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Recovery of Distal Arm Movements in Spinal Cord Injured Patients with a Body-Machine Interface: A Proof-of-Concept Study

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1. Introduction

covariance matrix and combining them in a matrix H that generated the linear mapping from body to cursor vectors:

$$p^{(n)} = \begin{bmatrix} h_{1,1} & \cdots & h_{1,8} \\ h_{2,1} & \cdots & h_{2,8} \end{bmatrix} q^{(n)} = H\, q^{(n)} \quad (1)$$

where $q^{(n)}$ is the 8-dimensional "body vector" and $p^{(n)}$ the 2-dimensional control vector encoding the position of a computer cursor. More details of this procedure are in [30]. By establishing a correspondence of the task space—the space of cursor's positions—with this plane, we associated the control variables with the degrees of freedom that the impaired subjects spontaneously used with the greatest ease.

The training protocol (Figure 1B) consisted of 15 sessions of practice with the BoMI of about 45 min that were repeated for 5 weeks. The sessions were organized in four main blocks of increasing difficulty: 1 block of familiarization and 3 blocks of training. Through these, the user completed a series of different tasks, already adopted in [15,16]:

- Reaching. The subjects, starting from the center of the screen, had to reach for three times eight external targets equally spaced in eight directions (0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°), for a total of 24 center-out reaching movements. The external target was positioned at 8.5 cm from the center and appeared randomly in each of the eight directions. The subjects were to reach the external target before it changed color from green to red and then to come back to the central one. This color change happened 1 s after the external target appeared. The target was considered acquired when the cursor remained inside it for 500 ms. The reaching task was performed at the beginning (named 1st Reaching) and at the end (named 2nd Reaching) of each session.
- Vertical pong simulation. The subjects, by controlling the x and y coordinate of a paddle, were asked to hit a ball moving in the 2-d space of the game field. The prevalent motion of the ball was along the vertical direction (up/down). Subjects obtained a point for every hit, sending the ball to bounce off the top wall. During each session subjects played five epochs of pong, each lasting 2.5 min.
- Horizontal pong simulation. This task was the same as the vertical pong, but the movement of the ball was mostly horizontal (left/right) and the target wall was along the right side of the screen.
- Flash games. The BoMI had a library of flash games that the subjects could choose (e.g., Solitaire, Uno, or Arkanoid).

In the first block (familiarization block), the subjects began practicing and became acquainted with the BoMI. From session 5 the PT, thanks to a graphical user interface, introduced the modifications intended to encourage the cSCI subjects to recruit movement combinations that were more difficult to execute. The modifications consisted of:

(i). changing the contributions that each sensor gave to the movement of the cursor, by modifying the elements of the matrix H through the multiplication with the matrix D. D is a 2 × 8 matrix whose first row $\boldsymbol{d}_1 = [d_{1,1} \ \ldots \ d_{1,8}]$ contains the contribution of each sensors' channel to the horizontal cursor movement, and the second row $\boldsymbol{d}_2 = [d_{2,1} \ \ldots \ d_{2,8}]$ the contribution to the vertical movement. All its elements were initialized to 1, and to change, for example, the contribution of all sensor channels to the horizontal movement it was sufficient to set the coefficients of $\boldsymbol{d}_1$ >1.

(ii). changing the IMU signals by multiplying one or more IMUs by the gains contained in the matrix S, an 8 × 8 diagonal matrix. All the elements s_i were initialized to 1, if then s_i was set to be >1 the correspondent body signal q_i increased.

These operations are already described in [29,31], are expressed as:

$$H_{change} = H \odot (D\, S)$$

where D is 2 8, S 8 8 and the Hadamard product that operates a pairwise multiplication between the elements of the two matrices. The GUI, through few textboxes and

- Movement Time, time elapsed as the cursor reaches a target since it left the starting position;
- Linearity Index, length of the cursor trajectory to the external target normalized by the distance between start and end points. A linearity index equal to 1 means that the cursor moved along a straight line;
- Number of peaks in the velocity profile. We considered every peak larger than 15% of the maximum speed of each trajectory [33

The same approach was used in the body space to compute the relative contribution of each body side (b_L and b_R) and district (b_P and b_D) from the standard deviations (*std*) of the 2 channels (pitch and roll) of each IMU:

$$\frac{std_{pitch1}+std_{roll1}}{std_{tot}} + \frac{std_{pitch2}+std_{roll2}}{std_{tot}} + \frac{std_{pitch3}+std_{roll3}}{std_{tot}} + \frac{std_{pitch4}+std_{roll4}}{std_{tot}} \quad b_{LD} + b_{LP} + b_{RP} + b_{RD} = b_L + b_R = 1 \tag{8}$$

with $std_{tot} = std_{pitch1} + std_{roll1} + std_{pitch2} + std_{roll2} + std_{pitch3} + std_{roll3} + std_{pitch4} + std_{roll4}$ Similar to Equations (5) and (7), we defined b_{sym} and b_{distal} as

$$b_{sym} = (1 \quad j b_L \quad b_R j)\ 100 \tag{9}$$

$$b_{distal} = (b_{LD} + b_{RD})\ 100 \tag{10}$$

Also, in this case, with high symmetry we will have b_{sym} 100% and with a greater use of the distal body parts b_{distal} 100%. Differently from the indicators computed from the trajectories in the task space, the ones extracted directly from the IMUs output are not influenced by the BoMI mapping. Therefore, they account for the actual body movements. We should consider that the movements of the upper arm influence both readouts of the distal and proximal sensors. So, for example, in the arm kinematic chain a movement of the upper arm results also in a movement of the forearm. Thus, decoupled distal movement due to the elbow joint, that are the main target of the BoMI-based exercises proposed in this work, are related to symmetry values above the 50%.

We computed these indicators during two sessions: (a) session 4, the last session of the familiarization phase, and (b) session 15, the last session of the training phase.

2.4. Clinical Evaluations

According to prevalent clinical practice we decided to use the Manual Muscle Test (MMT) [34], performed by expert clinicians blind to the subjects' training, to assess upper body strength. In particular, we focused on three upper body regions: scapulae, shoulders, and arms. See Table S1, for details on the tested movements. Each movement was evaluated with a number from 0 (no movement) to 5 (normal movement). The maximum achievable score for the scapula is 15, for the shoulder is 30, and for the arm is 10.

To assess upper body mobility, we measured the Range of Motion (ROM) of the shoulders and arms in all the possible directions using a goniometer, see Table S2 for more information. Since cSCI subjects were tested while sitting in their wheelchair, we did not include shoulder adduction and shoulder extension measures due to substantial range of motion limitations while being in this position.

2.5. Instrumented Evaluation—Stabilization Task

We also evaluated using an instrumented test the BoMI training' effects on movement kinematic before (T0), at the end (T1), and 3 months after the end of training (T2). There were some missing data for the cSCI population: subject SCI2 did not perform the instrumented evaluation at T1, while subject SCI4 did not perform the instrumented evaluation at T2. The instrumented evaluation was selected from those presented in the Van Lieshout Test (VLT) Manual [35]. The reason behind the choice of such task was that, differently from the tests usually adopted in the clinical practice, it involved both arms at the same time and required multi-joint coordinated movements in three-dimensional space. The clinical version of the

and A the locations of the markers placed respectively on C7, wrist, elbow and acromion (Figure 2B) we also extracted the following parameters for right and left body side:

- Elbow Angle (EA). The angle $W\hat{E}A$ formed by the segments WE and EA;
- Shoulder Angle on Frontal plane (SAF). The angle $C\hat{A}E$ formed by the segments CA and AE projected on the frontal plane;
- Shoulder Angle on Sagittal / Transverse plane (SAST). The angle $C\hat{A}E$ projected on the sagittal plane (for pose 2 and pose 3) or on the transverse plane (for pose 1 and pose 4);

It should be noted that this kinematic analysis is not complete in a geometrical and physiological sense as it does not consider for example rotations of the forearm along the elbow-wrist axis. Kinematic Symmetry (K_{sym}). This metric evaluates if the subject used left and right body side in a symmetric way while holding the different poses. It was computed by averaging together the symmetry indicator extracted from the three previously defined parameters:

$$K_{sym} = \frac{EA_{sym} + SAF_{sym} + SAST_{sym}}{3} \tag{11}$$

where each kinematic measure of symmetry (EA_{sym}, SAF_{sym} and $SAST_{sym}$) is defined as the ratio of the indicator computed from data of the right side of the body to the indicator computed from data on the left.

2.6. Statistical Analysis

The small sample size of our population did not allow for appropriate full statistical analysis of the data to assess the significance of the changes in the performance metrics during the BoMI training and during the instrumented evaluation. However, consistencies were tested using a Wilcoxon signed-rank test with 5 matched pairs [37,38] (Matlab function signrank). We acknowledge that because the small sample size the significance is debatable, but we still report the p-values in order to give an idea of the common trend, if any, of the population. The level of significance has been set as follows for the signed-rank test: $p^{***} = 0.03$ if all five differences were in the same directions, $p^{**} = 0.06$ if 4 out of3 than in previous studies [15,28], Figure 3. During the familiarization phase (block 1), they improved the cursor control skills in reaching tasks, becoming faster and making straighter and smoother trajectories (Figure 3A–C).

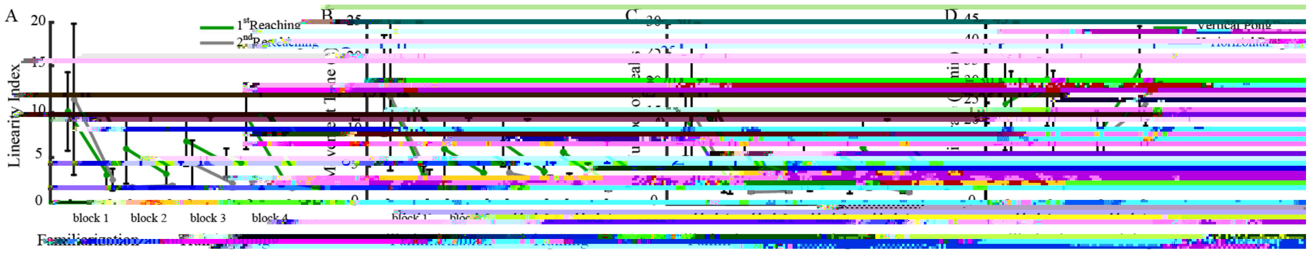

Figure 3. Performance metrics. Reaching tasks: linearity index (**A**), movement time (**B**) and number of peaks in the velocity profile (**C**). First and last sessions of the familiarization phase, first and last sessions after the 1st, 2nd and 3rd

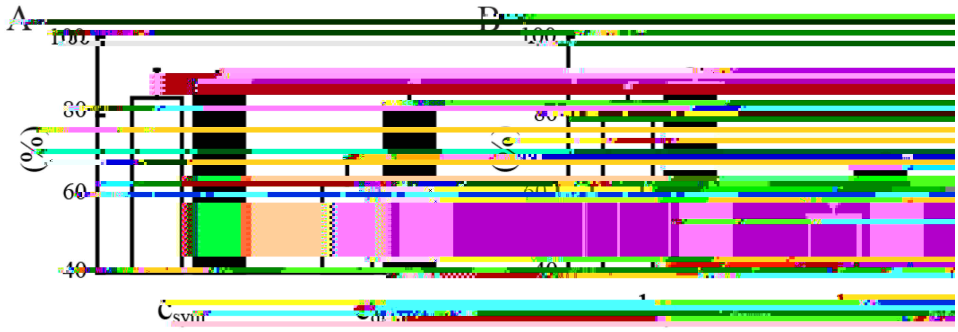

Figure 4. Symmetry and distality indices for body contribution to cursor movement (**A**) and for body mobility (**B**) at the end of the familiarization phase (white bars) and end of training (black bars). The indices are calculated for representing the symmetry between right and left upper body (c_{sym} and b_{sym}

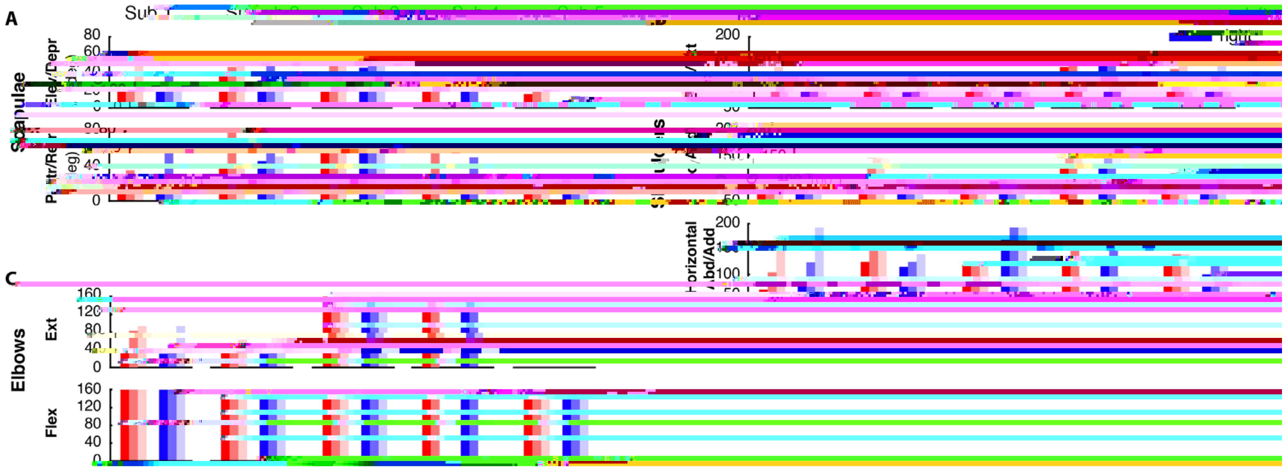

Figure 6. Range of motion. Results of the Range of Motion (ROM) for each subject before (dark shade), at the end (medium shade) and 3 months after the end of the training (light shade) for the left (shades of red) and right (shades of blue) body parts. The results are presented divided by upper-body districts: scapulae (**A**), shoulders (**B**) and elbows (**C**).

There was no noticeable change between the end of training and the follow-up for the right side of the body (p = 0.2318) while a change was still present for the left side (p = 0.0139).

3.4. Kinematics for the Stabilization Task

The subjects' kinematic during the arm stabilization task was assessed in two ways: by a visual inspection of the video recordings and subsequent scoring of the performance, and by extracting significant parameters from the markers placed on the upper limbs. Figure 7 reports the mean scores given to all the poses performed by each subject at the different time points (T0, T1 and T2).

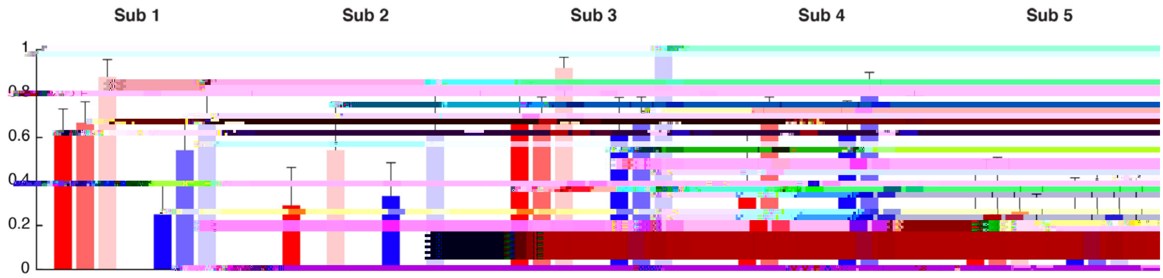

Figure 7. Normalized scores assigned to each body side (right in blue and left in red) averaged across the four poses performed by each subject (columns). The evaluation was performed before the BoMI treatment (T0, dark shades), at the end of the BoMI treatment (T1, medium shades) and three months after (T2, light shades).

The entire SCI population showed an improvement in all the poses between T0 and T1, especially for the right side of the upper limb (p = 0.0312). Pose 1 was the one that all the subjects were able to perform almost from the beginning; for the other poses, there was a clear trend of improvement from T0 and T1. The improvement was also maintained at T2. Subject 5, being the one with the highest level of lesion and so more impaired, was the subject that obtained the lowest scores being not able to perform the pose 2 and 4 in none of the evaluation sessions and the pose 3 only at T1 and T2.

Figure 8 depicts the trend of all the three kinematic parameters EA, SAF, and SAST computed for a representative subject (SCI1), respectively, to evaluate distal movements (EA) and proximal movements (SAF and SAST) for both left and right body side. This subject showed a global improvement in EA, while the other two kinematic parameters improved only for pose 2 and 3. The individual results for the other subject are similar and reported in the Supplementary Materials.

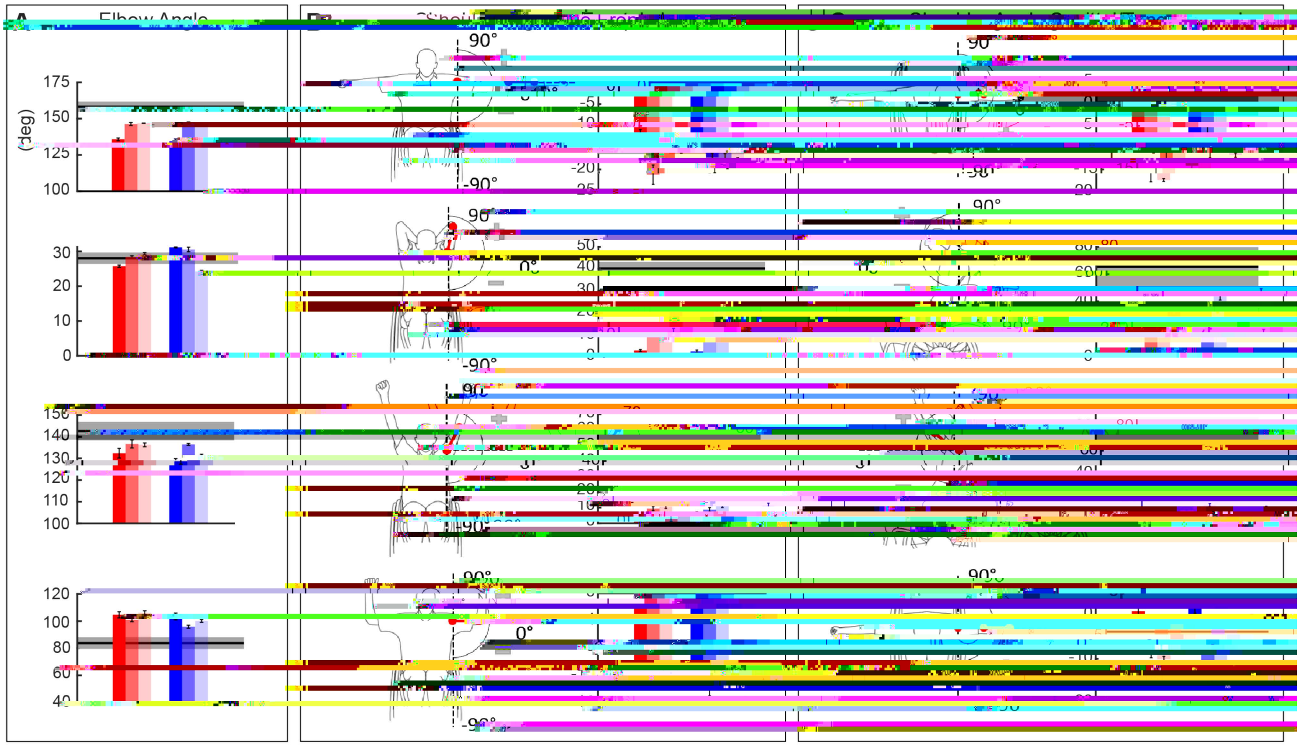

Figure 8. Kinematic parameters of the stabilization task for an example subject, SCI1. In each panel each row indicates the parameters relative to pose 1, pose 2, pose 3 and pose 4. In the shades of red the parameters extracted from the left body parts while in the shades of blue the one from the right body parts at T0 (dark shades), T1 (medium shades) and T2 (light shades). The grey area in each graph represents mean and standard error of each parameter for the control subjects (mean SE). (**A**) Elbow Angle—EA. (**B**) On the left a schematic description, for each pose, of the computed angle and on the right the results of the Shoulder Angle on the Frontal plane—SAF. (**C**) Schematic description, for each pose, of the computed angle on the left side and Shoulder Angle on the Sagittal / Transverse plane -SAST- graphs on the right.

The kinematic performance of the entire cSCI population is reported in Figure 9 where *EA*, *SAF*, and *SAST* metrics are displayed as distance from the control group values. Thus, the metrics close to zero indicated performance similar to the healthy ones, highlighting that subjects were able to correctly achieve the required postures. We found that after treatment (T0-T1), for all the poses, four out of five SCI subjects reported an improvement for the *EA* metrics ($p^{**} = 0.06$ for both left and right body parts), and this improvement was maintained in the follow-up evaluation (T1-T2: $p = 0.875$ for the right side and $p = 1$ for the left side). This result supports the findings previously described after the BoMI training, and it is an additional proof that improving distal body parts movements with the BoMI training was actually achieved. Conversely, the two kinematic parameters related to the proximal movements, *SAF* and *SAST*, did not reveal an overall improvement for the cSCI subjects in both T0-T1 comparison (*SAF*: $p = 0.43$ for right body parts, $p = 0.56$ for left body parts; *SAST*: $p = 0.3125$ for right, $p = 0.1857$ for left) and T1-T2 comparison (*SAF* metrics: $p = 0.12$ for both sides; *SAST*: $p = 0.75$ for right side, $p = 1$ for left side). As for the *Kinematic Symmetry* (K_{sym}), this parameter (Figure 9) improved between T0 and T1 for all the poses for 4 subjects out of 5 ($p^{**} = 0.0625$). No differences were evidenced between T1 and T2 ($p = 1$). Therefore, the performance achieved at the end of the training was maintained at follow-up.

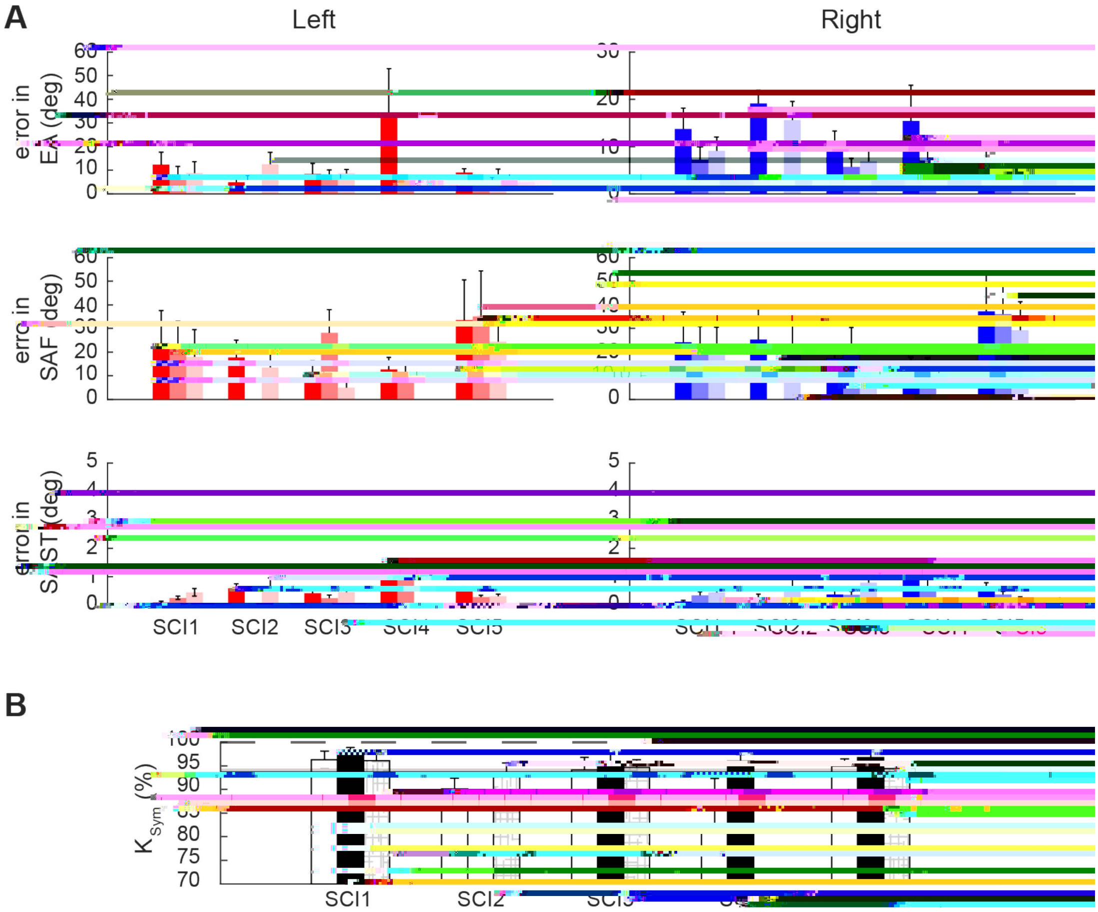

Figure 9. (**A**) Kinematic parameters of the stabilization task for the cSCI population normalized with respect to the control population. Elbow Angle, (EA, first row), Shoulder Angle on Frontal plane (SAF, second row) and on Sagittal / Transverse plane (SAST, third row) were averaged across poses for each subject, mean and standard error are reported in the figure. Shades of red represent the parameters extracted from the left body parts while in the shades of blue the ones from the right body parts at T0 (dark shades), T1 (medium shades) and T2 (light shades). (**B**) Overall kinematic symmetry parameter, K_{sym}, computed for each cSCI subject at T0 (white bars), T1 (black bars) and T2 (patterned bars).

4. Discussion

The BoMI presented in this study is a rehabilitative tool tested in a clinical environment that provides therapists with a simple technology with a high potential to help the training and recovery of upper limb movements of acute cervical SCI subjects. In this study, we described and quantified the efficacy of its use for distal movement skills recovery.

where the sensors were involving upper arms [15], no longer only shoulder movements like in [28]. Specifically, in studies where the control involved more distal movements, either shoulders and arms or arms and forearms movements, the initial performance was worse than when the control involved only shoulder movements. However, despite this sensors' location, after a short period of four sessions, all the subjects became proficient in the control, with movement time and smoothness performance similar to those observed in previous studies, including the works based on shoulder movements.

From the BoMI data, we also extracted indicators regarding body movements and body contributions to cursor control, that allowed the PTs to modify the interface to reach the individual rehabilitation objectives included in the recovery plan of each cSCI subject. All of them at the end of the familiarization phase were using the BoMI with similar recruitment of right and left upper body, therefore for everyone, the main rehabilitative goal was to increment the movements of the forearms over the arms. Indeed, using the forearms for a cervical SCI subject is more challenging due to a reduced innervation of peripheral muscles because of the lesion location on the cervical tract of the spinal cord [1,39]. The BoMI parameters' modifications succeeded in pushing the subjects to increase forearm movements, still maintaining a symmetrical body use. This was also confirmed by the results obtained from the instrumented evaluation. All the standard clinical tests, MMT and ROM, for all the cSCI subjects improved between pre and post assessments (T0 vs. T1). Also, the results of the stabilization task had the same trend both looking at the score provided by expert clinicians and at the kinematic data of the instrumented VLT. With training, all cSCI subjects improved and got closer to the posture assumed by the control subjects. The kinematic parameters that had the greatest improvement were the elbow angles, i.e., the main target of our new BoMI-based training. This finding confirms that this rehabilitation training aimed mainly to improve distal body parts' functionality, fundamental for several daily life tasks, lasted at follow-up. The choice of using and instrumenting the VLT test, a test that has been proven to be valid, reliable and responsive [40,41], was motivated by the need for having a test that consisted of a bilateral task as support of the standard protocol and selected indicators augmented the standard clinical evaluations and permitted to quantify with mode details the improvement brought by the BoMI training, combined with the standard rehabilitation treatment.

Supplementary Materials: The following are available online at https://www.mdpi.com/1424-8220/21/6/2243/s1, Figure S1, Kinematic parameters of the stabilization task for subject SCI2; Figure S2, Kinematic parameters of the stabilization task for subject SCI3; Figure S3, Kinematic parameters of the stabilization task for subject SCI4; Figure S4, Kinematic parameters of the stabilization task for subject SCI5; Table S1, Muscles tested with the manual muscle test (MMT); Table S2, Movements evaluated with the goniometer to extract the range of motion of the upper body in the frontal, sagittal and transverse plane.

Author Contributions: Conceptualization, C.P., A.D.L., L.L., A.M., F.A.M.-I. and M.C.; methodology, C.P., A.D.L., F.A.M.-I., M.C.; software, C.P., E.G., A.D.L. and M.C.; validation, C.P., A.D.L. and M.C.; formal analysis, C.P., E.G., A.D.L., F.A.M.-I. and M.C.; investigation, C.P., A.D.L., L.L., S.G.; resources, L.L., S.G., A.M., F.A.M.-I. and M.C.; data curation, C.P., E.G., A.D.L.; writing—original draft preparation, C.P., E.G., A.D.L., F.A.M.-I. and M.C.; writing—review and editing, C.P., E.G., A.D.L., A.M., F.A.M.-I. and M.C.; visualization, C.P., E.G., A.D.L. and M.C.; supervision, L.L., S.G., A.M., F.A.M.-I. and M.C.; project administration, A.M., F.A.M.-I. and M.C.; funding acquisition, A.M., F.A.M.-I. and M.C. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study procedures were conducted according to the guidelines of the Declaration of Helsinki. Subjects gave signed written informed consent to the analysis and publication of the data for research purposes. The local ethical committee (Committee Comitato Etico Regione Liguria N.92366) approved the retrospective analysis of the data and the publication of the results.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. Written informed consent has been obtained from the patients to publish this paper.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to patient privacy considerations (HIPPA).

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Conflicts of Interest: The authors declare no conflict of interest.

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