Body machine interface: remapping motor skills after spinal cord injury

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Abstract— The goal of a body-machine interface (BMI) is to map the residual motor skills of the users into efficient patterns of control. The interface is subject to two processes of learning: while users practice controlling the assistive device, the interface modifies itself based on the user’s residual abilities and preferences. In this study, we combined virtual reality and movement capture technologies to investigate the reorganization of movements that occurs when individuals with spinal cord injury (SCI) are allowed to use a broad spectrum of body motions to perform different tasks. Subjects, over multiple sessions, used their upper body movements to engage in exercises that required different operational functions such as controlling a keyboard for playing a videogame, driving a simulated wheelchair in a virtual reality (VR) environment, and piloting a cursor on a screen for reaching targets. In particular, we investigated the possibility of reducing the dimensionality of the control signals by finding repeatable and stable correlations of movement signals, established both by the presence of biomechanical constraints and by learned patterns of coordination. The outcomes of these investigations will provide guidance for further studies of efficient remapping of motor coordination for the control of assistive devices and are a basis for a new training paradigm in which the burden of learning is significantly removed from the impaired subjects and shifted to the devices.

Keywords—Spinal cord Injury, Movement reorganization, body machine interface, Learning, Wheelchair

I. INTRODUCTION

Injury to the cervical spinal cord causes a loss of motor and sensory functions, leading to limb weakness, uncoordinated movements and altered reflexes. However, even in individuals with injuries at a high level of the spinal cord, some residual motor and sensory capacity remains available. These residual functions are potentially very important, as they provide the means to control assistive devices such as wheelchairs, tools, or computers. To make optimal use of these residual movement capabilities, the injured person needs to learn how to redirect limb function to achieve alternative, potentially useful applications. In this framework one of the major problems stems from the limits of the interfaces for assistive devices. These interfaces are typically built with a “one-size fits all” approach, delegating the burden of learning to the impaired subjects. Powered wheelchairs are one important example. In the United States there are more than 150,000 [1-2] users of powered wheelchairs. However, the commercially available devices and their controls are operated by joystick or sip and puff switches [3] and only partially match the different degrees of impairments of subjects’ mobility. The lack of customizability is highlighted by a clinical survey [4]. The possibility of incurring difficulties and accidents is not uniformly distributed across types of disability [5] and subjects with poor control of the upper body are at the greatest risk.

Therefore, it is important to understand and facilitate the reorganization of residual motions for the control of powered wheelchairs and other assistive devices after spinal cord injury, through a user specific approach. Hence, we have developed a novel body-machine interface[6] based on two key concepts:

1. remapping the residual motion ability into a low dimensional control space, and
2. matching this control space to the evolving skills of the user.

The proposed interface establishes a form of continuous mobility that is analogous to the mobility of the natural limbs. This paradigm differs sharply from others previous approaches based upon the recognition of discrete control patterns. Our goal is to evaluate the feasibility of using this method as a new controller for training and for enhancing upper body motor skills in high level spinal cord injury (SCI) subjects. Our hypothesis was that by engaging subjects through practicing different actions, such as operating a virtual joystick and a keyboard for playing videogames or piloting a wheelchair in a virtual environment, they concurrently would learn how to improve the control of their residual movements and how to proficiently use the interface that links them to the external world. In this preliminary study, control and SCI subjects were able to improve their performance over different tasks and multiple sessions while the interface was adaptively recalibrated every day. Moreover, subjects modified the relationship between their movements and the control space over which they operated.
II. METHODS

This multisession study investigated the reorganization of upper-body coordination when performing tasks that required different motor skills. We developed a body-machine interface that provides impaired individuals with a continuous signal space operated directly by the combination of residual motions that the users are most capable of controlling [6]. Here, we used this interface for engaging subjects in virtual reality games that trained specific control actions. The evaluation of motor learning was based on a “reaching” task performed as a test at the beginning and at the end of each session.

A. Experimental setup and protocol.

We used an array of four infrared video cameras (V100, Naturalpoint Inc., OR, USA) to track four active light markers, which were attached to the subject’s upper-body garments (Fig.1). Shoulder and arm positions were captured at 75 samples per second using proprietary software (Modification of a C++ SDK supplied by Naturalpoint).

![Experimental setup](image)

Figure 1. Experimental set up. Subjects sit on a chair reclined at about 40 deg. Such position is easy to maintain for SCI subjects. The four markers were placed on the subject’s shoulders and upper arms, two for each side of the body.

The 8-dimensional body-signal vector (two dimensions for each camera) of sensor signals \[ h=[h_1, h_2, \ldots, h_8]^T \] was mapped onto the 2-dimensional command vector, \[ u=[u_1, u_2]^T \] via a linear transformation:

\[
\begin{bmatrix}
    u_1 \\
    u_2
\end{bmatrix} =
\begin{bmatrix}
    a_{1,1} & a_{1,2} & \cdots & a_{1,8} \\
    a_{2,1} & a_{2,2} & \cdots & a_{2,8}
\end{bmatrix}
\begin{bmatrix}
    h_1 \\
    h_2 \\
    \cdots \\
    h_8
\end{bmatrix} = Ah
\]  \hspace{1cm} (1)

where \( A \) is the matrix of mapping coefficients, \([A]_{i,j} = a_{i,j}\).

The control space \( u \) had reduced dimension with respect to the body signal space \( h \), thus we can decompose the body signals into their “null-space” components that do not change the control vector, and the orthogonal “task space” components that determine the value of the command vector [6-7]. At the same time this mapping offers a large variety of specifications. By setting the map coefficients, we were able to assign higher or lower relevance to different parts of the body. For example, the motions of a body part can be excluded by setting to zero the coefficients that multiply the sensor signals affected by that part. Conversely, the motions of a body part could be enhanced by large values of the related coefficients.

Calibration. The \( A \) matrix was set at the beginning of each session by a calibration procedure. Subjects wore the sensing elements and executed random motions with the upper arm, shoulder and trunk. No specific requirement was imposed except that of moving the upper body continuously in a natural and comfortable way. One minute of continuous recordings were taken. After this initial session, the data were analyzed and the body/cursor map, \( A \), was derived using principal component analysis (PCA), as explained in [6]. PCA was a means to identify an abstract low-dimensional subspace where subjects tend to move with more ease. We used PCA as a way to implement a good learnable map. This method also allowed us to detect changes in the subjects’ residual abilities or preferences and to modify the map accordingly. If during training subjects would improve and gain more mobility or if they had pain in one shoulder and couldn’t use it the space over where they move more easily may change. This change would be captured by PCA in the calibration phase and the BMI would generate a new and different control space.

Training sessions. After calibration, the subjects’ arm and shoulders movements controlled a cursor or a simulated wheelchair on a computer screen, using the two dimensional command vector described in Eq.1. Subjects engaged in the following tasks:

1. Reaching test I (30 center out movements).

Subjects controlled the position of a cursor on the monitor. Starting from the same initial position in the center of the workspace, subjects moved to six equi-spaced peripheral targets that were presented in random order. The distance of the targets from the center on the monitor was 5 cm. For 0.4 seconds after the cursor left the initial position, there was no visual feedback in two randomly selected trials per direction, corresponding to 2/5 of “blind” trials. The purpose of this part of the experiment was to understand if subjects were guided by visual feedback or if instead they learned a predictive, “feedforward”, map between their body and the cursor space.

2. Training: Playing videogames (Tetris, up to 35 minutes).

Subjects operated a virtual keyboard with four keys. Different shapes appeared at the top of the game board and dropped down. Subjects had to move and place shapes to complete rows. The completed rows disappeared, allowing the pile of shapes to fall. As subjects improved their performance, the speed of the shapes dropping increased, making the game more challenging. To manipulate the falling shape, subjects moved to the top, bottom, right and left keys starting from a key positioned in the center of the workspace; this performed the following actions on the shape: spin, drop, move right, move left.
3. Driving a simulated wheelchair (up to 10 minutes) over a path in various environments. Subjects controlled the virtual wheelchair by setting two variables: forward/backward linear speed and right and left turning speed. During the first two sessions, subjects navigated in a desert scenario, where they could practice maneuvering and avoiding collisions with obstacles. After the third session, they explored a more complex VR, moving inside a simulated village and the country around it. They could choose freely the directions, but they had to follow paved paths (custom modified from the Wheelchair Net Software 2.1, developed by Oregon Research Institute).

4. Reaching test II (30 center out movements, equal to test I).

Subjects participated in 2/3 sessions per week. Total number of sessions was 9 for control subjects and varied between 6 to 9 sessions for SCI subjects. Moreover, 6 control subjects were recalled 3 weeks later for testing retention (2 more sessions).

B. Subjects

Eight control subjects with no known history of motor impairment (age range 21-35 yrs, 7 male 1 female) and 6 SCI subjects (see table I) participated in this study, after signing the informed consent approved by Northwestern University Institutional Review Board. The inclusion criteria for SCI subjects were 1) have complete injuries at the C3-6 cervical level (ASIA A) or incomplete injuries in the cervical cord (ASIA B and C), 2) be medically stable, 3) able to see in adequate light, 4) able to perform shoulder protraction, retraction or elevation, 5) able to follow simple instructions. Subjects were excluded if there had significant concurrent complications, including skin breakdown, pulmonary insufficiency, urinary infection, or other systemic infections.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Gender</th>
<th>Age (y)</th>
<th>Level of injury</th>
<th>ASIA</th>
<th>Time after injury</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCI 1</td>
<td>M</td>
<td>56</td>
<td>C3-4</td>
<td>C</td>
<td>2 m</td>
</tr>
<tr>
<td>SCI 2</td>
<td>M</td>
<td>28</td>
<td>C5</td>
<td>A</td>
<td>6 y</td>
</tr>
<tr>
<td>SCI 3</td>
<td>M</td>
<td>50</td>
<td>C4</td>
<td>C</td>
<td>9 y</td>
</tr>
<tr>
<td>SCI 4</td>
<td>M</td>
<td>37</td>
<td>C6</td>
<td>A</td>
<td>2 ½ m</td>
</tr>
<tr>
<td>SCI 5</td>
<td>M</td>
<td>40</td>
<td>C4</td>
<td>C</td>
<td>2 m</td>
</tr>
<tr>
<td>SCI 6</td>
<td>M</td>
<td>30</td>
<td>C5-6</td>
<td>A</td>
<td>9 ½ y</td>
</tr>
</tbody>
</table>

Gender (M=male, F=female), Time after injury (m=months y=years).

We performed an evaluation of the SCI subjects’ shoulders before and after the training sessions to characterize residual mobility and to test if, from the clinical point of view, the training had a beneficial influence or, at least, no negative interference with the reorganization of the subjects’ upper body function. Therefore, SCI subjects were evaluated with a modified Manual Muscle Test (MMT)[8]. This modified test is used routinely at the Rehabilitation Institute of Chicago with the tetraplegic population who experience injury at the cervical level. All tests were performed while subjects were sitting in their wheelchair. We followed the procedure described in the Guide for Muscle Testing of the Upper Extremity, Department of Occupational Therapy, Ranchos Los Amigos Hospital. We omitted the tests in prone position i.e. scapular depression/adduction, because the majority of the SCI subjects in this study cannot lie prone (acute patients) due to spinal restrictions. Instead, we tested protraction/retraction, which is not in the Ranchos Los Amigos guide. The subjects might use these movements to play the games (Table II).

III. RESULTS

A. SCI subjects’ evaluation

All SCI subjects had a MMT score (fig 2 left panel) far below the controls’ score. The MMT score improved significantly for all subjects after training (F(1,5)=10; p=0.02). The Manual Muscle test is not a direct measure of strength,
however the correlation between the MMT total score and the total force measured with the force sensor (sum of the forces in the three tested directions) was high R=0.81 p<0.0001(fig 2, right panel). We found also significant correlations by comparing the force exerted by shoulder muscles in the upper, forward and backward directions with respect to the score obtained for the scapular elevation, shoulder protraction and retraction (respectively R=0.55 p=0.0073, R=0.72 p=0.0012, R=0.75 p<0.0001). Moreover, the total isometric force exerted by the subjects’ shoulders also improved after training for 5 out of 6 subjects.

B. Movement reorganization in the task space

**Reaching tests.** At the beginning of the first session, performing Reaching Test I (Figure 3, column I and II, top panel) was really difficult for both controls and SCI subjects. Next, they used the same interface for operating a computer game keyboard and for piloting the speed of a virtual wheelchair in a VR environment. After less than one hour, when we tested the subjects again in the reaching task (figure 3, test II), their performance were quite improved. They not only reorganized their movements; but they also transferred and generalized the learned skills across different tasks.

In the following sessions subjects kept improving. Most interestingly, the improvement was also evident during test I at the beginning of each session and before practicing any task, in spite of the initial recalibration. This result showed not only a retention of the learned skills through different sessions, but also demonstrated that the everyday recalibration had a positive or, at least, non negative, influence on the learning process. At the end of the training the performance at the beginning of the session (test I) converged toward the performance obtained at the end of the session (test II). SCI subjects had poor initial performance with respect to control subjects, but they improved significantly with practice both within the same session and across multiple sessions. These observations were confirmed by the analysis of an error measure, that is the distance between the target and the cursor position after 0.4 seconds that the subject left the starting position (figure 4 and table III). This measure [9] is particularly suitable for a global performance evaluation because it takes into account the effects of movements accuracy (aiming) and velocity. Comparisons were based on repeated measured

**Figure 4.** Control subjects: end point error with (VISION) and without (NoVision) visual feedback (mean ± SE). The results of test I are represented with red and black lines, while magenta and blue lines are referred to the reaching test II. Notice that the sessions 10 and 11 were referred only to 6 of 8 subjects.

ANOVA with three factors: session (first/ last), test (I,II), and vision (trials with/without visual feedback).

As expected, between the first and the last session, the errors decreased (Controls: F (1,7) = 21 p=0.002; SCI subjects: F(1,5)=9.35 p=0.028). Within the same session, the errors between the initial and final tests were different (Controls: F (1,7) = 18 p=0.003; SCI F(1,5) =42 p=0.001), but this difference decreased with practice (Controls: F(1.7) =7.47 p=0.03, SCI subjects: not significant p=0.07). All controls reached a similar and stable level of performance at the end of the training. Moreover, when 6 out of 8 control subjects were recalled after more than three weeks for testing retention, they didn’t show significant differences with respect to the last training sessions. Furthermore, the absence of visual feedback had no influence (Controls and SCI subjects p>0.1) on the endpoint error. Therefore, this multisession study proved that, both the control and SCI subjects improved their performance without visual feedback (table III) i.e. they were able to define a predictive map between their body and the cursor space.

**TABLE III.** SCI SUBJECTS: END POINT ERROR

<table>
<thead>
<tr>
<th></th>
<th>FIRST session</th>
<th>LAST session</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC1</td>
<td>3.94</td>
<td>2.90</td>
</tr>
<tr>
<td>SC2</td>
<td>4.50</td>
<td>2.07</td>
</tr>
<tr>
<td>SC3</td>
<td>4.78</td>
<td>3.41</td>
</tr>
<tr>
<td>SC4</td>
<td>3.75</td>
<td>3.51</td>
</tr>
<tr>
<td>SC5</td>
<td>2.19</td>
<td>2.26</td>
</tr>
<tr>
<td>SC6</td>
<td>3.88</td>
<td>1.49</td>
</tr>
</tbody>
</table>

End point error [cm] during reaching tests with (white columns) and without (gray columns) visual feedback.

**Training performance: play videogames (Tetris)**

During the first session, while all the controls were immediately able to play Tetris, half of the SCI subjects were not (Fig 5).
However, both control and SCI subjects improved significantly (Controls: F(1,7) =92.69 p<0.0001 SCI subjects: F(1,5)=18.5 p=0.007). At the end of the training, after a few hours of practice, every subject, even with different speed and performance, was able to play and – perhaps most importantly – enjoy the game. Moreover 6 out of 8 control subjects were recalled after more than three weeks from testing the retention of the learned skills. Retention was evident, even if some of the control subjects showed a slight decrease in performance with respect to the last training session.

Navigation in a VR environment.

After playing Tetris, all subjects drove a wheelchair in a VR environment. Surprisingly, the SCI subjects who exhibited a poor videogame performance at the beginning of the training (e.g. SCI 4) were immediately able to navigate in the virtual world. All subjects easily learned to remap the two control variables they learned to use for operating the environment. All subjects easily learned to remap the two control variables they learned to use for operating the videogame keyboard into the two speeds of the simulated wheelchair. Also, when the VR environment became more complex and they were forced to follow well defined paths, they were able to pilot the wheelchair without difficulties. All the spinal cord injury as well as all the control subjects succeeded to explore almost the entire virtual world as shown in fig.6.

Reorganization in the body movement space.

The signals derived from the upper body movements were mapped, by Eq.1 into two control variables. These were used, as described above, in different tasks with different operational functions.

However, the transformation (A) between high dimensional body space and low dimensional control space was always defined by the calibration map. This allowed us to investigate if subjects modified the relationship between their movements and the two dimensional structure over which they operated. Therefore, we looked at the percentage of the variance accounted for by the task space components of the movement signals with respect to the overall variance [6-7] and we investigated if it changed:

- Within the same session by comparing the reaching test at the beginning (test I) and at the end (test II) of the first session.
- Over multiple sessions by comparing the performance of the reaching tests I in the first and in the last session.

We focused on the data collected during the reaching tests when the subjects were on target because We did not want to “contaminate” the null-space variability with the natural variability of the cursor trajectories between the same start and end targets[6]. The statistical analysis was based on repeated measure ANOVA. Even if the percentage of the task space variance for the control subjects was on average slightly higher with respect to SCI group, we found no statistically significant differences between the behavior of the two groups. We found that the majority of the subjects -both control and SCI- had a marked tendency to align their movement subspace with the two dimensional space established by the cursor map not only within the same session, (F(1,12)=7.9 p=0.016), but also over multiple sessions (F(1,12)= 6.9 p=0.022). Subjects did not shift their variance from the low-dimensional task to the null-space. Instead, as learning progressed, variance in the null-space decreased, consistent with the hypothesis that the motor system built a map that matches the structure of the novel geometrical space over which they operated.

IV. DISCUSSION

After a severe injury, people have to “remake their body” and “reconstruct the self identity in relation to their new bodily state” [10]. Assistive devices are a part of this “re-embodyment”, because they will be no longer external object appended to the body, but they will become part of the “body schema”. Wheelchairs are a clear example. Since wheelchairs are the only way to regain mobility, SCI survivors don’t use a wheelchair as we use a bicycle, they become “en-wheeled” [11]. Consequently, learning how to use an assistive device is a different and wider process than learning a motor skill and the body machine interfaces play a key role in this process.

This work validated a new approach for operating assistive devices that can be beneficial for individuals who suffered substantial injuries limiting, but not totally suppressing, their
mobility. This is the case, for example, of high level spinal cord injury.

Here, we tested the feasibility of a new interface design based on three important concepts:
- Tapping into a broad spectrum of residual subject movements
- Providing the impaired users with a continuous signals space operated directly by the combination of residual motions that the users are most capable of controlling.
- Adaptively changing the body-device map based on the user’s residual abilities and preferences

We engaged subjects in practicing virtual reality games aimed at training specific control actions. These actions include: a) interacting with a virtual keyboard; b) practicing wheelchair maneuvers, and c) reaching targets. We found that control and SCI subjects were both able to improve their performance over different tasks and multiple sessions while the interface was adaptively recalibrated every day. We discovered that subjects easily remapped the two control variables that they were using for activating the videogame keyboard into the two speeds of the simulated wheelchair. To drive the wheelchair was easy also when playing the game was hard. This initial study supports the feasibility of using a same controller for solving tasks with different operational functions. Training based on different tasks has a beneficial effect on the learning process[12], because it induces a wider knowledge of the possibilities offered by the controller and requires a more versatile reorganization of the body movements.

Implication for rehabilitation

Our preliminary observations indicate that the proposed training has no negative interference with the subject’s clinical recovery and may lead to enhanced mobility of the shoulder and upper arms. The proposed body-machine interface is suited to exercise all of the available upper body degrees of freedom through targeted practice of control actions in VR environments. It is also possible to create a transformation from body motions to a “command” space that emphasizes degrees of freedom that are more difficult to control (as determined by principal components during the calibration). This would likely facilitate strengthening a subject’s weaker muscle combination. The reduced or absent mobility of upper arms and/or hands limits shoulder use in daily living activities. This contributes to shoulder weakness, poor posture and, with time, produces pain and attenuates voluntary control of shoulder motion [13-14].

Our interface can map any targeted residual movement capacity into a specific operational function, which makes this system capable of finding a natural balance between ease of device control and exercise underutilized muscle to prevent atrophy and enhance the recovery process. The rehabilitative potential of the BMI may be beneficial for different types of disabling conditions (e.g. SCI and stroke), where the secondary shoulder complication is frequently a focus of the rehabilitative programs[15].

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