Autonomous Robots 19, 271–284, 2005

A Simple Robotic System for Neurorehabilitation

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Abstract. In the recent past, several researchers have shown that important variables in relearning motor skills and in changing the underlying neural architecture after stroke are the quantity, duration, content, and intensity of training sessions. Unfortunately, when traditional therapy is provided in a hospital or rehabilitation center, the patient is usually seen for few hours a week. Robot-mediated therapies could improve this situation but even if interesting results have been achieved by several groups, the use of robot-mediated therapy has not become very common in clinical practice. This is due to many different reasons (e.g., the "technophobia" of some clinicians, the need for more extensive clinical trials) but one of the more important is the cost and the complexity of these devices which make them difficult to be purchased and used in all the clinical centers.

The aim of this work was to verify the possibility of improving motor recovery of hemiparetic subjects by using a simple mechatronic system. To achieve this goal, our system (named "MEchatronic system for MOtor recovery after Stroke" (MEMOS)) has been designed with the aim of using mainly "off-the-shelf products" with only few parts simply manufactured with standard technology, when commercial parts were not available. Moreover, the prototype has been developed taking into account the requirements related to the clinical applicability such as robustness and safety.

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The MEMOS system has been used during clinical trials with subjects affected by chronic hemiparesis (>6 months from the cerebrovascular accident). The results obtained during these experiments seem to show that notwithstanding the simple mechatronic structure characterizing the MEMOS system, it is able to help chronic hemiparetics to reduce their level of impairment.

Further clinical experiments with acute and chronic subjects will be carried out in order to confirm these preliminary findings. Moreover, experiments for tele-rehabilitation of patients will be also carried out.

Key words: biomedical robotics, rehabilitation robotics, stroke

1. Introduction

Stroke is one of the leading causes of adult disability in the world. Most of the persons affected have an important form of paralysis and need for professional help for rehabilitation. A global increase of 117% in the number of hospitalisations is to be expected for the age category older than 75 and a remarkable upward trend of demand for rehabilitation is on the way. This will lead to a steady growth in expenses for medical care and rehabilitation in Europe.

Impairments such as muscle weakness, loss of range of motion, and impaired force generation create deficits in motor control affecting the stroke survivor's capacity for independent living and economic self-sufficiency. For this reason, many traditional therapeutic interventions have been designed and are currently used in rehabilitation to promote functional recovery. Typical therapeutic activities include manual manipulations of patient's limbs, either with the patient passive or attempting voluntary movements. This procedure has been shown to be able to facilitate functional recovery of the subject trough a re-organization of the motor cortex (Gomez-Pinilla, 2002).

However, several researchers have shown that the quantity, duration, content, and intensity of training sessions are important variables in relearning motor skills and in changing the underlying neural architecture. In fact, looking at the effects of different intensities of physical therapy treatment, a significant improvement in activities of daily living as a result of higher intensities of treatment has been reported (Kempermann et al., 2000; Jones et al., 1999). Unfortunately, when traditional therapy is provided in a hospital or rehabilitation center, the patient is usually seen for one-hour sessions, once or twice a day.

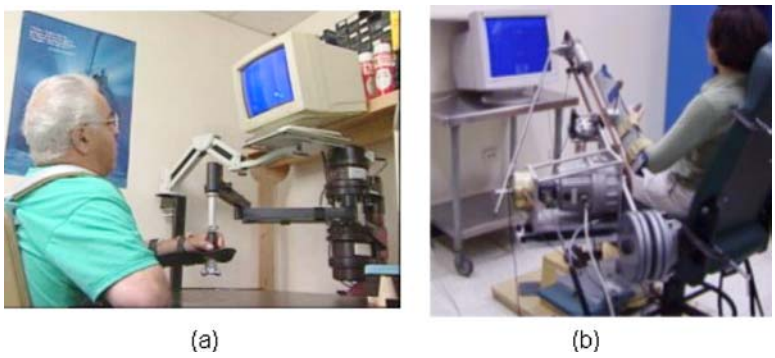
For this reason, the possibility of increasing the efficacy of the rehabilitation by exploiting the potentialities of robot-mediated therapies is becoming more and more popular around the world. In this case, the physiotherapist must programme and control a mechatronic device able to replicate (and when possible improve) the traditional therapeutic strategies making also possible a quantitative, intensive, and repeatable "dosage" of the therapy and a quantitative evaluation of the outcome for each patient.

Therefore, in the recent past, several robotic and mechatronic systems have been developed to achieve this important goal. In particular, two different types of devices can be defined (see Table 1 for a synthesis of the characteristics and Figs. 1 and 2 for some examples):

1. Exoskeleton-like machines (Kiguchi et al., 2003; Tsagarakis and Caldwell, 2003; Rosen et al., 2001): there are wearable biomechatronic systems that follow the limb movement of the subject. In this case the human-machine interface is extended all along the limb (or its part of interest) and the number of degrees of freedom (DOFs) of the machine is at least the same as that of the joints on which the therapy is expected to have an effect. The motor exercise can be directly defined in the joint space and for this reason these machines are very complex but seem to be useful for severely disabled persons whose natural synergies have been altered by stroke (Micera et al., 2005) and need for a separate control of the different joints in order to restore the natural motor control strategies;
2. Operational machines (Reinkensmeyer et al., 1999; Volpe et al., 1999; Fasoli et al., 2003; Lum et al., 2004; Werry et al., 2001; Louriero et al., 2003; Hesse et al., 2003): in this case the contact between the

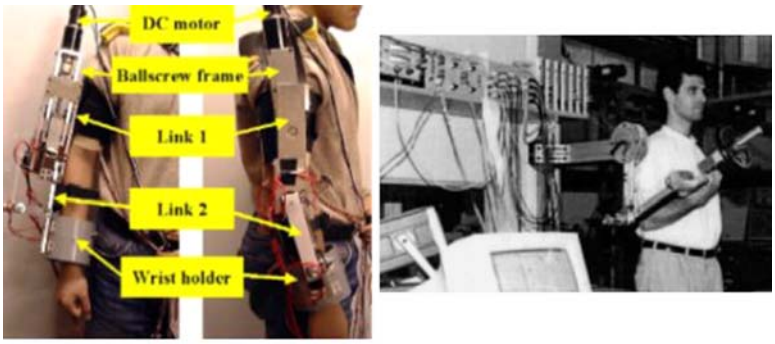
Table 1. Characteristics of the different machines for neurorehabilitation.

Device	Control different DoFs	Backdriv	Complexity	Cost
Exoskeleton	Yes	Yes	High	High
Operational Class I	No	Yes	Moderate	Moderate
Operational Class II	No	No	Low	Low



(a) (b)

Figure 1. Two operational machines: (a) MIT-MANUS; (b) ARM-GUIDE.



(a) (b)

Figure 2. Two exoskleletal systems: (a) the system under development at Saga University (Kiguchi et al., 2003); (b) the system currently under development at Washington University (Rosen et al., 2001).

patient and the machine is only at the end effector, through a purposive mechanical interface (e.g., pedal or handle). The movements can be programmed in the robot operational space and the patient is expected to exploit her/his own synergies at joint level to follow a trajectory in the operational space. This means that these machines can be used with patients with moderate disabilities (when the patients feature a sufficient level of natural motor synergies).

Moreover, among the operational machines, two different classes of devices can be identified: (i) Class I systems (Volpe et al., 1999) characterized by a low mechanical inertia/friction, a high back-driveability, fine tuning of viscoelastic properties for force fields generation and measurement of the impedance of the human arm, and high cost; (ii) Class II (Reinkensmeyer et al., 2002) systems characterized by a simple mechanical structure, no back-driveability, (in some cases) an active compensation of inertia/friction and a low cost.

Even if Class II operational machines present some limits, they are very interesting because the low-cost and the simplicity of functioning can make them more acceptable in clinical practice and even for telerehabilitation. However, the potentials of these simple machines in terms of functional recovery are to be analysed. In this paper, the mechatronic structure of a simple mechatronic system for robot-mediated upper limb neurorehabilitation in stroke patients (named "MEchatronic system for MOtor recovery after Stroke" (MEMOS)) is presented together with some preliminary results in terms of motor recovery during clinical trials with chronic hemiparetic subjects.

2. The MEMOS System

2.1. Mechatronic Structure

As already explained in the previous Section, we focused our activity on the develop of an Operational

Machine and in particular on a Class II simple and low-cost device. For this reason, the MEMOS system has been designed with the aim of obtaining an "off-the-shelf product", using few parts simply manufactured with standard technology, when commercial parts were not available. Moreover, the prototype has been developed taking into account the requirements related to the clinical applicability such as robustness and safety.

Starting from these requirements we designed MEMOS as a planar robot in a cartesian configuration. The work plane is a rectangular shape area allowing the patient's movement during the rehabilitation. Two perpendicular linear guide rails move the handle in the workspace. Guide rails were chosen instead of cantilevers to increase the stiffness of the structure obtaining a robust design and reducing the variation of the parameters affecting the control of the device.

Usually guide rails need for precise assembling and pre-clamping in order to reduce backlash. However, pre-tensioning can introduce high friction and consequently more powerful motors (oversized with respect to the effective external load) have to be used. To avoid these friction-related problems (with a light structure), SKF (Speedi-roll series in anodized aluminium) guide rails were used together with a (commercial) slider endowed with rolling wheels (see Fig. 3). The MEMOS system is shown in Figs. 4 and 5.

The characteristics of the MEMOS device are given in Table 2. In Table 3, a rough estimation of the costs to develop the MEMOS device is given.

The actuation of the MEMOS device was achieved by using two DC motors (MAXON Motors, Sachseln, CH) with the following characteristics: max power 70 watt; max tension 18 V; max current 3,14 A. The actuators included encoders with a rated 0.07 V/rad/sec sensitivity. The transmission was performed by timing belt (Bea Ingranaggi SpA, series T5-10). Four pulleys lead the belt; three of them were idler pulleys while the fourth one was on the output shaft of motor gearbox.

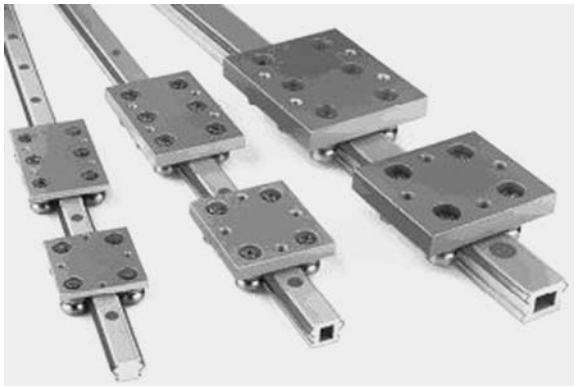


Figure 3. The guide rails and sliders used to develop MEMOS.

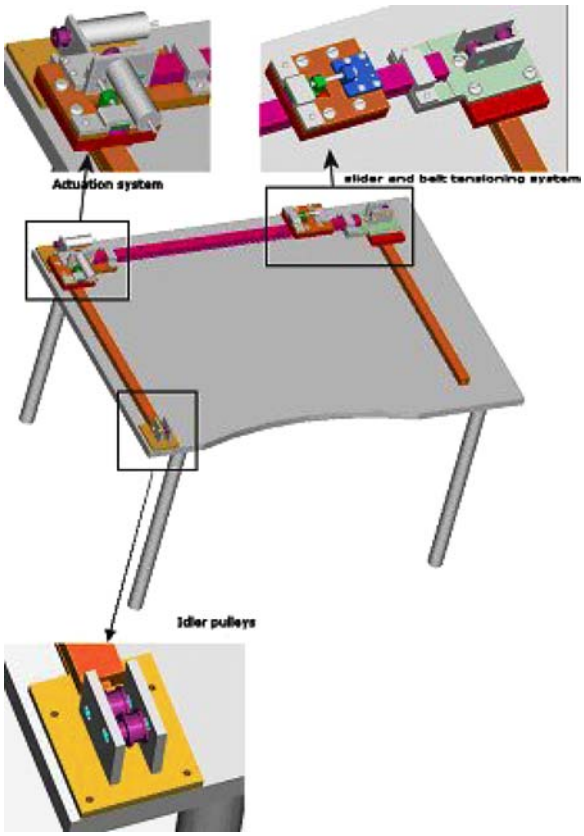


Figure 4. The mechanical structure of MEMOS.

Figure 5. The MEMOS system during clinical trials.

Table 2. The characteristics of the MEMOS system.

	Characteristics
Workspace	66 × 44 cm^2
Position resolution	0.15 mm
Nominal/max force	40–60 N
Max velocity	400 mm/s
Force sensitivity	0.05 N

Table 3. Estimation of the costs to develop the MEMOS device (in euro).

Components	Cost in euro
Mechanical parts	900
Ergogest	150
DC motors (with gearbox)	650
Electronic parts	750
PCI bus motion controllers	1250
Personal Computer	750
Total	4450

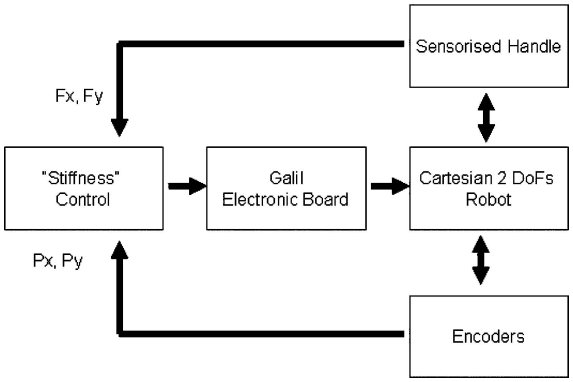


Figure 6. Scheme of the correlation among the main components of the MEMOS system.

A DMC-1820 board (Galil Motion Control, California, USA) was used to control the DC motors accordingly to the strategy illustrated in the next paragraph. The routines of the control algorithms were written using a macrolanguage environment. Some parts have been manufactured with standard technology (milling or lathing). The manufactured connecting parts have been obtained from aluminum intermediate materials. Optionally the Ergorest (Ergorest oy, Finland) forearm support can be assembled on the desk-board. The relationship among the main components of MEMOS is illustrated in Fig. 6.

It is important to point out that all these solutions were chosen after a comparative analysis with other operational machines and in particular with the MIT-MANUS, which is the most tested system in clinical trials. For example, classical cartesian structure instead of a SCARA structure can allow to avoid the use of cantilevers reducing the possibility of deflections (which should be eliminated by increasing the size and therefore the costs of the mechanical structure). The same type of considerations was done concerning the choice of the sensors to be embedded in the structure. For example, encoders, zero sensing (end stroke) switches, strain gauges were chosen instead of high resolution resolvers, tachometers, and torque sensors in order to reduce the costs of the system.

2.2. *Control Algorithm*

The MEMOS system was equipped with a handle fixed to a trolley that is moving in a horizontal (XY) plane thanks to the mechatronic structure previously described. A force transducer was located at the base of the handle near the fixation point so as to obtain an estimation of the patient's exerted force in the X (lateral) and Y (front to back) directions. It was used to estimate the force by measuring the bending moment produced by the force applied in the middle point of the handle. Even if this is not the actual force produced by the subject, this approach can be adequate for clinical trials providing also in this case a robust and simple solution. The force information recorded was used to implement the control algorithm during the tracking tasks (see next Section for the details).

In particular, three possible control strategies have been implemented: (1) completely servo-assisted movements; (2) shared control of the movements (i.e., the system will help the subject carrying out the part of the task she/he is not able to do autonomously); (3) completely voluntary movements. Thus, the following control rule has been implemented:

$$s(t) = k_p F_p(t) + V_R t \delta(F_{\text{MIN}}, T_D) \qquad (1)$$

where the first addendum of the sum is related to the voluntary activity and the second to the servo-controlled movements. In particular, F_p represents the estimation of the force produced by the subject in the two components, k_p is a stiffness 2 DoFs matrix translating the force produced into a position displacement. The function $\delta(F_{\text{MIN}}, T_D)$ is used to turn on the servo-

assisted movements. In fact, if the patient was not able to produce any force over a pre-defined level (F_{MIN}) for a selected period of time (T_D), the robot moves the handle to the final target with a constant velocity V_R. All the different parameters (F_{MIN}, T_D, V_R) can be selected off-line before the clinical trials. In this study the FMIN threshold was set to a very small value (0.2 N). In this way the patients had not feeling of resistance during the movement of the handle. The period TD was set to 3 s and the velocity VR to 100 mm/s.

3. Preliminary Clinical Trials

3.1. Protocol

Eight patients (mean age 55, 4 years old, range 33–67 years old) affected by chronic hemiparesis (>6 month from the cerebrovascular accident, mean months after the event 20) were enrolled in the study. Considering this study as preliminary to a more extensive clinical trials, only moderate to mildly impaired subjects were included. Light sensory and visual field impairment and Broca's aphasia were not exclusion criteria. We did not administered MMSE to our patients but considered only subjects able to follow simple instructions and to complete the learning session of the motor task assigned.

The patients underwent treatment for forty minutes twice a day, for three weeks, with the robotic device. Each training session consisted of a sequence of motor tasks followed by a resting phase. All the patients executed four cycles of exercise lasting 5 minutes each followed by a 3 minute resting period. A practice session preceded the treatment. In this phase the therapist looked for the optimal path and rest position of the patient in the robot plane, in order to exploit his residual motor ability. The patient faced a video screen that provided visual feedback of three circles having the following meaning (see Fig. 7): (1) a yellow circle indicated the task's starting position; (2) a red circle indicated the task's target position; (3) a green circle indicated the current position of the handle.

Subjects had to track, with the robotic handle, a figure in an horizontal plane reaching successive points representing the four corners of a square. During trials subjects were helped by audio-visual feedback allowing to control own performance. In particular patients received visual feedback during motor task execution. It consisted of a score, presented on the screen facing the patient, proportional to its voluntary motor activity developed during the task. This score was obtained by dividing into 10 segments the path between the starting point and the target. The score increased for each segment covered by means of the patient's active movement. If the patient was unable to complete the motor task the robot guided the patient's limb to the target and the score remained unchanged. Acoustic feedback was given providing prerecorded sentences signaling the start of each task, the resting periods between the cycles of work and the end of the exercise.

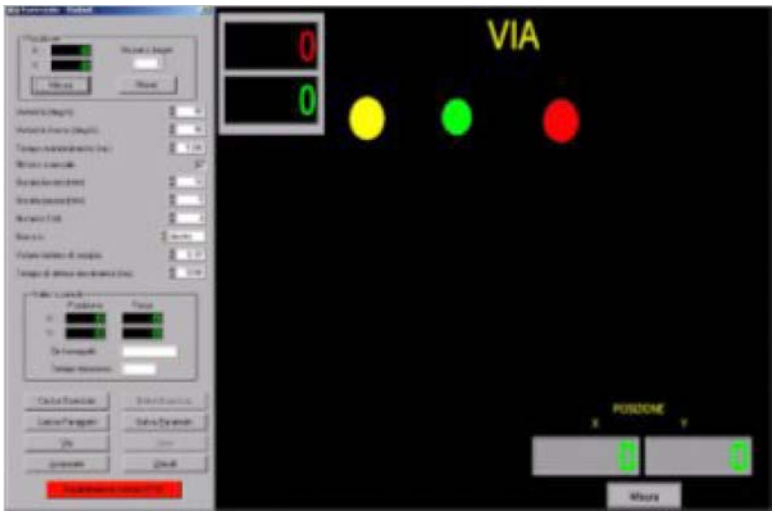


Figure 7. The interface for the rehabilitation games with the starting (yellow), the final (red) and the actual (green) positions of the handle. The therapist can control the different parameters (F_{MIN}, T_D, V_R) before each trial.

According to residual motor ability of each patient, the therapist could easily set-up the device during each training session. The path size was graphically selected and the handle was manually set at the appropriate starting point of the task. The selection of parameters like task duration, maximum speed, force threshold was obtained by means of a user friendly interface. For example, the "k" parameter (in Eq. (1)) in the control law could be changed for each patient in order to have different values of the "stiffness" during the experimental trials.

All the patients included in the study received physical therapy by blinded professionals according to the Italian Stroke Prevention and Educational Awareness Diffusion (SPREAD) guidelines for 45 minutes a day on the same days as robot treatment. A standard assessment procedure was used at the start and the end of treatment for all patients. The assessment was carried out by the same rehabilitation professional specifically trained for upper limb evaluation and masked to the study. These criteria allowed us to maximize the reliability of clinical evaluation. This procedure included the following widely accepted and validated clinical scales: (i) the Fugl-Meyer (FM) modified by Lindmark (Fugl-Meyer et al., 1975) was used to assess the upper limb motor deficit of the different subject FM (range: 0–115); (ii) the Motor Status Score (MSS) (Ferraro et al., 2002) was selected to increase the number of isolated muscle groups assessed in the paretic limb. The subsection on the upper limb assessment was used in this study, (range: 0–82); (iii) the Motor Power (MP) scale (Granger et al., 1993) measures strength in proximal muscles of the arm, specifically grading shoulder flexors and elbow flexors and extensors on a standard six point scale, (range: 0–20); (iv) the Range of Motion (ROM) of the wrist, elbow and shoulder joints was included in the standard assessment procedure. At the onset of the robotic treatment the therapist supervised the whole exercise session until the patient showed a complete understanding of the task. After this learning phase the therapist was requested for a short time just for patient positioning and training monitoring.

A Wilcoxon signed rank test was used to verify the statistical significance of change in the post-treatment with respect to pre-treatment variables. This choice was mainly due to the small sample size of the patients considered in the study.

3.2. Results

The robot-assisted therapy was well accepted and tolerated by all the patients. They showed a significant increase in MP, MSS, in the modified FM scale, and ROM shoulder flexion and abduction. The ROM shoulder extension and ROM elbow flexion and extension showed a modest non-significant increase. Table 4 summarises the mean values ± standard deviations of PRE and POST treatment clinical variables, their changes

Table 4. Pre and Post treatment values of clinical scales variables obtained in patients.

Parameter	mean_PRE	sd_PRE	mean_POST	sd_POST	mean_change	sd_change	$p <$
MPS	12.86	1.96	14.54	2.21	1.69	0.77	0.02
MSS	27.14	9.44	31.29	11.22	4.14	3.79	0.03
FMP	64.57	7.28	70.43	10.47	5.86	5.87	0.03
ASH-Shoulder	1.14	0.69	0.83	0.59	−0.31	0.41	ns
ASH-Elbow	1.20	0.38	1.09	0.51	−0.11	0.51	ns
MRCFlex-Shoulder	2.86	1.09	3.20	1.13	0.34	0.47	ns
MRCFlex-Elbow	3.46	0.51	3.86	0.50	0.40	0.42	ns
MRCExt-Shoulder	3.09	0.62	3.29	0.76	0.20	0.38	ns
MRCExt-Elbow	3.66	0.53	3.91	0.54	0.26	0.34	ns
MRCAbd-Shoulder	2.66	1.04	3.14	0.69	0.49	0.76	ns
ROMFlex-Shoulder	35.71	25.73	47.14	28.70	11.43	10.69	0.05
ROMFlex-Elbow	122.86	7.56	125.71	5.35	2.86	4.88	ns
ROMExt-Shoulder	32.14	9.94	34.29	8.38	2.14	3.93	ns
ROMExt-Elbow	160.71	25.24	162.14	24.81	1.43	3.78	ns
ROMAbd-Shoulder	37.86	24.47	53.57	26.25	15.71	7.87	0.02

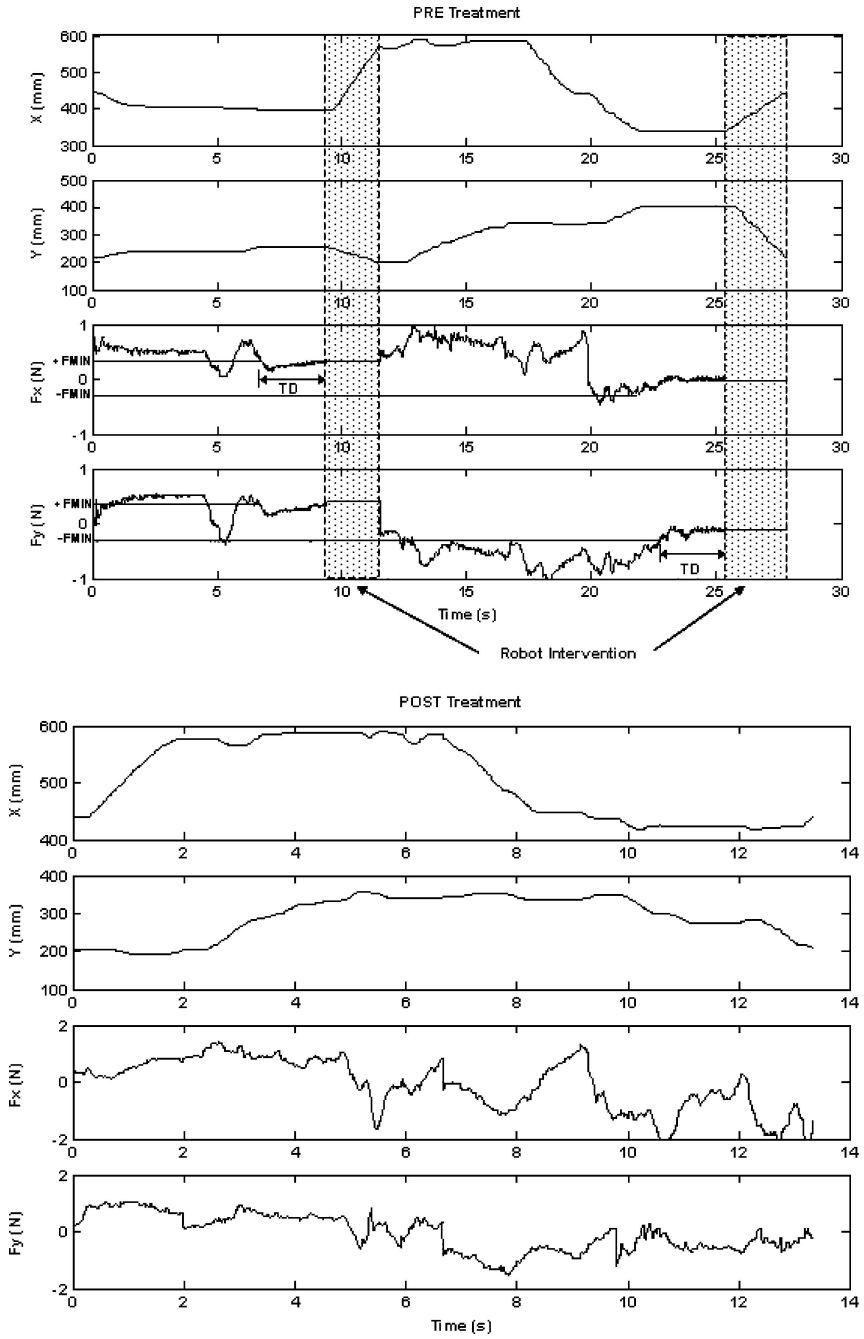


Figure 8. Two examples of trajectories for Subject S1 at the beginning and at the end of the treatment (Subject S1). The X and Y signals are the displacement of the handle respectively in the lateral and front to back directions of the robot plane. Fx and Fy are the components of the patient's force. The non shaded areas report the movements executed by patient's voluntary activity. During this activity the patient's force is maintained above the pre-defined threshold level (FMIN). The shaded areas show the activity during the task carried out by means of the robot. It is worth noting that in the portion of signal preceding these areas the force exerted by the patient is maintained under the pre-defined threshold level (FMIN) for the selected period of time (TD= 3s); after TD the robot moves the handle to the final target with a constant velocity VR.

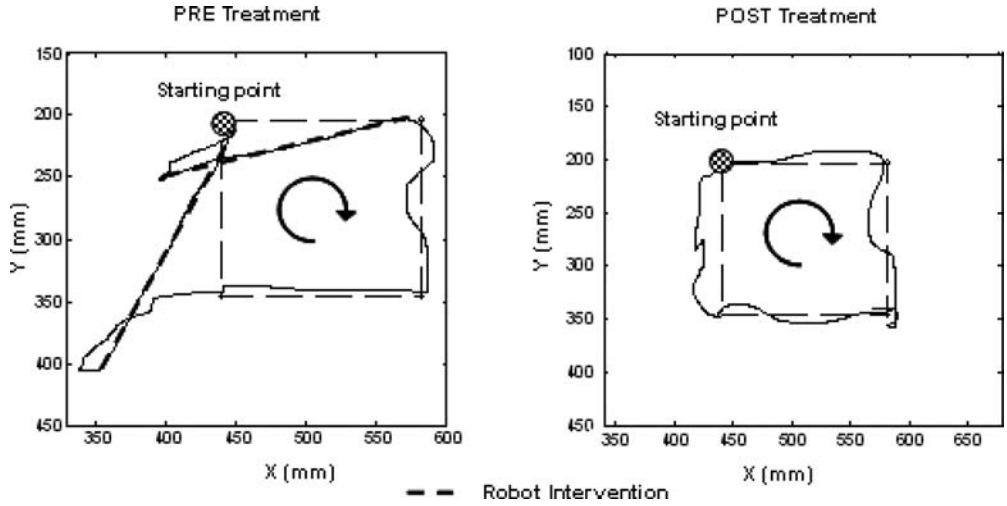


Figure 9. The two plots report the tracking of the squared trajectory for the movement reported in Fig. 8. The X and Y axes are respectively the lateral and front to back directions of displacement of the handle in the robot plane. Thick dashed lines highlight the activity during the task carried out by means of the robot.

and the p value of the PRE vs. POST comparison. In Figs. 8 and 9 some examples of trajectories showing the improvement of the performance are given.

For the different assessment indexes, the following patients improved their preformance: MPS: 7; MSS: 6; FMP: 6; ROM Flex-Shoulder: 4; ROM Flex-Elbow: 2; ROM Ext-Shoulder: 2; ROM Ext-Elbow: 1; ROM Abduction-Shoulder: 6.

4. Discussion

Robot-mediated therapies present several appealing characteristics such as the possibility of increasing the time of treatment of the patients, the possibility of recording information important for the assessment of recovery in an objective manner, and the possibility to standardize the treatment. However, even if encouraging results have been achieved by several groups, these systems are not commonly used in clinical practice for several reasons. One of the most important reasons is the complexity and the cost of these devices which make difficult for the clinician to buy more than one device partly reducing the potentialities of this approach.

The main aim of this work was to verify whether interesting clinical results in terms of motor recovery can be achieved by using a simple (and low-cost) mechatronic structure. Of course, these simple systems cannot substitute the more complex and advanced devices but they can be complementary to them and used during different phases of the rehabilitation process. These different devices must be seen as tools the clinicians can combine according to their experience and to the motor abilities of the subjects. This proves once again that rehabilitation by means of robot devices should not be considered as an instrument to substitute the therapist's role but as a complementary device able to facilitate and improve the therapist's task. For example (but this is not the only possibility), it could be possible to use exoskeletons during the first phase with severely disabled subjects helping them to restore motor control strategies lost after the accident (e.g., natural upper arm synergies (Micera et al., 2005)) while "Operational Class I" devices can be used for moderately disabled persons who still retain some levels of correct control strategies in order to use force fields to improve the smoothness of upper arm motor control (Patton and Mussa-Ivaldi, 2004). Finally, "Operational Class II" devices can be used for example for tele-rehabilitation increasing the time of rehabilitation exercises carried out.

The results achieved during the clinical trials showed that the MEMOS system is able to provide information about the movement efficacy and accuracy during the tracking tasks. This is very important because the quantitative evaluation procedure allowed by the robot measured parameters can improve the effectiveness of the rehabilitation treatment. Moreover, the results shown in Figs. 8–10 and Table 3 seem to prove the efficacy of this approach notwithstanding the simple mechatronic

structure characterizing the MEMOS system. These results demonstrate that functional recovery is possible even with position-controlled devices.

After the robotic treatment, all patients but one improved their performance in the execution of the motor task thus reducing need for an intervention of the MEMOS device. Moreover, the majority of classical clinical assessment scales showed a significant improvement. The ROM for shoulder and elbow increased in all the cases, but only shoulder flexion and abduction showed a significant change. This could be probably due to the particular task the subject had to track and to the level of disability before the rehabilitation (i.e., the ROM for some degrees of freedom has not been significantly reduced by the accident).

The research findings that have examined the time course of motor recovery after stoke have found that the greatest gains in motor function occur within the first month of onset. Recent studies revealed that chronic patients who received robotic therapy had significant gains in motor coordination and muscle strength of the exercised limb (Fasoli et al., 2004; Lum et al., 2002). Other studies reported that these improvements were sustained during the 3-year period after inpatient hospital discharge (Volpe et al., 1999). Despite traditional therapy is provided usually to subacute patients because the time in therapy is limited, the above considerations and the low economic impact of robotic technologies open the way to treatment also in this class of patients. Changes observed could be possibly due to the fact that they are compared to no training at all. But patient satisfaction, better joint mobility and improved arm function obtained with robotic therapy could justify this kind of treatment.

5. Conclusions

In this paper, the MEMOS system, a simple mechatronic device for neurorehabilitation has been presented and the results of the preliminary clinical trials on chronic hemiparetic subjects have been illustrated. Notwithstanding the simple mechatronic structure, the MEMOS system seems to be able to help in reducing the level of impairment in an effective manner. In the next future, some modifications to the mechatronic structure will be carried out in order to improve the performance of the system. For example, the workspace will be reduced because the clinical trials showed that it is not possible to ask the subjects to perform wide movements (more that 35 cm). This will also improve the performance and reduce the costs of the system. Moreover, as originally planned, the possibility of changing (with a passive mechanism) the inclination of the MEMOS will be investigated. Other possibilities will be investigated only if they cannot modify the low-cost and modular characteristics of the MEMOS.

Further clinical experiments with acute and chronic subjects will be also carried out in order to confirm these preliminary findings. Particular attention will be also devoted to the assessment of the effects of the robot-mediated rehabilitation therapy on the cortical learning by using imaging techniques (such as EEG, MEG or fMRI).

Moreover, the MEMOS system will be used in conjunction with different human-machine interfaces in order to verify whether the increased "participation" of the subject in the rehabilitation procedure can improve the final outcome in terms of motor recovery. A dedicated interface for clinical trials in tele-operation will be also carried out.

Finally, customised rehabilitation procedures are under investigation starting from the analysis of the motor control strategies implemented by the different hemiparetic subjects (Micera et al., 2005).

Acknowledgments

This work was partly funded by the project "Tecniche robotizzate per la valutazione ed il trattamento riabilitativo delle disabilit‡ motorie dell'arto superiore", 2001-175, funded by the Italian Ministry of Health.

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