Training and assessment of upper limb motor function with a robotic exoskeleton after stroke

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Abstract—This paper presents the results of the evaluation training performed in a group of chronic stroke patients with Light-Exoskeleton device. The rehabilitation treatment included passive, assisted and active reaching exercises based on an impedance control strategy with gain modulated by the patient’s ability to perform the task. The effects of training were assessed both by means of clinical evaluation in terms of Fugl-Meyer and Modified Ashworth assessment scales, and of functional evaluation, by means of Bimanual Activity test. Moreover, at each session an automatic assessment of performance was made through two robotic measures (task time and smoothness of movement), and these were analysed in term of correlation with the outcome of functional evaluation. Interestingly we found a significant improvement of both clinical and functional evaluation, and that the automatic assessment performed by the robot in terms of smoothness represents a strong predictor of transfer of functional ability to activity of every day life. The high correlation observed between functional outcome and robotic measures suggest the last ones can provide a rapid and useful feedback about the patient’s recovery progress, in addition to the pre- and post- clinical and functional measurements.

I. INTRODUCTION

Cerebrovascular disease, i.e. stroke, represents the first cause of acquired permanent disability in adults and the third leading cause of death in industrialized countries. Even after rehabilitation, about 80% of post-stroke patients still suffer upper limb disability, which impairs their daily living activities and often leads to major incapacities [1]. The mechanisms of functional recovery after stroke remain largely unknowns, but animal models and correlated human studies demonstrate that functional recovery after stroke is obtained through the use-dependent reorganization of neural mechanisms, exploiting basic properties of neural plasticity [2]. Current practices in standard care after stroke mainly rely on manual techniques provided by therapists. The basis of such techniques is task-oriented training, which combines cognitive and motor rehabilitation [3]. Importantly, such rehabilitation has to be intense, to start very early, and to be individualized depending on patient needs [4]. Recently, the researchers have focused increasing attention on the quantitative evaluation of patient’s motor abilities in order to obtain an objective evaluation of the rehabilitation treatment effects. Although the reliability and high acceptance, the standard clinical and functional scales have shown some drawback mainly due to high subjectivity, long duration and low resolution. The consequence is that clinicians need more efficient and more objective strategies for the assessment of patient recovery and, on the other hand, for the delivery of a high intense and controlled of rehabilitation training.

In the last two decades, many studies have proved the potential of robot-assisted rehabilitation arm in providing a great help to accelerate the recovery of upper limb function, with positive results on strength and motor function of patients [5], [6]. In addition, although the lasting effects on the quality of the activities of daily living of patients remains to be confirmed [7], robotic technology offers the opportunity of new therapeutic strategies based on recurrent evaluation of motor function to optimize the dose of the training and tailor the rehabilitation program to patients’ needs [8]. From the perspective of therapists, robotic technologies provide somewhat unique opportunities towards higher volume and more controlled rehabilitation. However, it might be even more important that robotic technologies and Virtual Reality allow to monitor the progress of patient recovery, in order to give useful and reliable performance feedback to the patient, and allow for on-line multisensory feedback, that may lead to a better retention of regained functions [9], [10], [11].

Many studies have carried out on the robotic rehabilitation therapy and their effectiveness evaluated at the start and at the end of protocol by means of the standard clinical and functional scales. However, few of the performed researches have shown a correlation between the clinical outcomes and the robot measurements [12], [13].

The main difficult to propose some of the robotic measures used in the past studies as a standard feedback of therapy progress, depends on their task or device peculiarity [12], [14], [15]. Two of these measures, commonly based on the reaching movement, are the smoothness and the execution time of movement, which were selected as robotic measures for the present study. Moreover, movement kinematics may be used to assess movement recovery in a more precise way [16], [17], going far beyond clinical tests that often do not clarify how the movement has been built, and what is a due to motor recovery or compensation. As a consequence, measuring movement smoothness not only informs about patient’s capability of executing a given movement, but also about movement quality [18], [19], [20].
A. Active Rehabilitation Exoskeletons

A class of rehabilitation robots that deserve a particular interest in upper limb rehabilitation is constituted by active exoskeletons: robotic devices with kinematic isomorphic to the human arm, that can be worn on the user upper limb. They present several significant advantages compared to end-effector based system [21]. They may track the full arm kinematics, so not only the hand, but the full kinematic chain of the arm, and consequently apply a force assist at the level of each joint independently, e.g. shoulder, elbow and wrist, offering the unique opportunity to re-train interjoint synergies. The workspace covered by these systems is three dimensional and large, so that the training can be conducted on fully spatial movements and along different directions. In the simplest way the assistance provided by the robot can consist in a gravity counterbalancing of weight of the arm, as this has been proved to enlarge the workspace of the arm [22] and to be effective for motor recovery. Alternatively the robot can provide a guided assistance to the task to be performed, according to an impedance-based model or more advanced controls [23].

In this work we present the last results of the robotic-based training and clinical assessment for upper limb rehabilitation performed with a robotic exoskeleton training system in hemiplegic patients after stroke. The aim of this work is to define some automatic measurements of motor function associated to the training exercises, and to analyse the correlation of these indexes with the outcome of standard clinical measures.

II. METHODS

A. Instruments

The rehabilitation platform used for this clinical treatment is composed of the the Light-Exoskeleton device (L-Exos) mounted on a mobile support of device, a control system and a graphic workstation with associated display [24]. The L-Exos [25], [21] is a right-arm rehabilitation robot used for stroke patients rehabilitation; it is composed of five degree-of-freedom (DoF), of which four active, i.e. shoulder and elbow flexion/extension, shoulder internal/external rotation and, abduction/adduction Fig.1a. This device is capable to exert a controlled force up to 100N on the hand palm of the patient. The weight of each moving link is totally compensated by the controller, while the inertia and dynamics of the device are assumed to be negligible, due to the low masses (each actuator is posed on the fixed base, as shown in [25]) and low speeds involved in the exercises. The high level control system provides three different strategies for movement training: Passive Mode (Impedance Based Assistance), Assisted mode (Triggered Gain Position Mode) and Free Mode (Direct Force Mode and Counterbalancing assistance). The Assisted Mode implement an “assistance as needed” training strategy based on a gain scheduling. A set of VR-based exercises (shown in Fig.1b) can specifically train arm movements in the frontal, ipsilateral and contralateral areas. The system is endowed with the virtual reality training scenarios projected on a stereoscopic projection wall embedding the rehabilitation exercises and the graphic user interface for controlling the system parameters and adapting the exercises to the specific patients needs.

B. Outcome and Clinical Assessment

The patients were evaluated by means of functional and clinical tests at both enrollment and discharge. Assessment took place during one week before the start of training, within one week after training had stopped, and at 5 months follow-up. The primary outcome measure was the Bimanual Activity Test (BAT), consisting in evaluating in terms of time and quality of movement (estimated on 0-4 scale) the execution by the patient of a set of Activities of Daily Life (ADL) tasks requiring bimanual coordination. The Fugl-Meyer Assessment scale (FMA) [26] was used as clinical test for the evaluation of motor function, sensation qualities and joint function in hemiplegic patients. Only the upper limb subsection (66 points) was considered for this study. The Modified Ashworth Scale (MAS) [27] was used as qualitative scale for the assessment of spasticity (measure resistance to passive stretch). The chosen set of clinical measures was justified by providing both motor impairment and functional ability measures. In addition, the clinical reliability of these scales (mainly the FMA) with the stroke population has been proved in past researches [28], [29].
C. Participants

Stroke survivors who volunteered to participate in the study were people who met the following inclusion criteria: aged between 18 and 80 years, able to understand the study purpose and procedure, and provide informed consent, moderate upper limb paresis, MAS greater than 2, stabilized before the beginning of the treatment.

Ten patients, of which 7 males and 3 females and with stroke event occurred at least six months ahead, were enrolled in the experimental group that was administered the robotic treatment. Two of the patients were unable to complete the treatment and they were excluded from the study. The rest eight patients (2 females and 6 males, 62.9±9.9 years old) were enrolled in the treatment and scheduled to perform six weeks of training with three sessions per week. Six of the eight patients underwent also a follow-up clinical assessment 5 months after the end of treatment to evaluate the retention of regained function. All participants provided informed consent in accordance with the Declaration of Helsinki prior to participation in this study, which was approved by the Ethical Committee of the Cisanello hospital in Pisa.

D. Protocol

Patients who satisfied the inclusion criteria were instructed to desist from different rehabilitation treatment during the study period. The rehabilitation training consisted in two training exercises and one evaluation test, performed with the assistance of the L-Exos. The first exercise consisted in a reaching task (see the left side of Fig.1b) performed with an impedance assistance by the robot with level of assistance modulated by the robot according to the position error (Passive Mode), or with variable gain adjusted according to the force input by the patient (Assisted Mode), to enhance patient’s active participation in the task. The second training exercise consisted in a training scenario in which the patient has to compose a virtual puzzle with the gravity assistance only provided by the robot (Free Mode). The exercise was then followed by an evaluation session (see the right side of Fig.1b) allowing to assess the performance in movement execution over different direction of space, since a set of target to be reached where placed in the vertical plane, along twelve possible positions arranged equally spaced along a circumference, resembling the hours position of a clock. Difficulty of sessions was tailored to the patients ability. In order to reduce the influence of fatigue and to avoid the starting of spasticity, 1 minute rest period was administered after every trial. The absolute hand position and the angular joints displacements were recorded at a sampling rate of 1 kHz. The tangential velocity were calculated by deriving the hand position and digitally filtered by using a low-pass second order forward and backward Butterworth filter with cut-off frequency at 5 Hz. To assess the improvement of motor recovery, two robotic performance indexes, measured in the evaluation session, were selected:

- Execution Time (ET), computed as the time to move from the start position in the centre to the peripheral target. The movement time was defined as the difference between the movement onset and offset, which were defined as the times when the tangential velocity respectively rose above and fell down 5% of the maximum velocity.
- Smoothness Index (SI), computed by counting the number of peaks in the velocity profile for each movement. A peak was counted if the increase from a minimum to the next maximum of the norm of the tangential speed was above 15% of the global maximum speed. As a consequence a decrease of the smoothness index means an increase of smoothness of movement.

III. RESULTS

We observed a significant clinical improvement in all patients. Clinical assessment at the enrollment the average FMA assessment score was of 24.6±12.9 and the average MAS of 14±8.8; at the end of treatment the outcome revealed an increase of FMA to 34.3±17.2 (p<0.01), with no significant change in spasticity (MAS after treatment 10.8±6.9). On the functional level (BAT), we observed a significant reduction of time in the execution of movement from 17.05±3.59 s to 13.15±3.77 s (p<0.005) with an overall increase of quality of movement from 1.99±0.77 to 2.94±0.92 (p<0.05). The results of the clinical tests performed by the subjects pre- and post-treatment are shown in Tab.I.

The assessment of the two indexes of performance achieved with the robot revealed a similar trend, as shown in Fig.2: a marked decrease of movement time from 2.55±1.15 to 1.02±0.68 s (p<0.005) and a marked increase of smoothness going from 6.63±0.92 to 2.75±1.54 (p<0.005).

![Fig. 2. Assessment of movement performance with the L-Exos.](image)

Moreover, we investigated the correlation of the BAT functional index with the robot assessment scale, to assess whether the improvement of performance observed with the robot was effectively transferred as ability to perform daily living activities. A strong correlation was observed between the two robotic performance indexes and the functional indexes of the BAT scale (p<0.05), as shown in Fig.3,
TABLE I
CLINICAL SCORES OF TREATED STROKE SUBJECTS BEFORE (PRE) AND AFTER TREATMENT (POST).

<table>
<thead>
<tr>
<th>Subject</th>
<th>Birth Year</th>
<th>Gender</th>
<th>FMA (66pts)</th>
<th>MAS</th>
<th>BAT</th>
<th>time</th>
<th>quality</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PRE</td>
<td>POST</td>
<td>PRE</td>
<td>POST</td>
<td>PRE</td>
<td>POST</td>
<td>PRE</td>
</tr>
<tr>
<td>P1</td>
<td>61</td>
<td>M</td>
<td>12</td>
<td>11</td>
<td>19,36</td>
<td>14,95</td>
<td>1,91</td>
</tr>
<tr>
<td>P2</td>
<td>78</td>
<td>M</td>
<td>6</td>
<td>13</td>
<td>15,84</td>
<td>11,73</td>
<td>2,95</td>
</tr>
<tr>
<td>P3</td>
<td>67</td>
<td>M</td>
<td>27</td>
<td>19</td>
<td>20,94</td>
<td>19,79</td>
<td>0,95</td>
</tr>
<tr>
<td>P4</td>
<td>72</td>
<td>F</td>
<td>-3</td>
<td>17</td>
<td>15,84</td>
<td>14,66</td>
<td>1,83</td>
</tr>
<tr>
<td>P5</td>
<td>57</td>
<td>M</td>
<td>13</td>
<td>13</td>
<td>10,60</td>
<td>8,68</td>
<td>1,08</td>
</tr>
<tr>
<td>P6</td>
<td>50</td>
<td>M</td>
<td>55</td>
<td>10</td>
<td>19,81</td>
<td>11,01</td>
<td>2,42</td>
</tr>
<tr>
<td>P7</td>
<td>55</td>
<td>F</td>
<td>13</td>
<td>13</td>
<td>17,05</td>
<td>13,15</td>
<td>1,99</td>
</tr>
<tr>
<td>P8</td>
<td>51</td>
<td>M</td>
<td>59</td>
<td>6</td>
<td>11,35</td>
<td>7,53</td>
<td>3,00</td>
</tr>
</tbody>
</table>

Mean 62.86 24.63 34.25 14.00 10.75 17.05 13.15 1.99 2.94
SD 9.96 12.88 17.21 8.82 6.86 3.59 3.77 0.70 0.92

Paired t-test two-tailed (p) 0.008 0.143 0.002 0.015

confirming that the improvement of performance observed with the robot was effectively transferred as ability to perform ADL activity. The performance improvement in the contralateral space.

In Fig. 3, Correlation of BAT scales outcomes with both robotic performance indexes.

Fig. 3. Correlation of BAT scales outcomes with both robotic performance indexes.

In Fig. 4a the means and standard deviations of differences between execution time at first and last session of treatment, averaged over each patient and over all sessions, for each of twelve direction are shown; while in Fig.4b the same analysis is depicted about the smoothness index. A significant improvement is observed mainly in the ipsilateral space (p<0.05), while no significant improvement is obtained in the contralateral space.

In the group of patients that underwent a follow-up evaluation at month 5 (shown in Fig.5), we found a percentage

Fig. 4. Improvement of smoothness index and time execution observed (Mean±SD) along different direction from central position (**p<0.01, *p<0.05, o:0.05<p<0.1)).
improvement of FMA of 39% that was maintained also at the follow-up assessment with a percentage improvement of 22% (p<0.01), indicating a retention of the acquired motor skill.

![FMA Scale](image)

**Fig. 5.** Follow-up evaluation (FMA) performed at 5 months.

### IV. DISCUSSION

The aim of this clinical study was to evaluate the feasibility of robotic therapy in chronic stroke patients. Subjects were motivated to participate to the training sessions and the improvement observed in smoothness of movement represents a predictive indicator of both clinical assessment and of recovered ability to perform activities of everyday life. This represents an important result, since it allows mapping directly the measured performance to improvements in terms of functional activity. Furthermore, the first preliminary results from follow-up evaluation performed at 5 months of distance since treatment allowed us also to hypothesize that such a regain of function is retained over time. These data were confirmed also by analysing the Execution Time required to move virtual cubes from the central point of a circle along different radial directions, performing movements in a vertical plane. Changes in Execution Time and Smoothness Index, before and after robotic training, where larger for movements performed in the ipsilateral space, which constitutes a very important goal in rehabilitation of the upper arm after stroke. This confirms that exoskeleton systems in combination with specifically design exercises might be used not only to enhance the process of recovery, but also to evaluate the progress of therapy. In confirmation of the obtained results, some of the patients declared to have noted little increase right about the stabilization and precision of reaching movements during some common daily life tasks.

### V. CONCLUSIONS

Robotic technologies offer the unique opportunity to individually tailor the physical therapy during neurorehabilitation training to the specific patient’s needs, creating the conditions to enhance the patient involvement in the training program, through the interplay of different factors, such as motivation, feedback, controlled assistance and ecological presentation of exercises. Results from our studies demonstrate that robotic training can be effective both in terms of clinical efficacy and regain of motor function, assessed by functional tests in everyday life actions. Moreover, the recording capabilities of robotic technologies make it possible to perform a continuous evaluation of motor performance through quantitative and objective indexes that correlate well with clinical scales, providing an on-line and dynamic assessment of patient’s status and a record of the recovery process.

### VI. ACKNOWLEDGMENTS

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### REFERENCES


