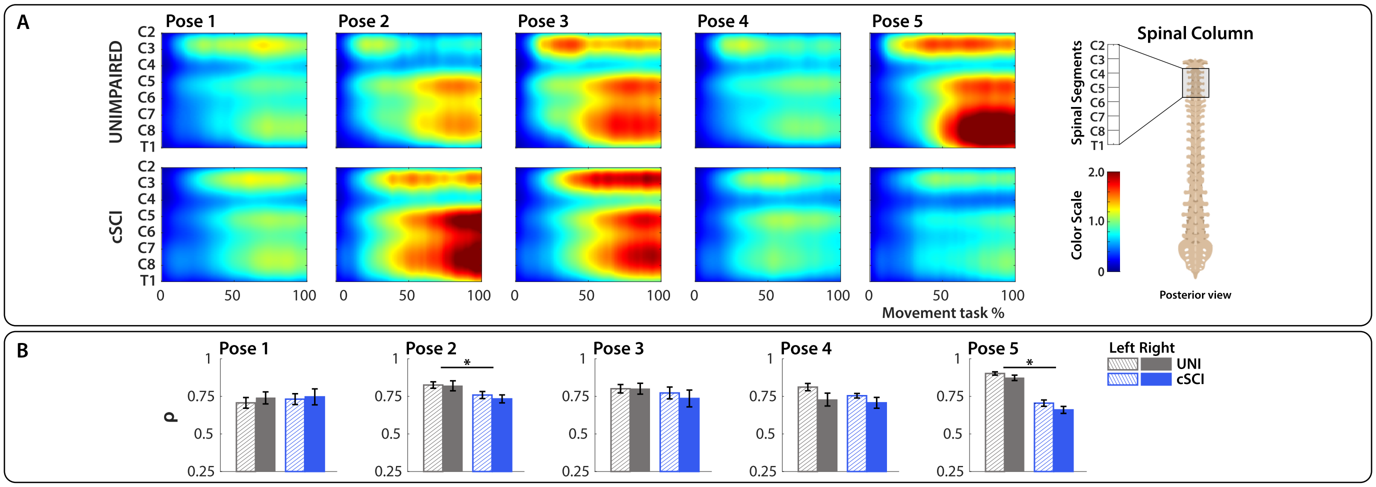

Fig. 6. Panel A: Spinal maps activity for each pose from the Left side of the body (see Fig. 4 in Supplementary Materials for complete figure) averaged among all subjects of each population. Panel B: 2D Pearson's correlation coefficients (ρ, mean ± standard error) of the spinal maps for all poses. Grey bars represent the values within the unimpaired population (ρ_{UNI}) and blue bars represent values between populations (ρ_{SCI}).

the movement task). Moreover, the activity in C5-T1 segments of the cSCI population was higher in amplitude compared to the unimpaired population, especially in the final part of the movement execution where the activity of the C5-T1 segments in the cSCI population reached its maximum peak. The correlations analysis (Fig. 6B, 2nd panel) confirmed that the MN activity was significantly different between populations ($F(1,85) = 8.66$, $p = 0.004$), while there were no differences between body sides.

In pose 5, unimpaired participants had higher activation amplitudes than the cSCI participants, with different activation timings of most of the spine segments. The C2-C3 segments of both populations were mainly active between 20-100% of the movement execution with a higher activation amplitude for the unimpaired participants. The C5-T1 segments appeared to be active in the second part of the movement execution (50-100%) with a peak in the amplitude over C7-T1. The C5-T1 segments of the cSCI population were already active at ∼40% of the movement execution until its completion with no changes in the activity amplitude which appeared to be stable during the entire activation period. The correlation analysis of the spinal maps (Fig. 6B, 5th panel) highlighted a significant difference in the MN activity between populations ($F(1,85) = 8.94$, $p = 0.004$).

IV. Discussion

The results of our assessment offer a first objective quantification of the bilateral neuromotor changes post-cSCI.

The ROM and MMT tests unveiled the main deficits of the single joints/muscles, while the instrumented data provided an overall description of how the interplay of these deficits affects the ability of cSCI participants to perform bilateral movements.

Both clinical tests highlighted a strong alteration in the motor function of the upper limb's most distal joints, with the ROM test also revealing, in accordance with the literature [43] and with the level of injury, severe limitations in shoulder motion, especially in its abduction and flexion. The instrumented analysis, on the other hand, highlighted how these limitations have impacted the multi-joint kinematic-muscular patterns adopted by cSCI to execute the arm stabilisation task.

In the following, we will discuss in detail the main findings.

A. Bilateral Arm Extension With External Shoulder Rotation Is Mostly Retained After cSCI

Despite the severe limitations in motor functions evidenced in the ROM and MMT, the instrumented assessment revealed that, even after a cervical lesion, cSCI participants retained most of their ability to extend both arms along the medio-lateral axis when their shoulders are in a state of external rotation and their elbows are either completely extended or flexed 90° (poses 1 and 4). These findings are consistent with previous research conducted [19], which demonstrated that individuals with C5-C6 injuries exhibit kinematic characteristics similar to those observed in unimpaired individuals when performing reaching movements in the lateral direction. Our muscle analysis corroborated these results, revealing that this ability is maintained without substantial alterations in the muscular strategies adopted to perform such movement. Both cSCI and unimpaired participants exhibit comparable spinal maps activity during poses 1 and 4, as well as a similar structure of the muscle synergies that mainly describe these poses. In both analyses, the muscle usually recruited to externally rotate the shoulder, the INFRA, appears to have activation levels comparable with the unimpaired participants.

B. Bilateral Arm Extension With Internal Shoulder Rotation and Overhead Movements Are Affected by cSCI

The effect of the interaction between the motor deficits identified by the clinical tests is evident in poses 2, 3 and 5. The cSCI participants have severely lost their ability to extend both arms along the medio-lateral axis with the elbows completely extended when their shoulders are in a state of internal rotation (pose 5), and partially lost their ability to raise both arms above shoulder level (poses 2 and 3). Confirming our previous assumptions, these inabilities were linked to alterations in the neuromotor functions of the shoulders and elbows. The inability of cSCI participants to internally rotate the shoulder joint with the elbow fully extended appears to be related to a combined weakness of the primary internal rotator muscles of the shoulder and the primary extensors muscles of the elbow. The muscle analysis revealed, indeed, a change in the muscle synergies that mainly describe this type of movement (synergy 1 and partially synergies 4 and 5), as well as an alteration in the MN activity. More in detail, the spinal maps analysis unveiled an alteration in the amplitude and time of activity of the spinal segments that mainly innervate the LAT and PECT (shoulder internal rotators) and TB muscles (elbow extensors), whereas the synergies analysis unveiled a change in the W recruited to perform this type of movement. The synergies of cSCI participants display a significantly lower contribution of the LAT, PECT and both TBs.

The partial loss of ability to raise both arms above shoulder level observed in cSCI participants (poses 2 and 3) is in line with previous research findings. Robinson et al. [19] reported reduced kinematic capacity in individuals with C5-C6 SCI when reaching in the superior direction, which was attributed to low humeral elevation angles. Weakness in the shoulder glenohumeral joint muscles and elbow joint extensors were identified as possible causes of this reduction in kinematic capacity. Similarly, Acosta et al. [20] noted a restricted range of humeral elevation in individuals with C5-C6 SCI and observed differences in scapular kinematics between unimpaired and cSCI individuals. During shoulder flexion, reduced lateral rotation of the scapula was observed in cSCI individuals, suggesting that limitations in shoulder elevation could be primarily due to scapular instability. Our muscle analysis indicates that the loss of the ability to raise both arms above shoulder level in cSCI participants may be related to a combined weakness of the PECT, usually recruited to flex and horizontally adduct the shoulder, and of the main stabilizers of the spine and torso (RHOM and TRAP). Again, the muscle analysis revealed a change in the synergies that mainly describe this type of movement (synergy 2 and 5). The weights adopted by cSCI participants are characterized by a lower contribution of these muscles compared to the ones adopted by unimpaired individuals. The loss is "partial" as the ability to perform this movement appears to be highly dependent on the positioning of the forearm: the greater the extension of the elbow, the harder it was for cSCI participants to find kinematic-muscle strategies to stabilize the forearm and the more difficult it was to perform the movement. This is confirmed by the difference in kinematic performance (VAF% and nH) observed between pose 3, which requested to position both arms over the head with the elbows completely extended, and pose 2, which requested to point both elbows upward while completely flexed with the hands touching the neck. cSCI participants appear to be able to perform better kinematically in the latter pose. The instrumented analysis revealed that this difference in performance was due to the use of a kinematic compensatory strategy. To maintain both elbows flexed above the head level, cSCI participants fixed both wrists on the neck to increase and maintain the stability of the elbow joint. However, the challenge faced by cSCI participants in executing this pose is evident from the muscle synergies analysis. Pose 2 is characterized by a coactivation in the final part of the movement of the BPs (synergy 3), PECT, DELT-Ant and TRAP muscles (synergy 2), all of which exhibit higher levels of activation compared to the unimpaired population. This finding is in line with a previous study [43], that reported increased muscle activations in the humeral elevators (BPs, PECT and DELT-Ant) and scapula rotators (TRAP) of individuals with C6 SCI during movements involving shoulder elevation above 90° and elbow flexion. As also mentioned in [43], our results suggest that the altered muscle strategy could be attributed to compensating for the weakness in the shoulder glenohumeral joint muscles and the compromised distal control of the arm. Notably, consistent with [43], the variability in the activation profile of synergy 3 for this pose indicates that this compensatory strategy was adopted to differing extents within the cSCI population.

The observations made so far also confirm another of our initial hypotheses. Since the set of movements selected for the instrumented assessment requires participants to position the arms and forearms at different heights and configurations along the frontal/longitudinal axis, we also expected to uncover neuromotor changes related to the effects of gravity. Indeed, the deficiency of the shoulder glenohumeral joint muscles and of scapula/torso stabilisers was more observable in the task that required performing over-the-head movements (poses 2 and 3), while the deficiency of the elbow joint extensors was more visible in the movements that required a complete extension of the elbow against gravity (pose 3 and 5).

C. The High Inter-Individual Kinematic Variability in cSCI Population Had a Moderate Impact on Muscle Synergies

The assessment revealed high variability in the kinematic strategies adopted within the cSCI population. Notably, cSCI participants took longer to complete the poses compared to unimpaired participants. This difference in duration might have influenced the timing and/or magnitude of muscle activations. Prior studies [44], [45] on unimpaired participants have shown that variations in speed, and thus in duration, during reaching movements primarily impact muscle activations amplitudes rather than timing. The low within-population variability of the muscle synergy activation profiles, and the similarities between the arm stabilisation and reaching task, suggest that, also in this case, the difference in time execution might have a low impact on the timing of the muscle activation patterns. However, this should be verified with an ad hoc study.

Despite the considerable kinematic variability, the analysis of the muscle synergies weight coefficients and activation profiles within cSCI population, revealed a moderately high similarity within this population, consistent with previous literature on other neurological impairments [39], [46]. However, it is important to note that the similarity of the weight coefficients of the unimpaired population for specific muscle synergies was still significantly higher than those in the cSCI population. Furthermore, the level of similarity between the two populations was generally close to that of the SCI participants. These findings suggest that the similarity between populations was mainly influenced by the slightly higher inter-individual variability of the cSCI population, resulting in lower similarity values compared to those of the unimpaired participants.

D. The Efficacy And Applicability Of The Proposed Assessment Method

Despite intentionally opting for a simplified setup to expedite the assessment process and enhance clinical applicability - which resulted in a reduced number of markers and in the inability to conduct precise joint angle analysis - the selected kinematic parameters effectively captured the motor limitations and kinematic strategies employed by the cSCI participants. Similarly, the muscle analysis techniques employed (spinal maps and muscle synergies) proved to be effective in enhancing the comprehensiveness of the assessment. These approaches complemented the findings obtained from kinematic analysis by revealing any abnormal, weakened, or latent muscle activations associated with the observed kinematic outcomes. The efficacy of the proposed assessment is also supported by the literature. Our findings not only substantiate prior research on unimanual arm movements [19], [20], [43], [47], but also introduce new insights into the kinematic and muscle strategies employed by cSCI individuals when executing bilateral coordinated movements of increasing difficulty.

It should be noted, however, that not all clinical settings have access to a movement analysis laboratory, which limits the universal applicability of the proposed evaluation. Nevertheless, the assessment can be easily adapted to utilize more accessible technologies such as markerless approaches based on RGB video [48], [49] and depth or wearable sensors.

In the future, we intend to address these limitations by adapting the assessment to more accessible technologies, testing it on larger groups of unimpaired participants, and increasing the sample size of subjects with cSCI to validate our findings and improve applicability.

E. Future Developments and Limitations of the Study

Although the findings suggest that the proposed evaluation has the ability of providing relevant information regarding the changes in bilateral neuromotor function of the upper limbs in cSCI, the small data sample size does not allow a full generalization of the results. Nevertheless, the main goal of this study was to define and validate a functional evaluation capable of performing a more detailed and in-depth assessment of the upper limb bilateral impairment by investigating changes in kinematic performance, muscle activity and clinical outcomes.

We acknowledge that the number of unimpaired subjects tested in our study is small and not age-matched. However, we included these participants to characterize the instrumented task and establish the best performance in the proposed exercises.

Moreover, due to limited knowledge of the impact of additional information on therapeutic decision-making, future research will also examine the effect of the supplementary data provided by our assessment on rehabilitation outcomes.

V. CONCLUSION

The loss of upper limb bilateral function post-cSCI has a significant impact on independence and quality of life. To date, new improved methods are needed to thoroughly evaluate these motor functions across the continuum of care. To address this gap, we have developed and validated an evaluation approach that integrates standard clinical tests with an instrumented assessment, based on sEMG and motion capture systems. Unlike previous studies [4], [5], our approach provides quantitative measures, describing the kinematic-muscle strategies adopted by cSCI individuals during bilateral tasks. In a clinical setting, the reliability and accuracy of our proposed approach will allow clinicians to conduct an objective and longitudinal tracking of the cSCI subjects' motor deficits.

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Open Access funding provided by 'Università degli Studi di Genova' within the CRUI CARE Agreement