Robotic assisted rehabilitation in Virtual Reality with the L-EXOS

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Abstract. This study presents the evaluation results of a clinical trial of robotic-assisted rehabilitation in Virtual Reality performed with the PERCRO L-Exos (Light-Exoskeleton) system, which is a 5-DoF force-feedback exoskeleton for the right arm. The device has demonstrated itself suitable for robotic arm rehabilitation therapy when integrated with a Virtual Reality (VR) system. Three different schemes of therapy in VR were tested in the clinical evaluation trial, which was conducted on a group of nine chronic stroke patients at the Santa Chiara Hospital in Pisa-Italy. The results of this clinical trial, both in terms of patients performance improvements in the proposed exercises and in terms of improvements in the standard clinical scales which were used to monitor patients receovery are reported and discussed. The evaluation both pre and post-therapy was carried out with both clinical and quantitative kinesiologic measurements. Statistically significant improvements were found in terms of Fugl-Meyer scores, Ashworth scale, increments of active and passive ranges of motion of the impaired limb, and quantitative indexes, such as task time and error.

Keywords. Exoskeleton, robotic-assisted rehabilitation, task-oriented movement, reaching target, clinical protocol, Virtual Reality, Range of Motion, Fugl-Meyer assessment

Introduction

Several studies demonstrate the importance of an early, constant and intensive rehabilitation following cerebral accidents. This kind of therapy is an expensive procedure in terms of human resources and time, and the increase of both life expectance of world population and incidence of stroke is making the administration of such therapies more and more important. The impairment of upper limb function is one of the most common and challenging consequences following stroke, that limits the patient's autonomy in daily living and may lead to permanent disability [1]. Well-established traditional stroke rehabilitation techniques rely on thorough and constant exercise [2, 3], which patients are required to carry out within the hospital with the help of therapists, as well as during daily life at home. Early initiation of active movements by means of repetitive training has proved its efficacy in guaranteeing a good level of motor capability recovery [4]. Such techniques allow stroke patients to partially or fully recover motor functionalities during the acute stroke phase, due to the clinical evidence of a period of rapid sensorimotor recovery in the first three months after

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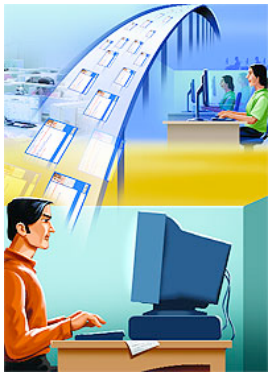

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stroke, after which improvement occurs more gradually for a period of up to two years and perhaps longer [5, 6]. However after usual therapies, permanent disabilities are likely to be present in the chronic phase, and in particular a satisfying upper extremity motor recovery is much more difficult to obtain with respect to lower extremities [7].

Several studies have attempted to investigate the efficacy of stroke rehabilitation approaches [8, 9]. Intensive and task oriented therapy for the upper limb, consisting of active, highly repetitive movements, is one of the most effective approaches to arm function restoration [10, 11]. The driving motivations to apply robotic technology to stroke rehabilitation are that it may overcome some of the major limitations that manual assisted movement training suffers from, i.e. lack of repeatability, lack of objective estimation of rehabilitation progress, and high dependence on specialized personnel availability. Robotic devices for rehabilitation can help to reduce the costs associated with the therapy and lead to new effective therapeutic procedures. In addition, Virtual Reality can provide a unique medium where therapy can be provided within a functional and highly motivating context, that can be readily graded and documented. The cortical reorganization and associated functional motor recovery after Virtual Reality treatments in patient with chronic stroke are documented also by fRMN [12].

Among leg rehabilitation robot devices, Lokomat [13] has become a commercial and widely diffused lower limb robotic rehabilitation device. It is a motorized orthosis able to guide knee and ankle movements while the patient walks on a treadmill.

Concerning arm rehabilitation devices, both cartesian and exoskeleton-based devices have been developed in the last 10 years. MIT Manus [14, 15] and its commercial version InMotion2 [16] are pantograph-based planar manipulators, which have extensively been used to train patients on reaching exercises and have been constantly evaluated by means of clinical data analysis [17]. It has been designed to be backdrivable as much as possible and to have a nearly isotropic inertia. ARM-guide [18, 19] is a device which is attached to the patient's forearm and guides the arm along a linear path having a variable angle with respect to the horizontal position. Constraint forces and range of motion are measured throughout the exercises. The MIME (Mirror Image Movement Enabler) system [20] is a bimanual robotic device which uses an industrial PUMA 560 robot that applies forces to the paretic limb during 3-dimensional movements. The system is able to replicate the movements of the non-paretic limb.

Exoskeletons are robotic systems designed to work linked with parts of the human body and, unlike robots, are not designed to perform specific tasks autonomously in their workspace [21]. In such a condition, the issue of the physical interaction between robots and humans is considered in terms of safety. The design of exoskeleton systems stems from opposite motivations that intend the robotic structure to be always maintained in contact with the human operators limb. Such a condition is required for several applications that include the use of master robotic arms for teleoperation, active orthoses and rehabilitation [22].

Experiments on exoskeletons have been performed at the JPL during 1970s [23]. Sarcos [24] developed a master arm used for the remote control of a robotic arm, while at PERCRO arm exoskeletons have been developed for interaction with virtual environments since 1994 [22, 25, 26]. Exoskeletons can be suitably employed in robotic assisted rehabilitation [27].

Two exoskeleton-based systems have been developed at Saga University, Japan. The older one [28] is a 1-DoF interface for the human elbow motion, where angular position and impedance of the robot are tuned relying on biological signals used to interpret the human subjects intention. The newer neuro-fuzzy controlled device [29] is a 2-DoF interface used to assist human shoulder joint movement. Another device, the ARMin, has been developed at ETH, Switzerland [30, 31]. This device provides three active DoFs for shoulder and one active DoF for elbow actuation. The patient is required to perform task-oriented repetitive movements having continuous visual, auditory and haptic feedback. The Salford Exoskeleton [32], which is based on pneumatic Muscle Actuators (pMA) and provides an excellent power over weight ratio, has also been used in physiotherapy and training.

A recent survey [33] on the efficacy of different robot assisted therapies outlines that robotic-aided therapy allows a higher level of improvement of motor control if compared to conventional therapy. Nevertheless, it is to be noted that no consistent influence on functional abilities has yet been found.

This chapter presents the results of an extended clinical trial employing the L-Exos system [34], a 5-DoF force-feedback exoskeleton for the right arm; the system was installed at the Neurorehabilitation Unit of the University of Pisa, where it was used for the robotic assisted VR-based rehabilitation in a group of 9 chronic stroke patients[35, 36]. This work is intended to extend previous works concerning a pilot study with the L-Exos system by providing significant therapy and clinical data from a much larger set of patients.

Section 1 presents a general description of the L-Exos system, underlining the main features which make the device useful for rehabilitation purposes, and a description of the developed VR applications may be found in Section 2. Section 3 and Section 4 discuss the main results which have been obtained with the L-Exos both in terms of improvements in the metrics used to assess patient performance in the therapy exercises and in terms of improvements in the standard clinical scales which have been used to monitor patients' recovery. Conclusions and perspectives opened by this pilot study are briefly reported in Section 5.

1. The L-EXOS system

L-Exos (Light Exoskeleton) is a force feedback exoskeleton for the right human arm. The exoskeleton is designed to apply a controllable force of up to 100 N at the center of the user's hand palm, oriented along any spatial direction and it can provide active and tunable arm weight compensation. The device mechanical structure has been extensively described in [37], whereas a description of the model of its novel tendon transmission may be found in [38]. For sake of clarity, a brief review of the device kinematics will be provided in this section.

L-Exos has 5 DoFs, 4 of which are actuated and are used to define the position of the end-effector in space (see Figure 1). The system is therefore redundant, allowing different joint configurations corresponding to the same end-effector position, which is fundamental for chronic stroke patients. Such subjects are likely to implement compensatory strategies in order to overcome force and Range of Motion (ROM) limitations remaining after stroke rehabilitation [39]. The 5th DoF

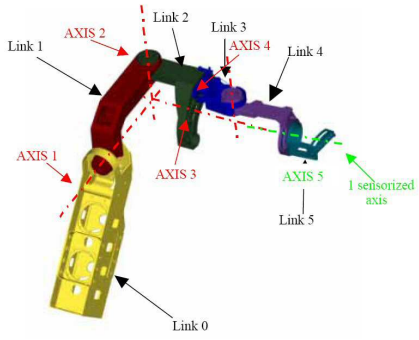


Figure 1. L-Exos kinematics.

is passive and allows free wrist pronation and supination movements. Moreover, design optimizations allow total arm mobility to a healthy subject wearing the device.

The structure of the L-Exos is open, the wrist being the only closed joint, and can therefore be easily wearable by post-stroke patients with the help of a therapist. In order to use the L-Exos system for rehabilitation purposes, an adjustable height support was made, and a chair was placed in front of the device support, in order to enable patients to be comfortably seated while performing the tasks. The final handle length is also tunable, according to the patient's arm length.

After wearing the robotic device, the subject's elbow is kept attached to the robotic structure by means of a belt. If necessary, the wrist may also be tightly attached to the device end-effector by means of a second belt, which was used for patients who were not able to fully control hand movements. A third belt can easily be employed in order to block the patient's trunk when necessary.

The L-Exos device was integrated with a projector used to display on a wide screen placed in front of the patient different virtual scenarios in which to perform rehabilitation exercises. The VR display is therefore a mono screen in which a 3D scene is rendered. Three Virtual Rehabilitation scenarios were developed using the XVR Development Studio [40]. The photo shown in Figure 2 was taken during a therapy session, while one of the admitted patients was performing the required exercises, and is useful to visualize the final clinical setup.

Figure 2. One admitted patient performing the robotic-aided therapy exercises.

2. Methods

A clinical pilot study involving 9 subjects with the main objective of validating robotic assisted therapy with the L-Exos system was carried out at the Santa Chiara Hospital of Pisa, Italy, between March and August 2007. Potential subjects to be enrolled in the clinical protocol were contacted to take part in a preliminary test session used to evaluate patients acceptance of the device. Most of the patients gave an enthusiastic positive feedback about the opportunity.

Patients who were declared fit for the protocol and agreed to sign an informed consent form concerning the novel therapy scheme were admitted to the clinical trials. The protocol consisted of 3 one-hour rehabilitation sessions per week for a total of six weeks (i.e., 18 therapy sessions). Each rehabilitation session consisted in three different VR mediated exercises. A brief description of the goal of each exercise will be provided in the next paragraphs, whereas a more detailed description of the VR scenarios developed may be found in previous works [35, 36]. Some relevant control issues concerning the proposed exercises will be reported as well.

The patient was on a seat as shown in Figure 3(D), with his/her right forearm wearing the exoskeleton and a video projector displaying frontally the virtual scenario. A preliminary clinical test was conducted to evaluate the ergonomics of the system and the functionality as a rehabilitation device on a set of three different applications. The test was intended to demonstrate that the L-Exos could be successfully employed by a patient, and to measure the expected performance during therapy.

To assess the functionality of the device, three different scenarios and corresponding exercises were devised:

- A reaching task;
- A motion task constrained to a circular trajectory;
- An object manipulation task.

The tasks were designed in order to be executed in succession within one therapy session of the duration of about one hour, repeated three times per week.

(A)

(B)

(C)

(D)

Figure 3. The arm exoskeleton during the execution of the reaching task. A: the starting position of the reaching task; B: a subject in the middle of the path of the reaching task; C: a subject at the end-point of the path of the reaching task; D: The overall system.

2.1. Reaching task

In the first task, the represented scenario is composed of a virtual room, where different fixed targets are displayed to the patient as gray spheres disposed on a horizontal row, as shown in Figure 4. The position of the hand of the patient is shown as a green sphere, that is moved according to the end-effector movements.

The starting position of the task was chosen as a rest position of the arm, with the elbow flexed at 90°, as shown in Figure 3(A). In this position, the exoskeleton provides the support for the weight of the arm, so that the patient can comfortably lean his arm on the exoskeleton.

When one of the fixed targets is activated, a straight trajectory connecting the starting point and the final target is displayed in the simulation. The patient is instructed to actively follow the position of a yellow marker, whose motion is generated along the line connecting the start and end points according to a minimum jerk model [41], approximated by a 5th degree polynomial with a displacement profile as represented in Figure 5.

The patient is asked to move the arm to reach the final target with a given velocity, minimizing the position error between the yellow marker that moves automatically toward the target, and his/her own marker, represented by the green sphere. The yellow marker reaches the target with zero velocity, and comes back on the blue line towards the initial position. The patient is alerted of the start of the exercise by a sound, that is generated automatically by the system. The therapist can set the maximum speed of the task, by choosing among three maximum speeds (v_1 = 5 cm/s, v_2 = 10 cm/s and v_3 = 15 cm/s) and change the position of the fixed targets that should be reached by the patient, both in terms of target height and depth within the virtual room.

The movement towards multiple targets disposed on the same row and backwards is activated in sequence, so that the patient can perform movements in both medial and lateral planes, reaching targets at the same height. There are 7 fixed targets placed symmetrically respect to the sagittal plane of the subject and the fixed targets can be disposed at two different heights relative to the start position of

the task (h_1 = 0.01 m and h_2 = 0.12 m). During each series, the height of the fixed target is not changed, and the following steps are executed in succession for each series:

1) The first movement is executed towards the leftmost fixed target;
2) Once the fixed target is reached the moving marker returns back to its start position, it stops for 2 seconds, and then it starts again towards the next target on the right;
3) The last target of each series is the rightmost one.

In order to leave the patient the possibility to actively conduct the task and be passively guided by the robot only when he/she is unable to complete the reaching task, a suitable impedance control was developed. The control of the device is based on two concurrent impedance controls acting respectively along tangential and orthogonal directions to the trajectory.

2.2. Constrained motion task

In the second exercise the patient is asked to move freely along a circular trajectory, as shown in Figure 6, where it is constrained by an impedance control. The virtual constraint is activated through a button located on the handle. Position, orientation and scale of the circular trajectory can be changed online, thus allowing the patient to move within different effective workspaces. No guiding force is

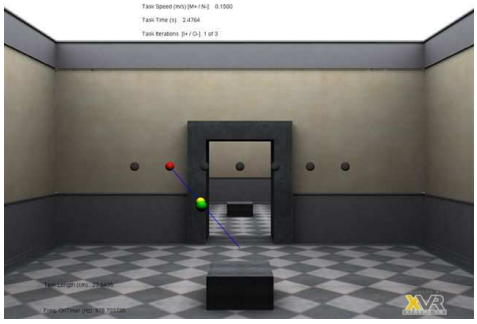


Figure 4. The virtual scenario visualized in the reaching task.

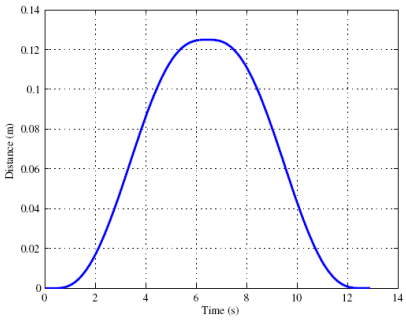


Figure 5. The motion profile to be followed by the patient in the reaching task.

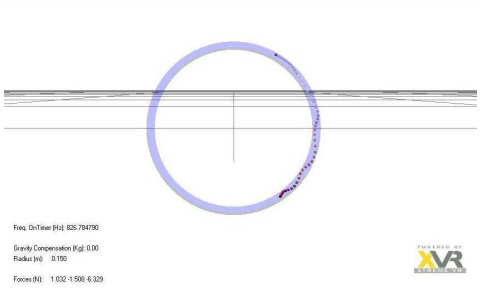


Figure 6. Example of the free motion constrained to a circular trajectory.

applied to the patient's limb when he/she is moving within the given trajectory, along which the patient is constrained by means of virtual springs.

Also in this task the therapist can actively compensate the weight of the patient's arm through the device, until the patient is able to autonomously perform the task. This is accomplished by applying torques at the level of the joints, based on a model of the human arm, with masses distributed along the different limbs with a proportion derived from anatomical data. The absolute value of the each limb mass is determined according to the weight of the subject.

2.3. Free motion task

In this task the patient is asked to move cubes represented in the virtual environment, as shown for instance in figure 7, and to arrange them in a order decided by the therapist, e.g. putting the cubes with the same symbol or with the same color in a row, or putting together the fragments of one image.

For this task the device is controlled with a direct force control, with the interaction force computed by a physics module based on the Ageia PhysX physics engine [42]. By pressing a button on the handle, the patient can decide to select which cube wants to move and release the cube through the same button. Collision with and between the objects are simulated through the physics engine, so that it is actually possible to perceive all the contact forces during the simulation.

Also in this task the device can apply an active compensation of the weight of the patient arm, leaving to the therapist the possibility to decide the amount of weight reduction.

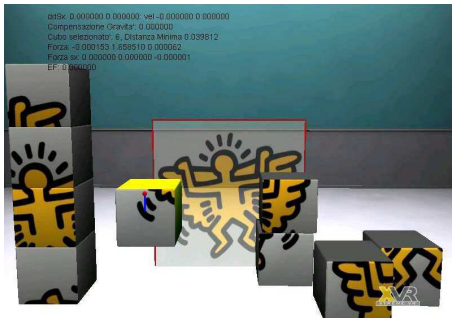


Figure 7. An example of the manipulation of objects task.

3. Therapy results

The following paragraphs will describe the metrics used in order to quantitatively evaluate patients' performance in the reaching task and in the path following task exercises. No quantitative data was computed for the last proposed task. A first obvious possible quantitative measure, such as task completion time, was thought as being not significant to evaluate patient performance improvements. This was due to the high variability in the task difficulty among different therapy sessions (initial cube disposition was randomly chosen by the control PC), and to the high variability in patient's attitude to consider the exercise as completed, i.e. the accepted amount of cube misalignment and hence the amount of time spent in trying to perform fine movements to reduce such misalignment.

3.1. Reaching task

Figure 8 shows a typical path followed by a patient during the reaching task. The cumulative error for each task was chosen as being the most significant metric to analyze reaching data. After the definition of a target position and of a nominal task speed, the cumulative error in the reaching task is computed for iterations corresponding to the given target position and speed. The cumulative error curves are then fitted in a least square sense by a sigmoid-like 3-parameter curve, represented with Eq. (1), where *s* is the cumulative error at time t, whereas *a*, *b* and *c* are fitting parameters.

Fitting curves are then grouped and averaged on a therapy session basis, each set containing the fitting curves computed for a single rehabilitation session. Sample data resulting from this kind of analysis are shown in Figure 9, where a greater dash step indicates a later day when a given target was required to be reached with a given peak speed.

It is to be said that statistically significant improvements in the average fitting curves from Week 1 to Week 6 are recognizable for more than half targets in only 4 out of 9 patients enrolled in the protocol. A typical improvement pattern for a sample target is shown in Panel A of Figure 9 for Patient 6. This patient is constantly improving his performance in the exercise, leading to a significant

$$s(t) = \frac{a}{1 + e^{(t-b)/c}} \qquad (1)$$

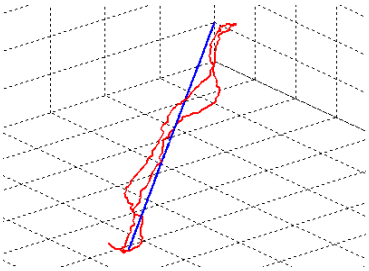


Figure 8. Typical path followed during a reaching task – Blue straight line: ideal trajectory, Red: actual trajectory.

decrease in the final cumulative error for a given target. A reducing of the mean slope of the central segment of the fitting curve is therefore present, thus indicating a higher ability to maintain a constant average error throughout the task.

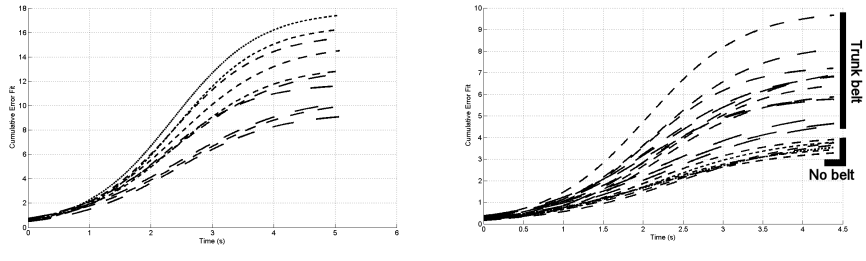
Panel B of Figure 9 reveals an interesting aspect of the application of the belt used to avoid undesired back movements. During the first therapy sessions, no belt was present, and each therapy session registered a comparable value of the cumulative error. As soon as the trunk belt is introduced, the error increases dramatically, as formerly employed compensatory strategies are not allowed. However, due to the fact that active patient's movements become much more stimulated, the cumulative error fitting curve improves significantly. It is to be noted that, by the end of the therapy, values which are nearly comparable to the ones obtained in the no-belt condition are reached.

3.2. Path following task

Total time required to complete a full circular path was the quantitative parameter used to assess patient improvement for the constrained motion task. 3D position data were projected onto a best fitting plane (in the sense of least squares), and the best fit circle was computed for the projected points. Time to complete a turn was then evaluated with regard to trajectory. Curvature along the trajectory, which is irregular for the three patients, was not evaluated. In particular, due to the deliberately low value of the stiffness which realizes the motion constraint, patients sometimes move in an unstable way, bouncing from the internal side to the external side of the trajectory and vice versa, requiring some time to gain the control of their movements again. This behavior has detrimental effects on curvature computation.

Although three of the patients report no significant decrease of the completion time from Week 1 to Week 6, three patients report a decrease of about 50% in the task completion time, whereas three other patients report a decrease of about 70% of the same performance indicator. Such results are significant from a statistical point of view ($p < 0.001$ for the t-Student test for each patient showing improvements).

Sample data from Patient 3 are shown in Figure 10, in order to visualize a typical trend which was found in the patients reporting improvements in the motion constrained exercise. It is interesting to note that, along with the significant reduction in the mean time required to complete a circle, a significant reduction of



A *B*

Figure 9. *A*: sample reaching results for Patient 6; *B*: sample reaching results for Patient 3.

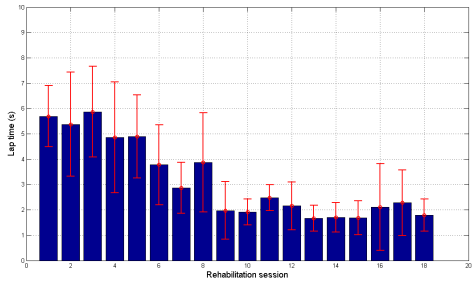


Figure 10. Sample constrained motion task results - Patient 3.

the associated standard deviation is recognizable, hence suggesting an acquired ability of performing the exercise with a much higher regularity level.

4. Clinical results

All patients were evaluated by means of standard clinical evaluation scales:

- Fugl-Meyer scale: this scale [43] is used for the evaluation of motor function, of balance, and of some sensation qualities and joint function in hemiplegic patients. The Fugl-Meyer assessment method applies a cumulative numerical score. The whole scale consists of 50 items, for a total of 100 points, each item being evaluated in a range from 0 to 2.33 items concern upper limb functions (for a total of 66 points) and are used for the clinical evaluations.
- Modified Ashworth scale: it is the most widely used method for assessing muscle spasticity in clinical practice and research. Its items are marked with a score ranging from 0 to 5, the greater the score, the greater being the spasticity level. Only patients with modified Ashworth scale values ≤ 2 were admitted to this study.
- Range Of Motion: it is the most classical and evident parameter used to assess motor capabilities of impaired patients.

Clinical improvements in each scale have been observed by the end of the therapy protocol for every patient, and they will now be discussed.

4.1. Fugl-Meyer assessment

The Fugl-Meyer assessment was carried out before and after robotic therapy. Every patient reported a significant increment ranging from 1 to 8 points, 4 points (out of 66) being the average increment ($p<0.005$, paired t-Student test). Such results is absolutely comparable with the results which may be found in the scientific literature [33].

4.2. Ashworth assessment

Slight decrements of some values of the Modified Ashworth scale may be found examining detailed clinician assessments. The following improvement index was defined for each value of the Ashworth scale:

+1: decrement of one step (e.g. from 1 to 0/1);
+2: decrement of two steps (e.g. from 1+ to 0/1);
+3: decrement of three steps (e.g. from 1+ to 0);
-1: increment of one step (e.g. from 1 to 1+).

The total improvement index was computed for each patient. A mean improvement of 6.2 points in the overall improvement index has been found, with a standard deviation of 4.2 points. It can therefore be asserted that the robotic therapy with the L-Exos device leads to improvements in patients' spasticity levels.

4.3. ROM evaluation

Different ROM measurements, both active and passive, were conducted. Statistical significance data elaborations on total ranges were performed by means of the paired t-Student test. Statistically significant improvements ($p < 0.05$) have been demonstrated for many ROMs, whereas many other ROM improvements reached marginal significance ($0.05 < p < 0.10$). Only 1 ROM increment has been found as not statistically significant.

It is to be noted that marginally significant or non significant improvements were found for passive ROMs, whereas each active ROM improvement is statistically significant. This observation confirms that the therapy with the L-Exos has beneficial effects on the maximum range of motion both for joints directly employed when performing the therapy exercises and for joints not directly exercised by the rehabilitation exercises (e.g. wrist) and blocked in a fixed position during the therapy. This evidence supports the theory stating that a dedicated shoulder or elbow therapy and the resulting neural repair of cerebral areas involved in proximal segments motor control may lead to a natural neural repair of cerebral areas involved in the motor control of distal segments.

Further evidence supporting this theory is provided by a single patient who reported unexpected significant improvements in hand movements. In particular at the end of the therapy, he was able to control finger opening and closing motions at a slow speed, whereas he had not been able to perform any hand movement after the stroke event. It is to be noted that no hand movements are employed in any exercise performed with the L-Exos system, due to the fact that hand and wrist are blocked in a fixed position with respect to the forearm throughout the therapy.

5. Conclusions

The L-Exos system, which is a 5-DoF haptic exoskeleton for the right arm, was successfully clinically tested on a group of nine chronic stroke patients with upper limb motor impairments. In particular, the extended clinical trial presented in this paper consisted in a 6-week protocol involving three one-hour robotic-mediated rehabilitation sessions per week.

Despite most of the patients enthusiastically reporting major subjective benefits in Activities of Daily Life after robotic treatment, it is to be said that no general correlation has yet been found between such reported benefits and performance improvements in the proposed studies. In other words, patients who improve on the

reaching task exercise may fail to present a corresponding performance improvement in the path following task and vice versa, and this does not seem to be correlated to the generalized extremely positive qualitative feedback. This observation may be caused by a variety of factors and requires further studies to be conducted.

Nevertheless, qualitative subject feedback is strongly supported by the clinical analyses which definitely underline significant improvements in clinical metrics deriving from robotic-mediated rehabilitation therapy, thus suggesting the possible need for more complex metrics to be used in order to analyze exercise performance. In particular, significant ROM increments for joints which are not actively exercised by the robotic therapy is considered an extremely important result. As a matter of fact, global cortical reorganization involving upper limb can be positively stimulated by exoskeleton devices like the L-Exos, even though some limitations in terms of number of DoFs are prgaigesent. Further differentiated clinical studies will be conducted in order to evaluate which kind of robotic-assisted therapy is able to provide the best possible rehabilitation outcome.

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