A pilot clinical study on robotic assisted rehabilitation in VR with an arm exoskeleton device

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***Abstract*—The development of new robotic devices for rehabilitation can lead to new and more efficient therapeutic procedures. Moreover, the use of VR-based scenarios in which patients perform rehabilitation exercises dramatically increases the patients' motivation and thus the final therapy outcome. In this paper preliminary results of a pilot study carried out with an exoskeleton for the robotic assisted rehabilitation of the upper limb are presented. The paper briefly describes the main kinematic and mechanical features of the exoskeleton system, showing its peculiar characteristics which make it useful for rehabilitation purposes. The implementation of three different robotic schemes of therapy in virtual reality with this exoskeleton, based on an impedance control architecture, are presented and discussed in detail. Finally, qualitative and quantitative results obtained in a 6 week pilot study with three chronic stroke patients are reported.**

I. Introduction

WELL-established traditional stroke rehabilitation techniques rely on thorough and constant exercise [1], [2]. Early initiation of active movements by means of repetitive training has proved its efficacy in guaranteeing a good level of motor capability recovery [3] during the acute stroke phase. However, permanent disabilities are likely to be present in the chronic phase, especially concerning upper extremities [4].

Several research studies have recently focused on both the development of novel robotic interfaces and the use of Virtual Reality technologies for rehabilitation. The former may overcome some of the major limitations manual assisted movement training suffers from, i.e. lack of repeatability, lack of objective estimation of rehabilitation progress, and the high dependence on specialized personnel availability. On the other hand, VR-based rehabilitation protocols may significantly improve the quality of rehabilitation by offering strong functional motivations to the patient, who can therefore be more attentive to the movement to be performed.

Several arm rehabilitation robotic devices, both Cartesian and exoskeleton-based, have been developed in the last 10 years. Some example include MIT Manus [5 – 7], ARM-guide [8, 9], MIME (Mirror Image Movement Enabler) [10], 1-DoF and 2-DoF devices developed at Saga University [11,12], ARMin [13,14] and Salford Exoskeleton [15]. A recent survey [16] outlines that robotic-aided therapy allows a higher level of improvement of motor control if compared to conventional therapy. Nevertheless, no consistent influence on functional abilities has yet been found.

On the other hand, several studies (e.g.: [17]) have demonstrated positive effects of Virtual Reality on rehabilitation, which enhances cognitive and executive functions of stroke patients [18] by allowing them to receive enhanced feedback on the outcome of the rehabilitation tasks he/she is performing. Moreover, VR can provide an even more stimulating videogame-like rehabilitation environment when integrated with force feedback devices, thus enhancing the quality of the rehabilitation [19].

This paper presents the first clinical results of the application of the L-Exos system [20], a 5DoF arm exoskeleton, to upper limb rehabilitation. L-Exos is installed at the Neuro-rehabilitation Unit of the University of Pisa, where it is currently being employed in schemes of robotic assisted VR-based rehabilitation.

Section II presents a general description of the L-Exos system, underlining the main features which make the device useful for rehabilitation purposes. A detailed description of the developed VR applications is given in Section III, details concerning selected patients and the experimental protocol used with them are given in Section IV, whereas Section V contains the main clinical results of this pilot clinical study. Conclusions and perspectives opened by this pilot study are briefly reported in section VI.

II. L-EXOS General Description

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 100N at the center of the user's hand palm, oriented along any spatial direction. L-Exos has 5 DoFs, 4 of which are actuated and are used to define the position of the end-effector in space. The system is therefore redundant, allowing different joint configurations corresponding to the same end-effector position, which is fundamental in a rehabilitation context. In particular, chronic stroke patients are likely to implement compensatory strategies in order to overcome force and

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Fig. 1. L-Exos worn by a user.

Range of Motion (ROM) limitations remaining after stroke rehabilitation [21, 22]. The 5th DoF is passive and allows free wrist pronation and supination movements. The system is fully backdrivable thanks to its tendon transmission, which is described in [23].

Wearability and usability are crucial factors when dealing with impaired people, i.e. the structure must be as open as possible, in order not to cause any major difficulty for the patient to wear it. The structure of the L-Exos is therefore open, the wrist being the only closed joint. 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 has been used for patients who are not able to fully control hand movements. In order to use the L-Exos system for rehabilitation purposes, an adjustable height support has been created, and a chair has been 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. The overall system has been placed in a hospital structure and is shown in Figure 2.

The L-Exos safety system has been a major concern in the design phase. Although the device has a wide workspace, no self-collisions are possible due to many mechanical stops which are present in the structure. Software saturations and a redundant electric and electronics safety system has been implemented in order to make the device fail-safe even in case of sudden power loss.

III. VR SCENARIOS

The L-Exos device has been 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 have been developed using the XVR Development Studio [24], and they will now be described.

Fig. 2. L-Exos – Rehabilitation configuration.

A. Reaching task

This 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 3. The position of the hand of the patient is shown as a green sphere, that is moved according to the L-Exos end-effector movements. According to the protocol specifications (see Section IV), each target is successively selected and thus "activated", i.e. it becomes red and a straight blue line connecting the starting position with the final target to be reached is displayed in the screen. The starting position of the task was chosen as a rest position of the arm, with the elbow flexed at 90°. 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.

After an acoustic signal indicating the start of the exercise, the patient is asked to keep the green sphere as close as possible to a yellow marker which moves along the line connecting the start and end points. The curvilinear coordinate of the marker is computed according to a minimum jerk model [9], which is approximated by a 5th degree polynomial with a bell-shaped displacement profile. The patient is instructed to keep the green sphere as near as possible to the moving yellow sphere. The yellow marker reaches the target with zero velocity, and comes back on the blue line towards the initial position. The therapist can set the maximum speed of the task and change the number and position of the fixed targets that should be reached by the patient (both in terms of target height and depth within the virtual room).

In order to leave the patient the possibility to actively conduct the task and being passively guided by the robot only when he/she is unable to complete the reaching task, an impedance control has been developed for the system. In particular, the implemented control scheme always

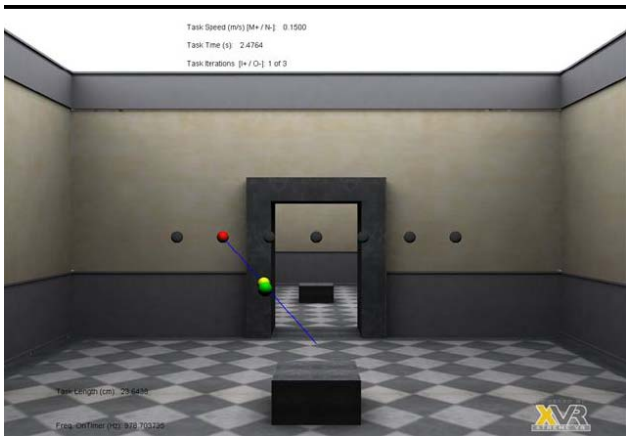

Fig. 3. The virtual scenario visualized in the reaching task.

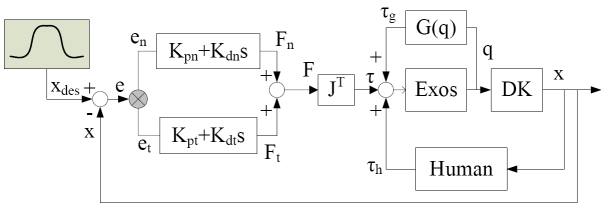

Fig. 4. Control architecture employed during the reaching task. x_{des}: desired endpoint position. e, en, et: error, error normal to the trajectory, error along the trajectory. K_{pn}, K_{dn}, K_{pt}, K_{dt}: proportional and derivative control coefficients normal to and along the trajectory. F: control force deriving from the impedance control. G(q): gravity model to compute the gravity compensation torque. Human: model of the weight of the human arm to compensate (part of) the arm weight. DK: direct kinematics.

guarantees that the device is gravity compensated and realizes two virtual springs of different stiffness along the direction of the task and on the plane normal to that direction. In particular, stiffness values of 500 N/m and of 1200 N/m have been used along the trajectory and on the plane perpendicular to the trajectory respectively. A stiffer virtual cylinder having its axis coincident to the line indicating the task direction was created. The patient is constrained inside this virtual cylinder, and can move more (although not completely) freely along the trajectory. Derivative-based (damping) terms are added to the control in order to increase the overall system stability. For the sake of clarity, Figure 4 shows a block diagram of the control architecture employed for the reaching task. The same control parameters are used for each patient in the actual protocol design. Patient-specific stiffness parameters could be employed in future studies.

B. Constrained motion task

In the second scenario the patient is asked to move (both clockwise and counterclockwise) along a circular trajectory, as shown in Figure 5, where it is constrained by an impedance control. Position, orientation and scale of the circular trajectory can be changed online, thus allowing the patient to move within different workspaces. No guiding force is applied to the patient's limb when he/she is moving

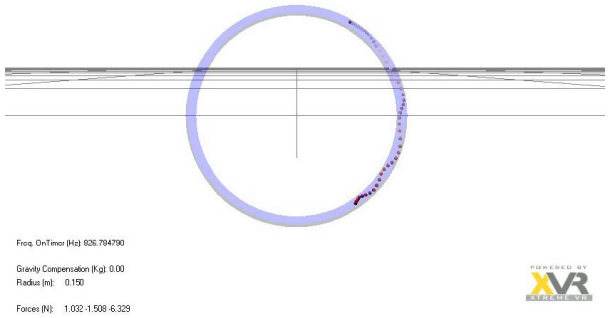

Fig. 5. The virtual scenario visualized in the constrained motion task.

Fig. 6. The virtual scenario visualized in the manipulation task.

within the given trajectory. The patient receives a visual feedback of his/her instant position as well as of the trace of the last positions of the hand. The patient can therefore have an online feedback on the correctness of the exercise he/she is performing. The therapist can tune the level of the active compensation of the weight of the patient's arm, until the patient is able to autonomously perform the task.

C. Manipulation task

In the third scenario the patient is asked to move some cubes, as shown in Figure 6, and to arrange them in order to recompose a given image which appears on the background. The image can be split in 4 or 9 parts in order to augment the task difficulty level, and it can easily be changed, thus proposing a new exercise to the patients for each rehabilitation session. The patient can move the cubes selecting and deselecting them by means of a button located on the handle or by means of verbal commands given to the therapists when severe hand impairment is present and the patient is not able to click the button. Also in this task the therapist can help the patient applying an active compensation of the weight of the arm.

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 [25], which guarantees a correct haptic feedback of possible contact forces.

IV. Experimental Protocol

A pilot study is currently being conducted with the main objective of validating the implemented therapeutic schemes and generally of evaluating the potential of performing robot aided therapy with the L-Exos system. In particular, an analysis of the compliance of the robot to the requirements (both user's and medical) for its use as a neurorehabilitation device has been carried out. Details about the patient selection phase and about the aforementioned tasks will now be presented.

A. Patient selection

Three male patients were selected to participate in this pilot study by the following inclusion criteria: right hemiparetic subjects; time from stroke greater than 12 months; no previous robotic treatment; stable motor functions for at least one month prior to participation in the study; residual voluntary motor control of the right arm with middle-low motor functions; and the ability to understand simple commands. The protocol consisted of 3 one-hour rehabilitation sessions per week for a total of six weeks. To assess voluntary motor control, ROM, and muscle tone prior to initiating the robotic treatment with the L-Exos system, each patient was evaluated with a subset of the Fugl-Meyer tasks related specifically to the proximal upper limb motor functions.

Further analyses have been conducted prior to patient admittance to the protocol by means of a motion tracking system and EMG signals. In particular, the relationship between the activation of biceps and triceps muscles with respect to the value of the elbow angle for standard reaching movements (forward and backwards) has been investigated. Some typical plots resulting from this analysis are reported in Figure 7, where angular displacement and rectified EMG data are reported. The purpose of such analyses is to obtain a detailed and quantitative clinical evaluation of the patient motor deficits and muscular tone. Moreover, it would be of particular interest to examine possible differences in the same analysis conducted after the end of the robotic therapy sessions. The three patients present noteworthy differences in muscle activation and maximum elbow angular displacement, which will now be briefly examined.

Patient 1 presents a high level of muscular activation, both for the biceps and the triceps muscles, without any apparent relationship to the phase of the reaching task he is performing. Moreover, the elbow angle spans from a minimum of 75° to a maximum of 110°. The plateau of the elbow angle which is reached while performing the task underlines a limited motion control capability. Further investigations performed by a clinician on this patient indicate a severe proprioceptive deficit of Patient 1, who is unable to locate his hand in space without visual feedback of the hand itself.

Patient 2 presents a correct activation pattern while performing the reaching task. The triceps muscle is contracted during the reaching phase, whereas it is released

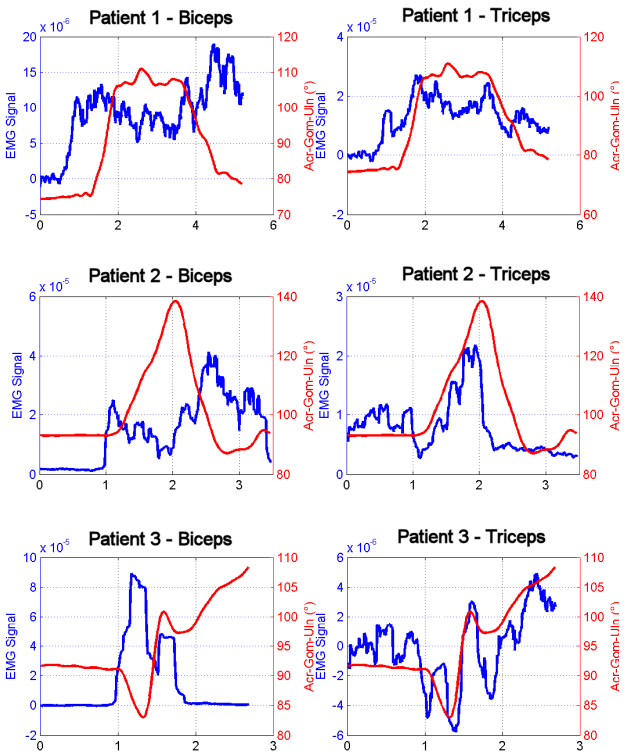

Fig. 7. Motion analysis for the selected patients.

in the backward phase. A complimentary behavior is shown for the biceps muscle. The elbow angle has a wide span from a minimum of 95° to a maximum of 140° , with a smooth profile indicating a good level of motor coordination.

Patient 3 presents an irregular muscle activation and elbow angle profile while performing the reaching task. Moreover, the elbow angle spans from a minimum of 85° to a maximum of 105°, representing severe limitations of elbow movement. Further clinical evidence clearly confirms these observations, revealing the presence of shoulder and back compensation strategies during reaching movements.

B. Detailed protocol - Reaching task

The virtual scenario used for this task contained seven spheres in a horizontal row, on a virtual plane about 15cm in front of the patient. Targets were initially idle, and were activated in sequence (i.e. the active target was displayed as a bright red sphere). Subjects were required to move their hands towards the active target and then back to the initial position. Three different heights (h_1 = 0.01 m, h_2 = 0.12 m, h_3 = 0.18 m) were used for the sphere row for each patient in each therapy session. Task velocity was set at two levels, (v_1 = 0.15 m/s, v_2 = 0.20 m/s). A two second pause followed each complete reaching movement (i.e. forward and backward movement). The patients were required to perform three series of seven movements for each height level and for each velocity level, i.e. a total of 7 (total number of spheres to be reached at each height level) x 3 (number of times each target at a certain height has to be reached at the same velocity level) x 3 (different height levels) x 2 (different velocity levels) = 126 forward and backwards

movements for each rehabilitation session. The duration of this exercise was of about 30 minutes.

C. *Detailed protocol - Constrained motion*

Patients were required to follow a circular trajectory, both clockwise and counterclockwise, being constrained by the exoskeleton and for approximately 2.5 minutes. Patients were then asked to follow the same trajectory without the robotic constraint, while the robot compensated for part of the arm weight. Two circular trajectories were used, having radii R = 0.1 m and R = 0.07 m. The second trajectory was tilted by 30° with respect to the vertical plane, and had a horizontal and vertical offset of about 20 cm in rightwards and upwards directions. The duration of this exercise was about 10 minutes. The final goal of this exercise is to enable the patients to draw smooth trajectories in space without the aid of the exoskeleton rather than making them able to perform perfect circular trajectories.

D. *Detailed protocol - Object manipulation*

Patients were required to reconstruct the puzzle as fast as they could, and with the minimum number of movements. Arm weight was compensated during the exercise, and the therapist was allowed to actively help the patients by suggesting the next move or by helping while performing fine movements when necessary. Scale of the mapping from end effector displacement to displacement in the VE varies depending on patient ROM. The aim of this exercise was merely to increase the arm mobility. Help from the therapist was important to help increase patient's interaction with the system and to improve the patient's attention level. 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. It was therefore decided not to monitor any quantitative measure for this exercise in the clinical protocol.

V. Clinical results

In our pilot study, we have gathered and analyzed quantitative and qualitative data including satisfaction feedback from the patients in order to guide the design and development of future L-Exos rehabilitation systems. Quantitative measures recorded at a sampling frequency of 100 Hz include: joint positions, end-effector positions and forces applied to the end-effector. Preliminary results of this pilot study are briefly presented herein.

A. *Qualitative results*

All three patients were enthusiastic about robotic therapy from the very first trial session with the system. They soon gained confidence with the robotic device and also with the staff (engineers and therapists) involved in the pilot study. Concentration levels were consistently very high, thereby improving the quality of the therapy. All patients reported an increase in arm mobility after the robotic therapy.

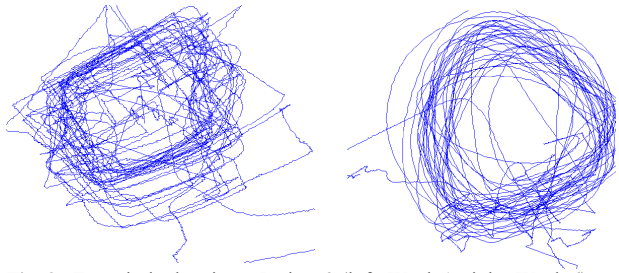

Fig. 8. Free circle drawing – Patient 3 (left: Week 1, right: Week 6)

Although quantitative results for the reaching task do confirm such increased motility for Patient 2 and Patient 3, no significant improvement has been demonstrated for Patient 1 after Week 6. Nevertheless, Patient 1 has reported much less pain and discomfort when at home. In particular, before robotic therapy, he had reported shoulder discomfort and sometimes pain at the level of the skin, when touched by another person or when in contact with an object, which have now disappeared. By Week 6 the patient reported the ability to sit at a table (e.g.: having lunch) keeping his arm on the table without any discomfort. Moreover, some negative symptoms of Patient 1, who initially reported a high level of shoulder and neck discomfort in the reaching task, have disappeared. On the other hand, macroscopic benefits have been encountered for Patient 3, who by the end of the rehabilitation protocol was able to perform the exercises without employing compensation strategies involving motion of the trunk. Moreover, by the end of Week 4, an increment of 20% of both speed level and ball horizontal span was possible for this patient.

The three patients were much more comfortable when performing the circle drawing task in the last therapy weeks. In particular, Patient 3, who was initially hardly able to move the exoskeleton without external aid, has become able to perform the required movement at a speed which was comparable to the speed of a healthy subject (more details will be given in the next paragraphs). The same patient has also become able to draw much smoother trajectories even without the activation of the impedance controller on the L-Exos, as shown in the comparison of Figure 8. It has been reported that the actual definition of the constrained motion task, i.e. first following the trajectory with the aid of the machine, and then try to replicate the same movements autonomously, can sometimes be rather discouraging for the patients. As a matter of fact, they sometimes became discouraged and skeptical about their improvements after seeing the much more irregular trajectory they were able to draw without the machine aid.

The object manipulation task has been found to be interesting for the three patients, who have become completely familiar with it. The patients no longer required hints on the best movement strategy by the end of the rehabilitation protocol. Moreover, patients initially required a great amount of external help while performing fine movements (e.g.: inserting a cube in a narrow space between two other cubes), which has become much less necessary by Week 6. It has been found that the proposed image to be reconstructed strongly affects the patient's capability of performing the task (i.e.: different images with the same exercise architecture yield to different amounts of help needed by the patients).

B. *Quantitative results - Reaching*

The normalized cumulative error has been chosen as being the most significant metric for a pilot study reaching task data analysis. In particular, the absolute value of the instant target following error computed at the endpoint (i.e. center of the user's hand palm) level was added to the cumulative error at each time step. The normalization factor for the cumulative error at time t ($t=0$ at the beginning of each movement) was then chosen as $100 \cdot t/T$, where T was the total time required to complete the forward and backward movement for each target to be reached. T can easily be pre-computed knowing the total distance to be covered and the speed profile which the machine the patient is asked to follow.

No significant data have been obtained for Patient 1, whereas Figure 9 shows the results for the reaching task for Patient 2, who reported the most significant improvement after the therapy. The plots report the cumulative error for each movement performed in the reaching exercise with respect to the task completion percentage. Data were recorded during a session in Week 1 and a session in Week 6. Data have been fit with a 5th order polynomial, the values of which have reduced by 50% after the robotic therapy. Moreover, the variance in the performance between different tasks of a same rehabilitation session has dramatically reduced from initial to final rehabilitation sessions, thus indicating a much more regular and repetitive level of motor coordination. Figure 10 reports the results for the reaching task performed by Patient 3 during Week 1 and Week 6. A mean reduction of the mean cumulative error of about 35% is clearly visible throughout the task, and a reduction in the error variance is clearly visible as well. However, the most significant improvement indicator for Patient 3 is the shape of the cumulative error curves. In particular, a trilinear-like curve (Week 1) with the typical low-slope, high-slope, low-slope trend indicates that the patient is not able to completely reach the desired end-point, thus making the cumulative error significantly increase in the middle phase of the reaching task. On the other hand, a straight line (Week 6) indicates a constant level of average error, which is independent of the task completion percentage. The Patient has therefore become able to perform the correct motion for the required task.

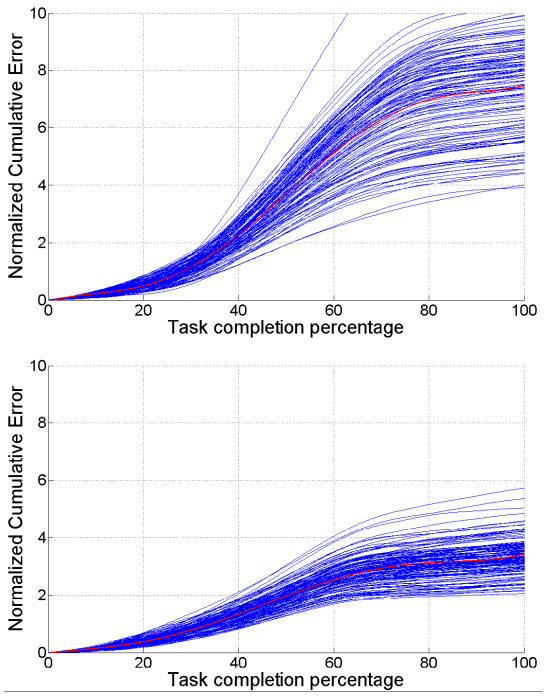

Fig. 9. Reaching results for Patient 2 (up: Week 1, down: Week 6).

C. *Quantitative results - Constrained motion*

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 have been projected onto a best fitting plane (in the sense of least squares), and the best fit circle has been 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 yet, and it will be analyzed in future studies. 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 phenomenon obviously introduces artifacts on measures of curvature or motion smoothness, and has to be thoroughly examined.

Figure 11 shows the results for the constrained motion task for Patient 3, who is the only patient reporting a statistically significant improvement after the robotic therapy. His turning time was of 5.7s±1.2s in session 1, and of 1.7s±0.6s in session 13, thus reporting a 70% decrease in the required time to complete the task.

VI. Conclusion and Future Works

The L-Exos system, which had been developed as a general purpose arm exoskeleton device for the interaction with Virtual Environments, has been successfully tested in the field of VR-aided neuron-rehabilitation with three chronic stroke patients. In particular, the patients report improvements after the therapy and their feedback is far

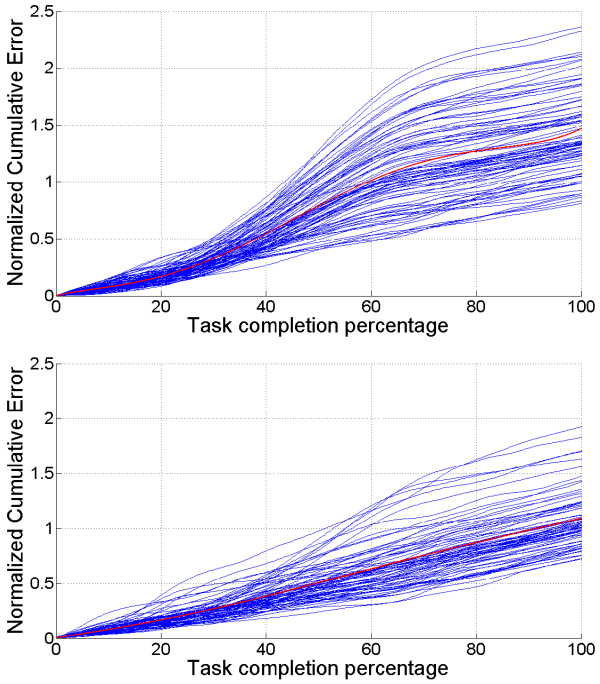

Fig. 10. Reaching results for Patient 3 (up: Week 1, down: Week 6).

more positive than what could reasonably be expected from a first pilot study.

This pilot study has highlighted many possible improvements which could be applied to the L-Exos system and to the related VR applications. From the VR-applications point of view, the reaching task could be made more functional by substituting the spherical targets with everyday objects, and possibly by presenting a hand avatar inside the Virtual Environment. The effect of shadows could be investigated in the same application, in order to enhance the 3D rendering of the scenario. No stereoscopic vision system has been employed yet in this first clinical study. Nevertheless, acceptance test will be performed making patients wear a HMD providing stereo vision. On the one hand, the employment of a HMD could enhance the quality of the therapy, by motivating patients even more; on the other hand, it could introduce a high cognitive load, which could possibly have negative effects upon the therapy outcome. The constrained motion exercise could become much more challenging when inserted on a functional scenario. In particular, the circle could become a virtual steering wheel and the patient could be asked to guide a car inside a virtual city. Although potentially very interesting, the additional cognitive load required for this kind of application is to be taken into account in the development of new applications. Moreover, it would be interesting to test a develop and test a software that adaptively adjusts the level of task difficulty, trial by trial, based on the patient's performance history. Last but not least, visual or acoustical biofeedback could be provided to the patients.

From a technical point of view, modifications in the L-Exos structure are planned in the future and will include the

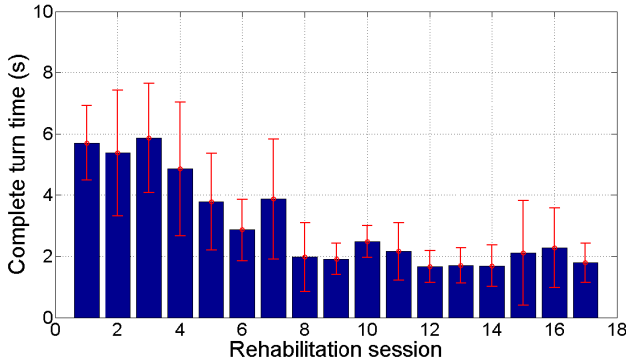

Fig. 11. Constrained motion results for Patient 3.

implementation of direct force control by means of a force sensor which will be placed onto the exoskeleton handle, joint position data recording, and the improvement of the structure general comfort and wearability.

REFERENCES

[1] L. Diller, "Post-stroke rehabilitation practice guidelines," *International handbook of neuropsychological rehabilitation. Critical issues in neurorehabilitation*. New York: Plenum, 167–182, 2000.

[2] J. van der Lee, R. Wagenaar, G. Lankhorst, T. Vogelaar, W. Deville, and L. Bouter, "Forced Use of the Upper Extremity in Chronic Stroke Patients Results From a Single-Blind Randomized Clinical Trial," *Stroke*, 30, 2369-2375, 1999.

[3] C. Butefisch, H. Hummelsheim, P. Denzler, and K. Mauritz, "Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand." *J Neurol Sci*, 130(1), 59–68, 1995.

[4] T. Olsen, "Arm and leg paresis as outcome predictors in stroke rehabilitation," *Stroke*, 21(2), 247–251, 1990.

[5] H. Krebs, N. Hogan, M. Aisen, and B. Volpe, "Robot-aided neurorehabilitation," *IEEE Transactions on Rehabilitation Engineering*, [see also *IEEE Trans. on Neural Systems and Rehabilitation*], 6(1), 75–87, 1998.

[6] B. Volpe, H. Krebs, N. Hogan, L. Edelstein, C. Diels, and M. Aisen, "A novel approach to stroke rehabilitation. Robot-aided sensorimotor stimulation," *Neurology,* 54(10), 1938–1944, 2000.

[7] S. Fasoli, H. Krebs, J. Stein, W. Frontera, and N. Hogan, "Effects of robotic therapy on motor impairment and recovery in chronic stroke." *Arch Phys Med Rehabil*, 84(4), 477–82, 2003.

[8] D. Reinkensmeyer, J. Dewald, and W. Rymer, "Guidance-Based Quantification of Arm Impairment Following Brain Injury: A Pilot Study," *IEEE Transactions on Rehabilitation Engineering*, 7(1), 1-11, 1999.

[9] D. Reinkensmeyer, L. Kahn, M. Averbuch, A. McKenna-Cole, B. Schmit, and W. Rymer, "Understanding and treating arm movement impairment after chronic brain injury: progress with the ARM guide." *J Rehabil Res Dev*, 37(6), 653–62, 2000.

[10] P. Lum, C. Burgar, P. Shor, M. Majmundar, and M. Van der Loos, "Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke," *Arch Phys Med Rehabil*, 83(7), 952–959, 2002.

[11] K. Kiguchi, S. Kariya, K. Watanabe, K. Izumi, and T. Fukuda, "An Exoskeletal Robot for Human Elbow Motion Support- Sensor Fusion, Adaptation, and Control," IEEE Transactions on *Systems, Man and Cybernetics*, 31(3), 353-361, 2001.

[12] K. Kiguchi, K. Iwami, M. Yasuda, K. Watanabe, and T. Fukuda, "An exoskeletal robot for human shoulder joint motion assist," *IEEE/ASME Transactions on Mechatronics*, 8(1), 125–135, 2003.

[13] R. Riener, T. Nef, and G. Colombo, "Robot-aided neurorehabilitation of the upper extremities," *Medical and Biological Engineering and Computing*, 43(1), 2–10, 2005.

[14] T. Nef and R. Riener, "ARMin-Design of a Novel Arm Rehabilitation Robot," *ICORR 2005. 9th International Conference on Rehabilitation Robotics,* 57–60, 2005.

[15] N. Tsagarakis and D. Caldwell, “Development and Control of a ’Soft-Actuated’ Exoskeleton for Use in Physiotherapy and Training,” *Autonomous Robots*, 15(1), 21–33, 2003.

[16] G. Prange, M. Jannink, C. Groothuis-Oudshoorn, H. Hermens, and M. Ijzerman, “Systematic review of the effect of robotaided therapy on recovery of the hemiparetic arm after stroke.” *J Rehabil Res Dev*, 43(2), 171–184, 2006.

[17] D. Jack, R. Boian, A. Merians, M. Tremaine, G. Burdea, S. Adamovich, M. Recce, and H. Poizner, “Virtual reality enhanced stroke rehabilitation,” Neural Systems and Rehabilitation Engineering, IEEE Transactions on [see also IEEE Trans. on Rehabilitation Engineering], 9(3), 308–318, 2001.

[18] L. Cardoso, R. da Costa, A. Piovesana, M. Costa, L. Penna, A. Crispin, J. Carvalho, H. Ferreira, M. Lopes, G. Brandao et al., “Using Virtual Environments for Stroke Rehabilitation,” *2006 International Workshop on Virtual Rehabilitation*, 1–5, 2006.

[19] J. Stewart, S. Yeh, Y. Jung, H. Yoon, M. Whitford, S. Chen, L. Li, M. McLaughlin, A. Rizzo, and C. Winstein, “Pilot Trial Results from A Virtual Reality System Designed to Enhance Recovery of Skilled Arm and Hand Movements after Stroke,” *International Workshop on Virtual Rehabilitation*, 11-17, 2006

[20] Patent N. WO2004058458, Exoskeleton Interface Apparatus. F. Salsedo, A. Dettori, A. Frisoli, F. Rocchi, M. Bergamasco, M. Franceschini. 2004

[21] L. Ferrucci, S. Bandinelli, J. Guralnik, M. Lamponi, C. Bertini, M. Falchini, and A. Baroni, “Recovery of functional status after stroke. A postrehabilitation follow-up study,” *Stroke*, 24(2), 200–205, 1993.

[22] M. Cirstea and M. Levin, “Compensatory strategies for reaching in stroke,” *Brain*, vol. 123, no. 5, pp. 940–953, 2000.

[23] A. Frisoli, F. Rocchi, S. Marcheschi, A. Dettori, F. Salsedo, and M. Bergamasco, “A new force-feedback arm exoskeleton for haptic interaction in virtual environments,” Haptic Interfaces for Virtual Environment and Teleoperator Systems, 2005. WHC 2005. First Joint Eurohaptics Conference and Symposium on, 195–201, 2005.