2022 9th IEEE RAS/EMBS International Conference for Biomedical Robotics and Biomechatronics (BioRob) | 978-1-6654-5849-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/BIOROB52689.2022.9925509

EMG Based Body-Machine Interface for Adaptive and Personalized Robotic Training of Persons with Multiple Sclerosis

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Abstract— **Multiple sclerosis is a complex neurological disease that results in motor impairment associated with muscle weakness and lack of motor coordination. Indeed, previous studies showed that, while activities in isolated arm muscles appeared generally similar to those of unimpaired subjects, shoulder muscle coordination with arm motions was affected by MS and there was a marked co-activation of the biceps and triceps in the extension movements. This inability to activate muscles independently has a significant impact in motor function therefore reducing the co-contraction could improve the overall arm function. In this pilot study, we developed a body-machine interface based on muscle activities with the goal of 'breaking' the abnormal triceps-biceps co-activation during planar flexion-extension movements of people with multiple sclerosis during a robot-based task. The task consisted in 2D center-out reaching movements with the assistance of a robotic manipulandum. When the subject was not exhibiting the abnormal triceps-biceps co-activation for three consecutive movements the robot was decreasing the assistance. Subjects trained for up to six 1-hour sessions in three weeks. Results showed that the assistance from the robot decreased within each session for most of the subjects, while the movement became faster and straighter. The comparison between muscle activity before and after the training with this body-machine interface demonstrated that subjects learned how to reduce the triceps-biceps co-activation.**

I. Introduction

Multiple Sclerosis (MS) is the most widespread disabling neurological condition of young adults around the world [1], [2]. Nearly 75% of people with MS experience upper limb dysfunctions mainly related to tremor, coordination deficit and muscle weakness [2]–[4]. These symptoms severely reduce their quality of life [2], [5], that might be further impaired by the arise of pain and fatigue. Neuromotor rehabilitation plays a crucial role in reducing these problems, improving manual dexterity, arm strength and performance of the activities of daily living (ADL) [6]–[8]. In particular, in the last decades robotic rehabilitation have been proven to be successful in MS rehabilitation [6], [9]–[11], given its advantage of high intensity training, volume and duration, and higher controllability of the training environment.

Nevertheless, to fully exploit the potential and the effectiveness of robotic rehabilitation, it is essential that these interventions are rooted on a deep knowledge of the mechanisms underlying the impairment of upper body functions after MS. In this contest, there are studies that well described and quantified motor impairment following MS either while performing planar movement in different mechanical environments using an end-effector robot [12], or while performing upper limb 3D tasks, monitoring the muscle activity and the movements with EMG sensors and/or motion capture trackers [4], [13], [14]. The evaluation of behavioural parameters together with the measure of neurophysiological signals, such as the EMG activity, opened the possibility for a comprehensive characterization of the onset, the expected prognosis and the functional consequences of motor impairments after MS. In particular, Pellegrino et al. [12] reported that, while subjects used the robot and interacted with different environments (i) in several subjects with MS, especially in the most impaired, here was a co-activation of biceps and triceps during planar movements that required the extension of the elbow; (ii) this abnormal synergy increased if subjects moved against a force while decreased in presence of an assistive force. Here, we built on these findings to verify the feasibility of designing a myo-controlled body-machine interface (myo-BoMI) specifically designed to target this problem and taking advantage from the fact that when a planar robot was assisting MS subjects during a reaching task, their abnormal coupling of biceps and triceps was reduced. We combined a body machine interface based on muscle activations recorded from the subjects' upper limb and a robot assistive technology to build a training exercise aiming at reducing this pathological behavior using an assistance-as-needed approach. Differently from the most widespread approach of assisted-as-needed robotic rehabilitation [15], [16] where the level of assistance is based on kinematic performance, here the assistance depends on muscle activity with a particular attention on the biceps-triceps coupling.

* Research supported by Italian Multiple Sclerosis Foundation (FISM, 2013- Cod. 2013/R/5), Marie Curie Integration Grant (REMAKE, FP7-PEOPLE-2012-CIG-334201), European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 896892 (REMAp).

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II. Methods

A. Subjects

Four subjects with clinically definite MS participated in the study, more details in Table 1. All subjects were right-handed with no problems of visual integrity. The study was approved by the local Ethical Committee (Comitato Etico Regionale Liguria, 06-10-2014, 201REG2014) and conformed to the ethical standards of the 1964 Declaration of Helsinki. Each subject provided written informed consent to participate in the study and to publish individual data.

TABLE I. Demographic information of MS subjects. EDSS stands for Expanded Disability Status Scale; 9HPT for the Nine Hole Peg Test; and FSS for the Fatigue Severity Scale. M = Male, F = Female

Subject ID	*Age (yo)*	*Sex*	*EDSS (0-10)*	*FSS (0-63)*	*9HPT right (s)*	*9HPT left (s)*
S1	40	M	6.5	59	45.96	85.15
S2	61	F	5	53	23	27.65
S3	42	F	5	22	40.21	50.29
S4	47	F	6.5	51	41.85	94

B. Set-up and protocol

We used a planar robotic manipulandum with 2 degrees of freedom characterized by low friction, low inertia, zero backlash, large elliptical workspace (80 × 40 cm) actuated by a pair of direct-drive brushless electric motors. The robot is impedance-controlled to transmit smoothly modulated force to the hand of the user. The control loop is closed at 1kHz. Kinematic data are computed starting from the encoders reading and saved at 1kHz. The has been fully described [17]. Subjects were seated on a chair grasping the handle of the robot Fig. 1A. The robot recorded the end-effector position and provided the external forces. The position of the seat was adjusted to keep the arm approximately horizontal at shoulder level; the movements were restricted to the horizontal plane, with no influence of gravity because there was a support relieving the arm weight. A 19′ LCD computer screen was placed vertically in front of the subjects, about 1 m away, at eyes level and displayed the position of the end-effector of the robot and the target the subject had to reach. We recorded with surface electrodes for electromyography (CometaWavePlus, Cometa Srl, Italy) the EMG activity of two muscles: triceps brachii long head (TRLO), biceps brachii long head (BICL). Electrodes were placed according to guidelines of the Surface Electromyography for the Non-Invasive Assessment of Muscles European Community project – SENIAM [18].

Subjects performed two experimental sessions per week for up to a total of six sessions (minimum four sessions), depending on the motor impairment or on the inclination to fatigue of each subject (Fig. 1C). The maximum duration of each session was about 1 hour. Each session started with a *test block*, followed by up to 5 *training blocks* and then a *last test block*. The test block consisted of reaching movements towards five targets equally spaced from a central target, i.e. at 18 cm distance on the screen, directions 30°, 60°, 90°, 120° and 150° (see Fig.1 B). Each target was reached three times for a total of 15 movements. In these blocks the robot was transparent to the user. During the training blocks, the subject reached 8 times three targets (red targets in Fig. 1 B, directions 30°, 90° and 150°) for a total of 24 center-out movements. Differently from the test blocks, in the training blocks the robot provided to the subjects an assistance force F in the direction of the target they needed to be reached, implemented as a spring that attracted the hand toward the target to reach with an initial level of stiffness coefficient (K) set equal to 16 N/m

$$F = K \cdot (x - x_0)$$

where x is the current position of the end-effector and x_0 the coordinates of the target the subject had to reach.

The level of assistance was not constant for the entire training, but changed depending on the activity of the triceps and biceps and on their coupling. The goal of the training with the myo-BoMI was to reduce the abnormal coupling of triceps and biceps during planar flexion-extension movements in absence of assistance provided by the robot. The initial level of assistance was chosen so that such abnormal co-activation was absent or reduced to minimum. Ideally, we wanted the TRLO to be mostly active during the extension movements, i.e. the center-out movement, and the BICL mostly active during the flexion movements, i.e. the out-center ones. During the training, we monitored TRLO and BICL activity, precisely their envelope, and the subjects received a positive feedback in the form of a rewarding sound and an increment (+1) of their score every time they were executing the center-out movement or the out-center movement with the correct muscle activations. Correct muscle activation was considered when the triceps envelope during out-center (flexion) movements did not exceed the threshold thr_{TRLO}; similar rule for the biceps that did not have to exceed the threshold thr_{BCL} while making center-out (extension) movements. Such thresholds, thr_{TRLO} and thr_{BCL}, were computed as the 30% of the maximum of the

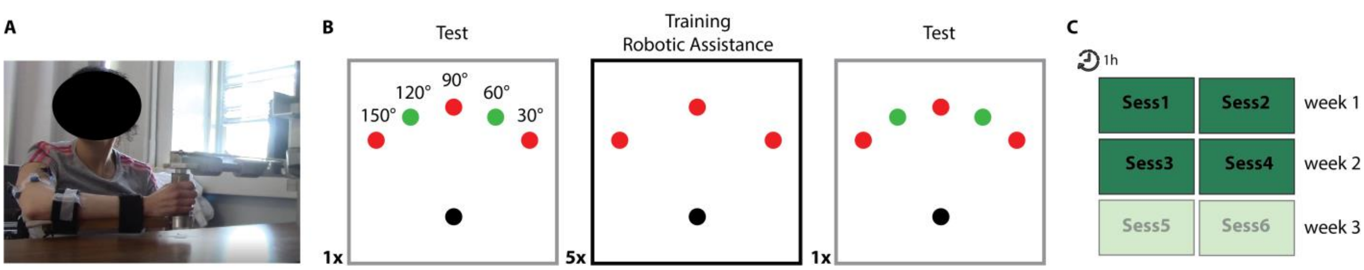

Figure 1. Experimental set-up (**A**) and protocol (**B**). Subject used a planar manipulandum to perform planar reaching movements. They executed center-out and out-center movements to/from 5 targets during the test blocks, and to/from 3 targets during the training blocks. In this last block the robot was assisting the subjects to avoid excessive biceps-triceps co-contraction. **C**: The training consisted in up to 6 sessions with a minimum of 4 sessions, twice a week. Each session lasted 1 hour.

respective muscle envelopes recorded during the first Test block and averaged across movement repetitions.

If every six movements subjects increased their score of 6 points, we decreased the robot-assistance by 1 N/m. If the score did not increase, the assistance increased by 1 N/m. Otherwise, the assistance did not change. Note: K was never higher than the initial value of 16 N/m. Both arms were trained and tested.

C. *Data Analysis*

Cursor movement trajectories were smoothed by using a sixth order Savitzky– Golay filter (cut-off frequency: ~11 Hz). The movement onset was defined as the first time instant the cursor speed exceeded the threshold of the 10% of maximum speed. The movement ended when the cursor was inside the target and the speed underwent and remained under the same threshold. We computed the following metrics: average speed of the cursor, and the linearity error as the percentage increase in the length of the trajectory traced by the cursor with respect to the nominal trajectory, i.e., the straight line that connects the initial and the final points of the trajectory. See Fig.2 for a schematic representation of the assistance protocol.

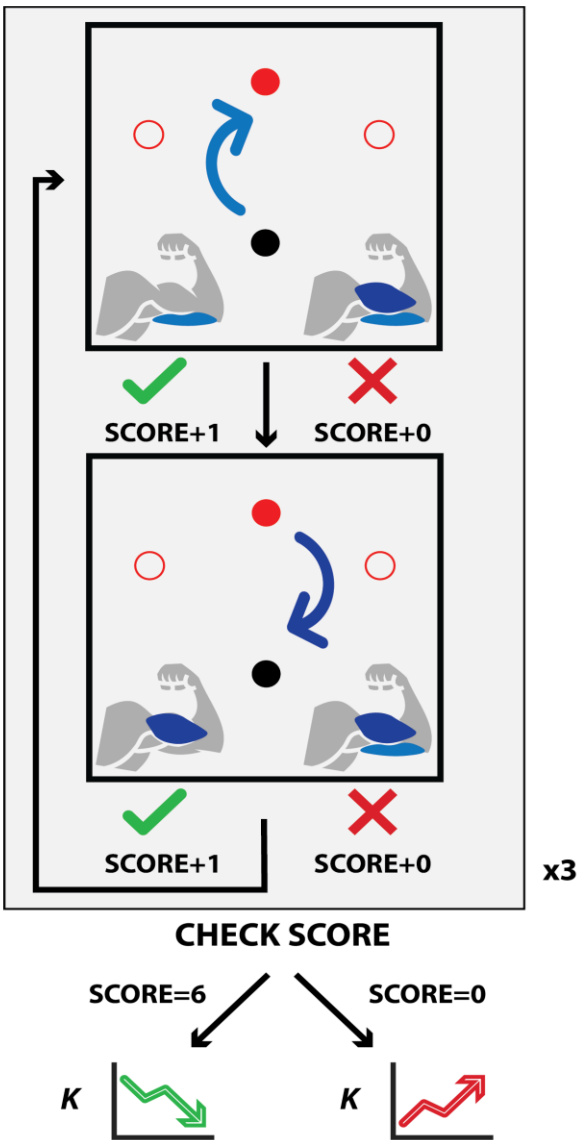

Figure 2. Scheme of the regulation of robotic assistance. Subjects increased their score of 1 point if during center-out movements they activated mostly the triceps avoiding triceps-biceps abnormal coupling. Similarly, if in the out-center movements they were mostly activating the biceps. If for 6 consecutive movements the score increased of 6 points, the robotic assistance K decreased of 1 N/m, if the score did not increase of any point the assistance increased of 1 N/m, otherwise the assistance did not change. K never exceeded the initial value of 16 N/m.

EMG signals were acquired at 2 kHz; band-pass filtered (30–550 Hz), rectified, low-pass filtered (cutoff: 10 Hz) to obtain the EMG envelopes [19]. For each trial, we considered a time window starting 250 ms before the movement onset (subjects leaving the central target) and ending with the subjects returning to the central target. The amplitude of EMG envelope of each muscle was normalized by its median computed from all movements in the five directions, and it was resampled in 100 time points. To investigate if the training with the robotic assistance had an effect that persisted trough sessions also in absence of assistive force, we visually compared the EMG envelopes during the *test block* of session 1 and the ones during the *test block* of the last session of training. In these blocks subjects were not receiving any sort of assistance and were also moving toward target that they did not practice in the training blocks. To assess if during the training with the myo-BoMI the subjects learned to reduce TRLO-BICL abnormal coupling, we analyzed the variation of the assistance level K through training blocks and sessions. Reduction of TRLO-BICL abnormal coupling will result in a reduction of the assistance.

III. Results

The concept of using the myo-BoMI to decrease the abnormal triceps-biceps co-contraction during extension and flexion movements by regulating the robotic assistance was successfully applicable to people with multiple sclerosis. Indeed, for all 4 subjects the intensity of assistance K showed

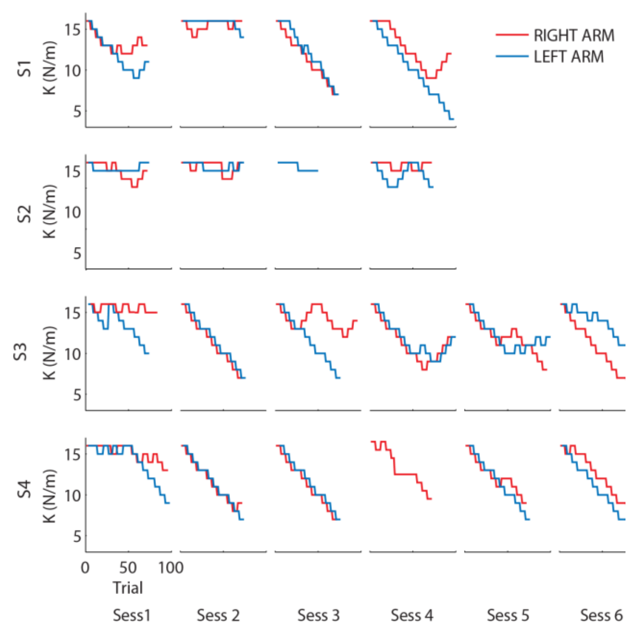

Figure 3. Evolution of robot assistance across sessions (columns) for the four MS subjects (rows). The assistance at each session started equal to 16 N/m and decreased if during the trials of the training blocks the subjects reduced the abnormal TRLO-BICL co-contraction. In red the assistance values for the right arm and in blue for the left arm.

a decreasing tend within each session for both arms, Fig.3. Nevertheless, it is visible how during the training subjects were not always exhibiting the correct TRLO-BICL coupling. For example looking at K for subject 1, we can see how in session 1 while training with the right arm the assistance decreased in the first half of the training while during the second half the robotic assistance increased. The same subject was always receiving almost the full robotic assistance during the entire session 2 for both arms. Also, through the training sessions the subjects were improving their performance as the assistance of the robot reached lower values at the end of day 4 for S1 and S2 and at the end of day 6 for S3 and S4 with respect to the one at the end of day 1, Fig. 3. These results suggest how the proposed protocol was adaptive to the different subject behaviors.

The myo-BoMI had an effect that persisted also after training. For example, subject 3 presented a coactivation of the left TRLO and left BICL during the first test block of the first session especially. The biceps always participated in the extension movement (0-50%) and similarly the triceps was almost never silent when the subject was flexing the arm, Fig 4 A, top. Instead after training, Fig. 4B, it is visible how in all five directions the activity modulation of TRLO and BICL was well distinguishable, specifically, TRLO was always mostly active during the extension while the BICL during the flexion (50-100%) movements. The improvement in muscle modulations after training is even more evident in the right dominant arm, Fig. 4 second row. Here, before training, TRLO and BICL were always co-contracted, with the exception of movements along direction 5. After the training instead, the activity of TRLO and BICL were in complementary: TRLO during extension and BICL during flexion.

The observed improvements in the muscle activations and modulation did not affect the kinematic. The metrics computed from the end-effector kinematic show how on average subjects moved along more linear trajectories (session 1: 28.6±5.7 %, last session: 23.6±4.7 %; mean±STD) maintaining a similar mean speed (session 1: 0.20±0.03 m/s, last session: 0.24±0.04 %; mean±STD). In the last training session there was an increase in the mean velocity and a decrease in the linearity error with respect to session 1.

IV. Conclusion

This result, although preliminary, suggest that a body machine interface based on muscle activities can be used to determine the control of a robot specifically designed for neuro-rehabilitation to decrease abnormal co-activation pattern in subjects with MS. Future development will include the recruitment of more MS subjects and the addition of a control group were MS subjects will train with the same robot and task but without the assistance modulated on biceps-triceps coupling.

Acknowledgment

The authors are grateful to all the study participants for volunteering their time. The authors would like to thank the volunteers of AISM (Italian Multiple Sclerosis Association) for their collaboration.

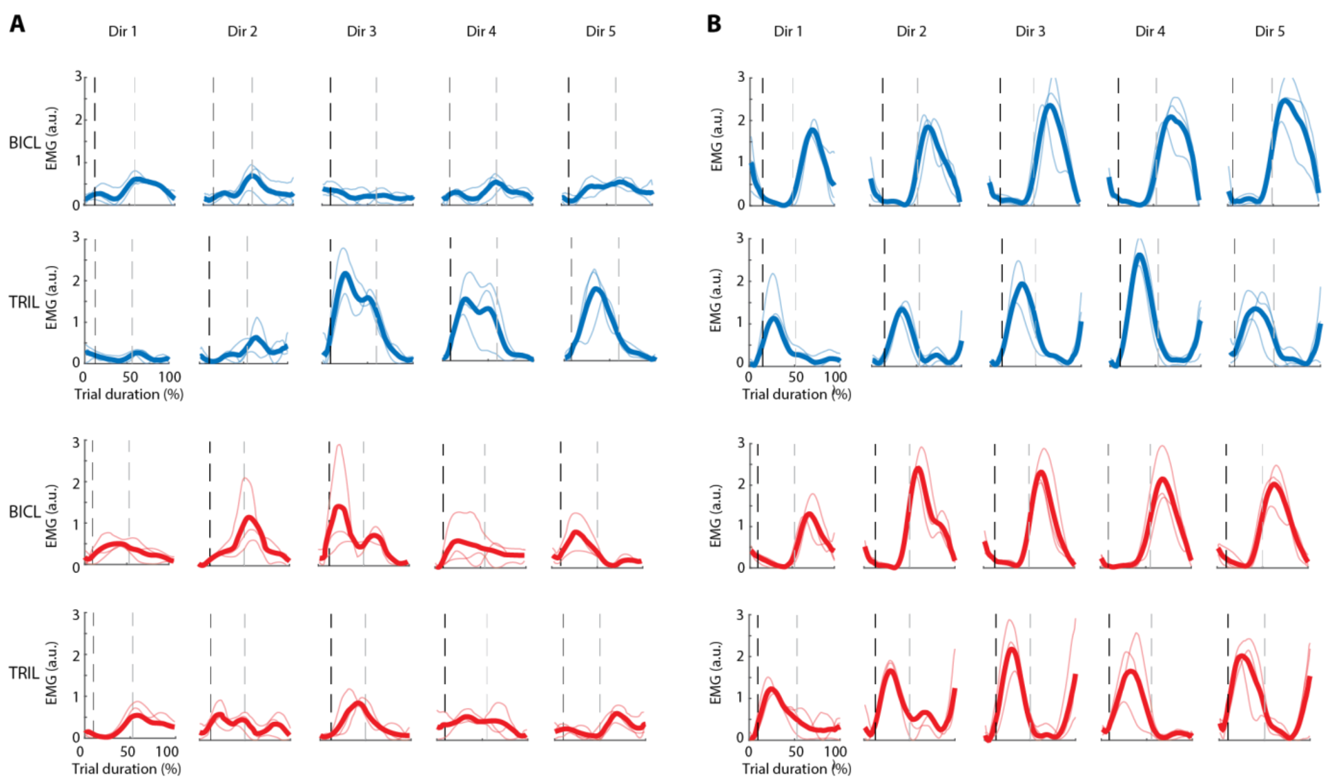

Figure 4. EMG envelope of an illustrative subject, S3, before and after training with the myo-BoMI. **A**: Envelope of biceps and triceps of the left (blue) and right (red) arm during the first test block of session 1. **B**: Envelope of biceps and triceps of the left (blue) and right (red) arm during the last test block of session 6. Black dashed lines correspond to the beginning of center-out movements while grey dashed lines to the beginning of the out-center ones.

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