Robotic Techniques for Upper Limb Evaluation and Rehabilitation of Stroke Patients

Roberto Colombo, Member, IEEE, Fabrizio Pisano, Silvestro Micera, Member, IEEE, Alessandra Mazzone, Carmen Delconte, M. Chiara Carrozza, Member, IEEE, Paolo Dario, Fellow, IEEE, and Giuseppe Minuco

Abstract—This paper presents two robot devices for use in the rehabilitation of upper limb movements and reports the quantitative parameters obtained to characterize the rate of improvement, thus allowing a precise monitoring of patient’s recovery. A one degree of freedom (DoF) wrist manipulator and a two-DoF elbow–shoulder manipulator were designed using an admittance control strategy; if the patient could not move the handle, the devices completed the motor task.

Two groups of chronic post-stroke patients (G1 n = 7, and G2 n = 9) were enrolled in a three week rehabilitation program including standard physical therapy (45 min daily) plus treatment by means of robot devices, respectively, for wrist and elbow–shoulder movements (40 min, twice daily). Both groups were evaluated by means of standard clinical assessment scales and a new robot measured evaluation metrics that included an active movement index quantifying the patient’s ability to execute the assigned motor task without robot assistance, the mean velocity, and a movement accuracy index measuring the distance of the executed path from the theoretical one.

After treatment, both groups improved their motor deficit and disability. In G1, there was a significant change in the clinical scale values (p < 0.05) and range of motion wrist extension (p < 0.02). G2 showed a significant change in clinical scales (p < 0.01), in strength (p < 0.05) and in the robot measured parameters (p < 0.01). The relationship between robot measured parameters and the clinical assessment scales showed a moderate and significant correlation (r > 0.53 p < 0.03). Our findings suggest that robot-aided neurorehabilitation may improve the motor outcome and disability of chronic post-stroke patients. The new robot measured parameters may provide useful information about the course of treatment and its effectiveness at discharge.

Index Terms—Assessment scales, biomechatronics, computerized analysis, neurorehabilitation, rehabilitation robotics, stroke.

I. INTRODUCTION

Cerebrovascular disorders and traumatic brain injury are at present the leading causes of disability resulting in partial or complete motor limitation in upper and lower limbs [1], [2]. Stroke is the third cause of death in Italy following cardiovascular diseases and cancer accounting for approximately 10%–12% of deaths [3]–[5]. Stroke incidence increases with age reaching its maximum in the >85 year age group and 75% of people affected are aged over 65 years old. Recent studies showed that in Italy there are 194 000 new stroke cases every year and about 30% of them survive with important motor deficits. This signifies a continuous increase in health care costs, particularly in terms of hospital care, nursing, and home assistance. Besides these direct costs, there are also costs due to inactivity and welfare that increase the burden both for families and society.

After the acute phase, all patients require continuous medical care. Rehabilitation is labor intensive, often necessitating one-on-one manual interaction with therapists [6], [7].

In the last few years, rehabilitators have focused increasing attention on the quantitative evaluation of residual motor abilities in the effort to obtain an objective evaluation of rehabilitation and pharmacological treatment effects. In this way, treatment efficacy and the motor outcome may be optimized. Patient autonomy may increase as a result, permitting an early reinstatement of the patient in the social and work environment and a consequent reduction in health care costs [8], [9].

Numerous factors affect functional outcome after stroke. Many researchers have investigated upper limb rehabilitation according to the facilitation approach with increased physical therapy, electrical stimulation, and passive manipulation [10]–[12]. Recently, a new sensory-motor rehabilitation technique based on the use of robot and mechatronic devices has been applied in stroke patients [13]–[26]. This technique, by aiding traditional therapy, can improve the patient’s motor performance, shorten the rehabilitation time, and provide objective parameters for patient evaluation.

These devices can be used to manipulate a paretic arm in a similar way as during a physical therapy exercise, and at the same time, they can be used to measure speed, direction and strength of residual voluntary activity. They combine facilitation-based and motor learning based approaches. The robot devices can interactively evaluate patients’ movements and assist them in moving the limb through a predetermined trajectory during a given motor task.

Systems for robot-aided neurorehabilitation currently developed for upper limb rehabilitation have two or three degrees of freedom (DoF). In particular, the MIT-Manus [13], [15], [17], [19], [20] and the mirror-image motion enabler (MIME) robots [16], [18], which were developed for unrestricted unilateral or bilateral shoulder and elbow movement, show that the recovery can be improved through additional therapy aided by robot technology. The ARM guide [23]–[25], which assists reaching
in a straight-line trajectory, and the Bi-Manu-Track [21], which enables the bilateral passive and active practice of forearm and wrist movement, show also that use of simple devices makes possible intensive training of chronic post stroke patients with positive results in terms of reduction in spasticity, easier hand hygiene, and pain relief. The Gentle/s system [14], [26] is an appealing device that, by coupling models for human arm movement with haptic interfaces and virtual reality technology, can provide robot mediated motor tasks in a three dimensional space; unfortunately, only preliminary data on its clinical application are available. The MIT-Manus and the Bi-Manu-Track implement an impedance control of the handle to move the patient limb. The MIME robot and ARM guide implement the robot movement by using a proportional-derivative position control. The Gentle/s system is based on an admittance controlled device. This means that it uses feedback from a force sensor mounted at the end-effector to specify the desired motion of the device; this concept will be further elaborated below.

All these systems have been applied in stroke rehabilitation and their effectiveness was evaluated at the start and end of treatment by means of widely accepted clinical scales and robot measurements. However, none of the previously performed studies addressed the quantitative evaluation of the patient’s recovery during the course of treatment with the use of these devices.

As with conventional physical therapy, these devices may induce motor recovery first at proximal level and then at distal. To verify if robot-aided rehabilitation at distal level can accelerate the recovery of wrist flexion and extension, we developed a specific one-DoF device for wrist rehabilitation. In addition, a two-DoF device was developed for elbow and shoulder movement treatment.

This study aimed to determine whether the use of simple robot devices based on admittance control could improve motor control in the arm of chronic hemiparetic patients. In addition, in order to implement targeted rehabilitative strategies, we tried to characterize the rate of improvement and possibly the underlying mechanisms by means of a simple new evaluation metrics obtained by the robot devices.

II. METHODS

A. Control Strategies

The devices developed to date have a significant impact on stroke rehabilitation through different machine designs ranging from simple control and geometry to complex multidegreed of freedom devices. Upper limb devices include an end-effector usually consisting of a sensorized handle which is grasped by the patient and moved through the workspace. Two complementary control strategies are usually employed to move the handle: impedance control devices and admittance control devices.

In systems using the impedance control strategy, the patient moves the handle of the device which reacts with a force (resistance) if an obstacle or virtual object is encountered in the workspace. The patient will inevitably feel the mass and friction of the device itself, so a careful mechanical design is required in order to minimize these effects. The block diagram of the device may be summarized as a single black box with the displacement as input and the force as output. Impedance control was first introduced by Hogan in 1985 [27].

Admittance control is the inverse of impedance control and has been widely used in flight simulator systems [28]. In admittance control, the patient exerts a force on the handle of the device which in turn produces a displacement. The block diagram of the device may be summed up as a single black box with force as input and displacement as output.

This type of control allows considerable freedom in the mechanical design of the device because tip inertia and backlash is drastically reduced. Admittance controlled devices are quite robust and can exert high stiffness and forces within a wide range of work. Both devices we developed are admittance control based; Fig. 1 illustrates a block diagram their functional principle.

B. Wrist Rehabilitation Device

The wrist rehabilitation device is presented in Fig. 2(a). It consists of a direct current (dc) motor fixed to the plane of a specific table. The motor shaft is connected to the handle used to displace the patient’s hand so as to obtain wrist flexion or extension movements. A torque transducer is located at the handle base near the motor shaft connection; the transducer was built by means of four strain gauge sensors connected in the full bridge Wheatstone configuration. Speed and position signals are obtained by a tachometer and potentiometer mounted on the motor shaft so providing feedback signals for the motor control.

Two control loops are included in the control system. The first provides the position, velocity, and acceleration control of the dc motor (PVA loop) and the second provides the admittance control; when the patient exerts a torque on the handle, the system reacts with a displacement which is defined by an appropriate response model.

The model is nonlinear and can be represented by means of the following equation:

$$\Theta = k \cdot Jp + \omega_r \cdot t \cdot \Gamma(\tau, \xi, Jp)$$

(1)

where $\Theta$ is the angular displacement provided by the robot in response to the patient’s torque $Jp$ and $k$ is the system’s stiffness that is usually a constant.

The second part of the equation models the behavior of the robot when the patient is not able to autonomously reach the target assigned in the motor task. In fact, if $Jp$ remains under a threshold level for a time lasting more than $\tau$, the first part of the equation is near zero and the second part involves a displacement at constant speed $\omega_r$ for a time $t$ until the target ($\Theta$)
is reached; i.e., until the error $\varepsilon = \Theta - \hat{\Theta}$ has been minimized by the robot. The function $\Gamma(\tau, \varepsilon, Jp)$ is the nonlinear function assuming the values 0 or 1, and implementing the above conditions.

The system allows a workspace for the patient of $\pm 90^\circ$ and a maximum resistant torque of $\pm 9$ N-m. The PVA loop is implemented by means of an analog control system and the admittance control loop is digitally implemented by a personal computer with A/D interface and update rate of 100 Hz. This allows a bandwidth of about 10 Hz in the admittance control loop that can be considered adequate for the velocity and acceleration performances required by our patients. The computer provides also a front-end function for the therapist in order to manage motor tasks administration.

C. Shoulder and Elbow Rehabilitation Device

The functional principles of the shoulder and elbow rehabilitation device are the natural extension to a two-dimensional space of those discussed above for the one-DoF device. In this case, it consists of a handle fixed to a trolley that is moving in a horizontal (XY) plane thanks to three linear motion guides. A force transducer is 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 estimates the force by measuring the bending moment produced by the force applied in the middle point of the handle. This, of course, is not a true force measurement but it is suitable for the clinical purposes of the device.

![Image 56x418 to 272x726](attachment:robotic_techniques_upper_limb_rehabilitation.png)

**Fig. 2.** (a) One-DoF robot device for wrist rehabilitation. (b) Two-DoF robot device for elbow–shoulder rehabilitation.

| TABLE I |
| TECHNICAL FEATURES OF THE WRIST AND ELBOW-SHOULDER REHABILITATION DEVICES |
| --- | --- | --- |
| Workspace | Wrist Device: $\pm 90^\circ$ (Deg) | Elbow-Shoulder Device: 2904 (66x44) (cm$^2$) |
| Position resolution | 0.05 (Deg) | 0.15 (mm) |
| Nominal / max torque/force | 7-9 (Nm) | 40-60 (N) |
| Maximum velocity | 500 (Deg/s) | 400 (mm/s) |
| Torque / Force sensitivity | 0.05 Nm | 0.05 (N) |

In this case, the equation representing the control model is the following:

$$s = k \cdot Fp + v_t \cdot t \cdot \Gamma(\tau, \varepsilon, Fp)$$

where the vector $s = \left[ \begin{array} {c} \tau_x \\ \tau_y \end{array} \right]$ represents the displacement provided by the robot in the plane XY in reaction to the patient’s exerted force $Fp = \left[ \begin{array} {c} F_{px} \\ F_{py} \end{array} \right]$; $k = \left[ \begin{array} {cc} kx & 0 \\ 0 & ky \end{array} \right]$ is the system’s stiffness array that is usually a constant.

The second part of the equation models the behavior of the robot when the patient is not able to reach the target assigned in the motor task. In fact, if $Fp$ remains under a threshold level for a time lasting more than $\tau$, the first part of the equation is near zero and the second part involves a displacement at constant speed $v_t$, for a time $t$ until the target $(\tilde{s} = \left[ \begin{array} {c} \tilde{\tau}_x \\ \tilde{\tau}_y \end{array} \right])$ is reached; i.e., until the error $\varepsilon = s - \tilde{s}$ has been minimized by the robot. The function $\Gamma(\tau, \varepsilon, Fp)$ is the nonlinear function assuming the values 0 or 1 and implementing the above conditions.

When the patient is driving the handle (active phase), the moving direction is obtained by vector composition of $Fx$ and $Fy$ components of the $Fp$ force. When the robot is driving the handle (passive phase), the direction is that of the line joining the current position of the handle and the target position.

The device can operate in a workspace of $660 \times 440$ mm with a resistant force of $40$ N.

The control system is fully digital (DMC 1804, Galil, USA) and runs at an update rate of 1000 Hz.

A personal computer provides also the front-end function for the therapist in order to manage motor tasks administration.

The features of both systems are summarized in Table I.

These features enable the devices to be used both for treatment and for patient evaluation.

The workspace of the devices is valid for both left and right limbs without need for any change in the mechanical setup.

D. Motor Tasks and Training Protocols

Both devices were applied in the upper limb rehabilitation of two groups of chronic poststroke patients. The robot treatment was performed in addition to conventional physical therapy. All patients received physical therapy by blinded professionals according to the Italian Stroke Prevention and Educational Awareness Diffusion (SPREAD) guidelines for 45 min a day on the same days as robot treatment [7].
Seven patients (GROUP1; aged 70 ± 7 years) were treated using the wrist rehabilitation device and nine patients (GROUP2; aged 56 ± 14 years) using the shoulder and elbow device.

Considering this study as preliminary to a more extensive clinical study, only moderate to mildly impaired subjects were included. Patients were enrolled on average, respectively, 12 and 18 months after their stroke. Mild sensory and visual field impairment and aphasia were not exclusion criteria. Patients needed to be able to follow simple instructions and to complete the learning session of the motor tasks assigned.

Patients were seated at the robot desk with the trunk fastened to the back of the chair by a specific jacket. The limb was placed on a foam support in such a way that it could easily grasp the robot handle; the wrist was in neutral position and the fingers were placed around the handle and fastened by means of a belt. In the wrist device, the forearm was fastened to the support in semi-prone position by means of two belts so as to allow only flexion or extension of the hand in the horizontal plane.

In the shoulder–elbow device, the patient’s paretic limb was supported at the elbow by a low friction pad that slid along the surface of the robot desk.

The patient faced a video screen that provided visual feedback in the form of three colored circles as follows: 1) a yellow circle indicated the task’s starting position; 2) a red circle indicated the task’s target position; and 3) a green circle indicated the current position of the handle. The path to follow was a circular arc for the wrist device and a square for the shoulder–elbow device. Before treatment the patient was instructed to move the robot handle from the starting circle to the end circle along the assigned path. If during the motor task execution, the patient could not complete the task autonomously, the robot evaluated the current position and, after a resting period of 3 s in the same place, guided the patient’s arm to the target position. During the treatment, the device provided visual and auditory feedback to the patient to signal the start, the resting phase, and the end conditions of the exercise. A push-button connected to a safety circuit could be managed both by the therapist or patient to switch off the power of the system in case of emergency.

All treatment sessions consisted of a sequence of motor tasks followed by a resting phase. Patients performed four cycles of exercise lasting 5 min each followed by a 3 min resting period (total time for each session approximately 40 min). Patients underwent treatment twice a day for at least three weeks. A practice session preceded the treatment. In this phase, the therapist sought to identify the optimal path and rest positions for each patient in the robot plane, in order to exploit fully the patient’s residual motor ability. In addition, a detailed set of instructions were given to shorten the learning phase and minimize the fast recovery effect of the first sessions due to exercise learning.

If during the course of treatment the patient was able to complete the motor task successfully, the therapist changed the difficulty level of the task by extending the path to cover (i.e., of the circular arc in the case of the one-DoF device; of the length of side of the square in the case of the two-DoF device).

Two scores were displayed on the video screen facing the patient during task execution: the first displayed the score obtained during a single task, the second the score for the whole session. The scores were increased only during patient’s voluntary activity in proportion to the distance from the target. They remained unchanged during the robot assisted movements.

These scores may be very useful in maintaining the patient’s attention high during the whole session, simulating a videogame experience. They may be also very useful for a quantitative evaluation of the patient’s performance; in fact, a higher score indicated a better performance. This point will be addressed later.

### E. Evaluation Procedure

A standard assessment procedure was used at the start and end of treatment for both groups. The assessment for all patients was carried out by the same rehabilitation professional. This procedure included the following widely accepted and validated clinical scales.

The Fugl–Meyer (FM) modified by Lindmark [30]–[32] evaluates the patient’s motor deficit both in upper and lower limbs; we considered only the upper limb subsection (range: 0–115).

The motor status score (MSS) [33] was included in the evaluation protocol in order to increase the number of isolated muscle groups assessed in the paretic limb; this scale may increase the sensitivity of recovery detection. Also, in this case, only the upper limb subsection was included (range: 0–82).

The Medical Research Council (MRC) scale [29] evaluates segmentary muscle strength at the wrist, elbow, and shoulder joints (range: 0–5 for each joint). For the patients treated with the two-DoF device, the score reported is the sum of the scores obtained in the three joints.

The motor power (MP) scale [15] measures strength in proximal muscles of the arm, specifically grading shoulder flexors and abductors and elbow flexors and extensors on a standard 6-point scale (range: 0–20).

In addition to clinical scales, the range of motion (RoM) of the wrist, elbow and shoulder joints was included in the standard assessment procedure.

### F. Robot-Aided Evaluation Procedure

The clinical scales reported above are standardized and validated but nevertheless, being administered by humans, they may lack in reliability. The measurement obtained is always subjective and depends on the ability of the rehabilitation professional.

Simple devices such as goniometers, to measure the range of motion, and dynamometers, to measure resistant strength or torque of an articulation, may be very helpful in rendering more reliable the evaluation of the clinical scales.

Robot devices have built-in technology to measure displacements, velocities, forces, and quantify other derived parameters. Therefore, they may be successfully employed both for training and for evaluation purposes. In fact, they can objectively quantify changes of biomechanical parameters so allowing a precise monitoring of the patient’s recovery during rehabilitation.

In this study, we devised an evaluation metrics that could be easy and effective to implement for clinical evaluation purposes. Here we discuss some parameters useful both for motor deficit evaluation and monitoring of the patient’s recovery.
COLOMBO et al.: ROBOTIC TECHNIQUES FOR UPPER LIMB EVALUATION AND REHABILITATION OF STROKE PATIENTS

G. Performance Evaluation

As discussed above, patients received visual feedback during motor task execution. It consisted of a score proportional to their voluntary motor activity developed during the task, here onwards referred to as “robot score.” This score was obtained by dividing into ten 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.

The video screen facing the patient reported the partial score relative to a single path and a total score relative to the current work cycle. It should be noted that the training protocol included four work cycles, each lasting 5 min per session. The global score of the training session was the mean value of the global scores obtained in the four work cycles. It is an index of the patient’s performance obtained during the session.

We mentioned above the patient’s potential progress in ability during training, stating that optimal performances can be achieved with maximal scores. In the case where a patient obtained a maximum score, the motor task was changed extending the range of movement required. In the shoulder–elbow device, this was done, for example, by selecting an extended square path. For this reason, we introduced a difficulty level, taking into account that a subset of sessions were executed in the same condition of difficulty. The time course of the patient’s performance was then obtained simply by the product of the Robot score and the difficulty level, i.e.,

\[
\text{Performance Index} = \text{Robot score} \times \text{Difficulty Level} \quad (3)
\]

An example of these parameters may be found in Fig. 3(a) and (b).

H. Active Movement Index

In order to quantify the patient’s ability in executing the assigned motor task without robot assistance, we introduced the active movement index given by the following formula:

\[
\text{AMI} = \frac{\text{RS}}{\text{TS}} \times 100 \quad (4)
\]

where RS is the robot score obtained by the patients during the task by active movement, and TS is the theoretical score if the patient completed all tasks by means of his/her voluntary motor activity. We will see that this parameter may provide useful information on the course of treatment and magnitude of recovery. An example of this index is reported in Fig. 3(c).

I. Mean Velocity

With both devices it was possible to record the current position of the handle, the force exerted by the patient (the Fx and Fy components) and a status variable indicating whether the current movement was voluntary or robot driven. In this way, it was possible to compute the mean velocity of the handle during the task.

This parameter in combination with the session score is very useful for deciding when a change in level of difficulty of the motor task is required. In fact, if the patient can complete the task with a score close to maximum (AMI $\geq 90\%$) and a mean velocity close to 50% maximum velocity of the exercise, a difficulty level change is required.

J. Movement Accuracy

Movement accuracy is another very useful parameter for the evaluation of performance with the shoulder–elbow device. Fig. 4 reports the paths covered by the patient during different sessions. It can be seen that the paths do not trace perfectly
Fig. 4. Plots show the paths covered by a patient to complete the assigned motor tasks during eight training sessions with the shoulder–elbow rehabilitation device. Each plot title specifies the session number and the values of the parameters MD (mean distance from the theoretic path) and AMI (index of patient’s voluntary activity).

the target (square) but waver roughly around it with a varying complexity corresponding to the patient’s level of recovery. The paths are very regular and closely resemble each other when they are mainly executed by the robot, and are irregular and scattered (more chaotic) when the patient’s voluntary activity is prevalent.
TABLE II
PRE- AND POST-TREATMENT VALUES OF CLINICAL SCALES VARIABLES OBTAINED IN PATIENTS OF GROUP 1 (WRIST DEVICE) AND GROUP 2 (SHOULDER–ELBOW DEVICE)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PRE (mean ± s.d.)</th>
<th>POST (mean ± s.d.)</th>
<th>Change (mean ± s.d.)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor Power Score (0-20)</td>
<td>13.67 ± 3.31</td>
<td>14.40 ± 2.84</td>
<td>1.13 ± 0.23</td>
<td>n.s.</td>
</tr>
<tr>
<td>Motor-Status Score (0-82)</td>
<td>28.40 ± 8.68</td>
<td>36.70 ± 12.15</td>
<td>8.73 ± 9.75</td>
<td>n.s.</td>
</tr>
<tr>
<td>Fugl-Meyer modified (0-115)</td>
<td>70.17 ± 11.62</td>
<td>75.83 ± 10.23</td>
<td>5.67 ± 4.68</td>
<td>0.04</td>
</tr>
<tr>
<td>MRC Wrist flexion (0-5)</td>
<td>2.86 ± 0.90</td>
<td>3.14 ± 0.69</td>
<td>0.29 ± 0.49</td>
<td>n.s.</td>
</tr>
<tr>
<td>MRC Wrist extension (0-5)</td>
<td>2.57 ± 0.98</td>
<td>2.86 ± 0.90</td>
<td>0.29 ± 0.49</td>
<td>n.s.</td>
</tr>
<tr>
<td>RoM Wrist flexion</td>
<td>30.71 ± 9.76</td>
<td>32.14 ± 9.51</td>
<td>1.43 ± 2.44</td>
<td>n.s.</td>
</tr>
<tr>
<td>RoM Wrist extension</td>
<td>20.71 ± 11.70</td>
<td>29.29 ± 10.58</td>
<td>8.57 ± 2.44</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group 2 (n=9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor Power Score (0-20)</td>
<td>12.96 ± 1.93</td>
<td>14.38 ± 2.15</td>
<td>1.42 ± 0.84</td>
<td>.01</td>
</tr>
<tr>
<td>Motor-Status Score (0-82)</td>
<td>30.22 ± 15.75</td>
<td>34.78 ± 15.52</td>
<td>4.56 ± 3.72</td>
<td>.01</td>
</tr>
<tr>
<td>Fugl-Meyer modified (0-115)</td>
<td>64.44 ± 12.11</td>
<td>71.11 ± 11.46</td>
<td>6.67 ± 5.61</td>
<td>.01</td>
</tr>
<tr>
<td>MRC Flexion (0-15)</td>
<td>7.93 ± 2.08</td>
<td>9.31 ± 2.31</td>
<td>1.38 ± 1.24</td>
<td>.05</td>
</tr>
<tr>
<td>MRC Extension (0-15)</td>
<td>8.11 ± 2.48</td>
<td>9.82 ± 2.24</td>
<td>1.71 ± 1.49</td>
<td>.05</td>
</tr>
<tr>
<td>MRC Shoulder abduction (0-5)</td>
<td>2.51 ± 1.07</td>
<td>3.11 ± 0.60</td>
<td>0.60 ± 0.70</td>
<td>.05</td>
</tr>
<tr>
<td>RoM Shoulder flexion</td>
<td>33.33 ± 18.71</td>
<td>46.67 ± 18.03</td>
<td>13.33 ± 8.66</td>
<td>.05</td>
</tr>
<tr>
<td>RoM Shoulder extension</td>
<td>23.89 ± 12.19</td>
<td>27.78 ± 12.28</td>
<td>3.89 ± 4.86</td>
<td>n.s.</td>
</tr>
<tr>
<td>RoM Shoulder abduction</td>
<td>28.33 ± 19.04</td>
<td>38.33 ± 16.96</td>
<td>10.00 ± 10.00</td>
<td>.05</td>
</tr>
<tr>
<td>RoM Elbow flexion</td>
<td>117.78 ± 24.38</td>
<td>118.89 ± 24.72</td>
<td>1.11 ± 6.01</td>
<td>n.s.</td>
</tr>
<tr>
<td>RoM Elbow extension</td>
<td>156.11 ± 20.88</td>
<td>159.44 ± 20.98</td>
<td>3.33 ± 7.07</td>
<td>n.s.</td>
</tr>
</tbody>
</table>

We defined the following parameter:

$$MD = \frac{1}{n} \sum_{i=1}^{n} |d_i|$$  \hspace{1cm} (5)

where MD represents the mean absolute values of the distance \((d_i)\) of each point of the path from the theoretic path (the square). When this parameter approximates zero, movement accuracy will be very high.

III. STATISTICAL ANALYSIS

Because of the small sample size of the two patient groups, we performed a Wilcoxon signed rank test to verify the statistical significance of change in variables post-treatment with respect to pre-treatment. The relationship between clinical scales and robot measured parameters was assessed by regression analysis. Statistical analysis was performed using the StatView statistical package (SAS Inst., Cary, NC).

IV. RESULTS

The robot-assisted therapy was well accepted and tolerated by all patients. Group 1 patients showed a significant improvement \((p < 0.05)\) in the modified Fugl–Meyer scale and RoM wrist extension. The motor status score improved, though not significantly. The motor power score, MRC wrist flexion, and extension and RoM wrist flexion showed a modest nonsignificant increase. Group 2 showed a significant increase in MP, MSS, and in the modified FM scale, MRC flexion and extension, MRC shoulder abduction, and RoM shoulder flexion and abduction. The RoM shoulder extension and RoM elbow flexion and extension showed a modest nonsignificant increase.

Table II summarizes the mean values \(\pm\) standard deviations of pre- and post-treatment clinical variables, their changes and the \(p\) value of the PRE versus POST comparison.
Table III summarizes the values obtained for the robot measured parameters.

In Group 1, the robot score and performance index improved significantly. The AMI parameter showed a nonsignificant increase, probably due to the small number of subjects.

In patients treated with the shoulder–elbow device (Group 2) mean velocity, robot score, performance index, and AMI showed a significant increase. MD (movement accuracy) decreased, but not significantly.

### A. Motor Performance Evaluation

Fig. 3 shows a typical example in one patient of the parameters employed for motor performance evaluation in the application of the wrist robot device. Fig. 3(a) shows the mean score obtained in the course of 40 training sessions: after a three day period, the mean score increased and reached a maximum value after the 20th training session.

The AMI parameter [Fig. 3(c)] shows that at the beginning of treatment the patient was able to complete only 20% of the motor task without robot assistance. In the remaining 80%, the robot had to intervene to complete the task because of the patient’s disability. After 20 training sessions, the patient was able to complete 90% of the motor task through voluntary activity.

At this point, the therapist decided to increase the difficulty level by extending the range of motion; both the score and consequently AMI parameter temporarily declined because the patient once again needed assistance from the robot device. Then voluntary activity gradually increased again to reach a high level of patient autonomy in completing the task.

The performance index [Fig. 3(b)], which takes into account also the increased level of difficulty, showed a time course that, after a brief plateau, was constantly increasing, indicating the continuous improvement of the patient’s performance throughout the treatment.

### B. Movement Accuracy

Fig. 4 shows an example of the paths covered by a patient during the motor task with the shoulder-elbow device. At the start of treatment, the paths are fairly regular and similar to each other because 50% of the path is covered by means of the robot device. As treatment proceeds the paths become progressively more chaotic up to the 15th session where this irregularity reaches a maximum. Afterwards, the paths return to being regular, showing a progressive resemblance to the theoretic motor target. The example showed in Fig. 5 covers a whole spectrum of details encountered with patients involved in this study. Fig. 5(a) shows the time course of MD (the mean distance from the theoretic path). On the same plot is reported AMI, which gives information about the robot assistance/independence during the movement.

At the start of treatment, due to the low level of patient voluntary activity, the motor task was performed with fair accuracy. Afterwards, as voluntary activity increased, so too did MD. In other words, it seems that in a first phase voluntary activity was gained at the expense of accuracy. It seems that motor program reorganization is done by a trial end error method and then with more chaotic paths. After the 15th session, MD decreased, i.e., the paths became more regular, so demonstrating a greater stability of the motor program. This fact corresponds to a clear increase in the patient’s voluntary activity after the 18th session. In fact, AMI showed a rapid increase, corresponding to a continuous increase in accuracy (decrease in MD). After the 30th session, the patient was discharged from hospital, but continued treatment three times a week. Fig. 4(h) shows the results at three weeks from discharge. We can see that both accuracy (MD = 31.5 mm) and voluntary activity (AMI = 92.0%) further improved.
C. Mean Velocity

Fig. 5(b) shows the time course of mean velocity for the same patient. This parameter showed a continual increase and at the end of treatment the patient could execute the motor task at a speed three times greater than at the beginning. The always increasing shape of the plot testifies to the continuity of patient recovery throughout the course of treatment.

D. Course of Recovery Assessment

In the example shown in Fig. 5(a), the voluntary activity recovery shows a three-phase process: the first is a very rapid phase (ph1) due to exercise learning. In the second phase, (ph2), the rate of change is slower likely due to the restoral of motor programs needed to carry out the movement. The third phase (ph3) has the highest rate of change and the patient obtains the maximum performance recovery. During the last two phases, the exercise mean velocity maintains a constant rate of change. In order to explore whether this three-phase course of recovery could be considered a general model of recovery in our chronic post-stroke patients, we used regression analysis to distinguish the different phases of recovery with different slopes. In particular, the regression analysis was applied to the 1 to 4, 5 to 17, 18 to 30 exercise session intervals. The results obtained in the Group 2 patients are reported in Table IV.

Four patients showed a fast increase of the AMI in phase 1, and maintained their performance in ph2 and ph3; the mean velocity increased with decreasing rates of improvement (with the exception of P4) over the three phases. Three patients increased the AMI parameter in ph1 and ph2, and maintained their performance in ph3. The mean velocity increased progressively with different rates of improvement during the course of treatment.

Two patients had a high rate of improvement of AMI in ph1 and ph3 and a low rate of improvement in ph2. Also in these patients, the mean velocity progressively increased during the three phases with different rates of improvement.

E. Relationship Between Variables

The relationship between the robot measured parameters and findings with the clinical scales at pre- and post-treatment evaluations was assessed by means of regression analysis between the variables. Fig. 6 shows the results obtained for the FM scale and robot score ($r = 0.55 \ p < 0.03$), mean velocity ($r = 0.53 \ p < 0.03$), and AMI ($r = 0.55 \ p < 0.03$). We obtained a moderate significant correlation coefficient for all three robot measured parameters and the FM scale and a weaker, nonsignificant correlation for the MP and MSS variables.

V. DISCUSSION

These results demonstrate that use of robot devices based on admittance control may be useful in the rehabilitation of chronic post-stroke patients in improving their movement ability. In addition, we proposed a new evaluation metric that is simple and, therefore, easy and effective to use for clinical evaluation purposes. Quantitative evaluation of the course of recovery by means of robot measured parameters enabled us to characterize the rate of improvement of our patients, and makes it possible to precisely plan and, if necessary, modify the rehabilitation strategies so as to improve the patient’s motor outcome.

Our study confirms previous work done in robot therapy with chronic stroke patients although we employed a different type of control. The systems based on impedance control can...
be programmed to interact with the patient’s arm with low impedance, giving it a soft, compliant feel during movements in the workspace. On the other hand, position controlled systems completely control position, velocity and orientation of the arm in the workspace and accommodate a large range of movement patterns. We believe that admittance control systems can combine the benefits of both the impedance and position control techniques so allowing the execution of a large spectrum of motor tasks and at the same time permitting a wide spectrum of “feel of interaction” and grading the level of assistance to the patient’s ability which changes in the course of the treatment.

The Bi-Manu-Track device applied by Hesse et al. made possible bilateral elbow and wrist training of severely affected stroke patients [21]. This device is based on the facilitatory effect on the affected extremity of bimanual practice. In fact, the joint activation of the non affected upper limb may stimulate ipsilateral corticospinal projections to the paretic muscles, which are regarded as relevant for recovery from hemiplegia. The device for wrist rehabilitation we developed is unilateral and allows only training of flexion and extension movements. The trajectory of the handle is displayed on a video screen together with the performance score, thus making interactive tasks possible, and providing visual feedback to the patient so as to maintain a high level of patient attention throughout the training session.

This device was found to be effective in our chronic patients; unfortunately, no direct comparison is possible with Hesse’s study because of the different patient conditions (mild and moderate versus severe) and parameters evaluated.

Patterns of distribution of weakness following stroke have been described by several authors. The clinical assumption is that the severity and the recovery of strength deficits in the paretic limb may follow a proximal to distal gradient, i.e. shoulder muscle strength should be less impaired and recovers more extensively and faster than wrist and hand muscle strength [34], [35]. Further, elbow flexion strength is less impaired than elbow extension strength [36]. The results we obtained are encouraging, but further specific studies are required to confirm the hypothesis that the wrist robot device can elicit an earlier distal recovery than that obtained with conventional rehabilitation treatments.

Lum et al. applied the MIME robot for the rehabilitation of subjects with chronic hemiparesis [22]. They compared results in their robot trained patients with those in a control group receiving neurodevelopmental therapy and 5 min of exposure to the robot in each session. After treatment, the robot treated patients showed larger improvements in the proximal movement portion of the Fugl–Meyer scale, larger gains in strength and larger increases in reach extent. Further, Fasoli et al. [37] studied the effect of robotic rehabilitation using the MIT-Manus device in chronic post-stroke patients. Also in this study improvements were found (admission versus discharge) in the Fugl–Meyer scale, in the motor status score for shoulder and elbow and in the motor power score.

The 5–6 points improvement obtained in the Fugl–Meyer scale of our patients is comparable to the average gains obtained in the Lum and Fasoli studies, thus confirming that goal-directed robot therapy can significantly improve motor abilities of the exercised limb in patients with chronic stroke. In addition, the shoulder–elbow rehabilitation device applied in our study is able to provide information about movement accuracy which is very important for obtaining an effective functional recovery of the upper limb. Furthermore, quantitative evaluation based on the robot measured parameters allows new insight both into the course of functional recovery (by characterizing patients’ rate of improvement) and the effectiveness of the rehabilitation treatment.

### Table IV

<table>
<thead>
<tr>
<th>Patient ID</th>
<th>Active Movement Index Slopes</th>
<th>Mean Velocity Slopes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(% / Exercise)</td>
<td>(mm/s / Exercise)</td>
</tr>
<tr>
<td></td>
<td>Phase 1</td>
<td>Phase 2</td>
</tr>
<tr>
<td>P1</td>
<td>1.38</td>
<td>0</td>
</tr>
<tr>
<td>P2</td>
<td>4.57</td>
<td>0.03</td>
</tr>
<tr>
<td>P3</td>
<td>2.71</td>
<td>0.02</td>
</tr>
<tr>
<td>P4</td>
<td>5.31</td>
<td>0.07</td>
</tr>
<tr>
<td>P5</td>
<td>7.77</td>
<td>0.97</td>
</tr>
<tr>
<td>P6</td>
<td>6.77</td>
<td>3.06</td>
</tr>
<tr>
<td>P7</td>
<td>8.31</td>
<td>0.28</td>
</tr>
<tr>
<td>P8</td>
<td>3.52</td>
<td>0.13</td>
</tr>
<tr>
<td>P9</td>
<td>3.16</td>
<td>0.34</td>
</tr>
</tbody>
</table>
The kinematic analysis of upper-limb movement has been usefully applied to quantify some aspects of the motor performance of the injured limb in post-stroke patients. Trombly evaluated the motor recovery with reaching movements during a nine week period. She found that, after treatment, the patient’s movement velocity increment correlated with movement smoothness and accuracy, but not with the strength and EMG activity increment of agonist muscles [38]. She interpreted this finding as evidence that the increment of movement velocity could be due to a motor learning phenomenon.

Our results confirm that treated patients increase their movement velocity, as well as movement accuracy during the course of treatment. Recently, Krebs and other authors showed that the movement during a motor task is the combination of a sequence of sub-movements with a bell-shaped velocity profile. He demonstrated that such components are clearly distinct at the beginning of treatment (jerky movements) but tend to merge in the course of treatment so producing a smoother movement [13]. Fig. 7 shows that our results are very similar. The velocity profiles obtained during the execution of the first three sides of the square in the third week had less peaks than those obtained during the first week. This phenomenon is not so evident for the fourth side of the square because the performance in this part is not so good, thus suggesting an incomplete recovery. In fact, the paths covered by the patient in this part of the task showed a greater dispersion [Fig. 4(h)].

Thanks to the quantitative performance evaluation metrics, we developed the process of post-stroke motor recovery may be precisely characterized and quantified in terms of rate of improvement of the patient’s voluntary activity. Moreover, conforming to the motor learning model, we speculate that the mechanisms underlying this recovery process and resulting in a voluntary activity increase are related to robot induced improvement in accuracy, velocity, strength, and RoM of the paretic upper limb. The three-phase process of recovery we observed cannot be considered a general model and further
studies on the recovery mechanisms are required in order to obtain a better understanding of the course of recovery.

The parameters here considered focused mainly on the recovery of voluntary activity and kinematic movement analysis. Using robot devices, it is possible to record the patient’s exerted forces during both passive and active movements to verify if the abnormal force deficit of the plegic limb is due to an alteration of mechanical properties of the limb and/or other mechanisms associated to the altered muscular activity. Measurement of the electromyographic activity during the movement plays a fundamental role in distinguishing the single mechanisms involved in the limb movement. The mere measurement of force does not permit to distinguish muscular weakness from asynergy phenomena. In fact, what could appear a weakness phenomenon in an agonist muscle asynergy may actually be a co-contraction phenomenon of agonist and antagonist muscles. These aspects are important not only for speculative purposes but can be very useful also for rehabilitative purposes. For this reason, after a complete recovery of voluntary activity, the motor tasks proposed should include different force reaction models or force fields with different preferential paths as proposed by Patton and Mussa-Ivaldi [39]. These force fields can be very useful in the recovery of movement accuracy, in strength improvement, and muscle coordination, thus reducing asynergy phenomena.

Furthermore, the parameters reported in Table III clearly show an improvement after robot-aided neurorehabilitation. They are objective measurements and do not suffer from the lack of reliability and effectiveness of the human-administered clinical scales. Their relationship with the FM scale confirms that they can be very useful for monitoring the course of treatment and evaluating motor outcome at discharge. Nevertheless, since they do not completely reflect the patient’s intention to use their upper limb in daily life (e.g., grasping and releasing objects, dressing, etc.), disability scales should complement the objective parameters.

We believe that the use of simple devices can be very helpful in the preliminary phase of recovery. In fact, simple devices make it possible to treat patients with a simple motor task that may elicit voluntary activity in advance in the various limb segments. In addition, they may enable the sensory-motor training of joints requiring more intensive stimulation.

Complex multidegree of freedom devices may be useful in a second phase of treatment when functional motor tasks are required. In fact, these tasks should address not only the recovery of the main motor programs, but also the co-ordination of the various muscles involved in the functional movement.

Some limitations of our study deserve mention. No control group was included in this study; therefore, it is difficult to say if the robot itself rather than traditional physical therapy or voluntary movement attempts by the patients improved the movement ability. Kahn et al. found in a recent study that in chronic post-stroke patients simple repetitive movement practice is about as effective as robot-assisted practice [40]. Thus, all sources of potential improvement should be addressed in the selection of the control group in further studies. The robot treatment was well accepted by all patients but a dedicated questionnaire assessing patient comfort, pain, fatigue, and other subjective feelings during robot treatment could be very helpful for an objective evaluation of the impact on patients in the introduction of new rehabilitative technologies.

VI. CONCLUSION

The devices and data here presented highlight the power of robot-aided neurorehabilitation. In particular, our findings show that this technique may improve the motor outcome and disability of chronic post-stroke patients. The new evaluation metrics proposed should allow the therapist to implement targeted rehabilitative strategies and, if necessary, prompt adjustment of the treatment, so producing better outcome results at discharge and shorter rehabilitation times. This technology, in combination with the diffusion of information and communication advances, opens the way to a successful application of robot-aided techniques directly in the patient’s home. Several studies in the literature have demonstrated the validity of this rehabilitation technique both in recent and in chronic post-stroke patients. Nevertheless, a larger study including recent and chronic patients and a control group is needed to confirm the results of this pilot study.

REFERENCES


Roberto Colombo (M’05) received the Dr. Eng. degree in electrical engineering from the Politecnico of Milano, Milan, Italy, in 1980.

Since 1981, he has been a Research Engineer in the Bioengineering Department of the “Salvatore Maugeri” Foundation, IRCCS, Rehabilitation Institute, Verano, Italy. From 1998 to 2001, he was a Partner of the European Community project “Prevention of muscular disorders in operation of computer input devices (PROCID)” From 2001 to 2004, he was the Coordinator of the project “Tecniche robotizzate per la valutazione ed il trattamento riabilitativo delle disabilità motorie dell’arto superiore,” 2001-175, funded by the Italian Ministry of Health. His research interests include robot-aided neurorehabilitation, muscle tone and spasticity evaluation, muscle force and fatigue assessment, speech production mechanisms study, cardiovascular control assessment by spectral analysis of heart rate variability signals, and respiratory mechanics assessment.

He has taught several national courses in the field of neurorehabilitation. He is the author of over 20 papers and the co-editor of one book on the subject of speech production mechanisms.

Fabrizio Pisano received the M.D. degree from the University of Milan, Milan, Italy, in 1981. In 1986, he completed his training as resident in neurology and became Neurologist at the same University

He was a teacher in “Electromyography” from 1991 to 1997 at the School of Physical Medicine and Rehabilitation, the University of Turin, Torino, Italy. He has taught several national and international electromyographic courses on hand neuromotor rehabilitation, occupational pathology, rehabilitation therapy, muscle fatigue, posture and movement, clinical neurophysiology, and EMG Culture. He was a Scientific Project co-leader of a telethon program (1994–1996); speech motor control in ALS; a search for an early marker of disease. He was the Project Leader of “Quantitative Analysis of Spastic Hypertonia” by the Istituto Superiore della Sanita during 1998–1999. He was the Clinical Scientific Leader of the INAHL project “International clinical survey over functional electrical stimulation.” He was the Scientific Project Leader of the Clinical Neurophysiology Unit of the project “Tecniche robotizzate per la valutazione ed il trattamento riabilitativo delle disabilità motorie dell’arto superiore,” 2001-175, funded by the Italian Ministry of Health. He is currently a Neurologist and the Head of the Clinical Neurophysiology Unit, “Salvatore Maugeri” Foundation, IRCCS, Rehabilitation Institute, Verano, Italy. He has been published in the clinical and electrophysiological field of neuromuscular diseases and on the topic of stroke patients rehabilitation. His current research interests are in evaluation and treatment of upper limb disorders like spasticity and paresis.

Dr. Pisano is a Member of the Italian Neurological Society and the Italian Clinical Neurophysiology Society.
Silvestro Micera (S’98–M’00) was born in Taranto, Italy, on August 31, 1972. He received the University degree (Laurea) in electrical engineering from the University of Pisa, Pisa, Italy, in 1996, and the Ph.D. degree in biomedical engineering from the Scuola Superiore Sant’Anna, Pisa, Italy, in 2000. From 1998 to 2001, he was the Project Manager of the EU GRIP Project (ESPRIT LTR Project 26322, “An integrated system for the neuroelectric control of grasp in disabled persons”). During 1999, he was a Visiting Researcher at the Center for Sensory-Motor Interaction, Aalborg University. Since May 2000, he has been an Assistant Professor of Biomechanical Engineering at the Scuola Superiore Sant’Anna. He is currently involved in several projects on neuro-robotics and rehabilitation engineering. His research interests include the development of neuro-robotic systems (interfacing the central and peripheral nervous system with robotic artefacts) and the development of mechatronic and robotic systems for function restoration in disabled persons.

Dr. Micera is an Associate Editor of the IEEE TRANSACTIONS ON NEURAL SYSTEMS AND REHABILITATION ENGINEERING.

Alessandra Mazzone received the degree (Diploma) in computer science, from the ITIS “Leonardo da Vinci,” Borgomanero, Italy, in 1988.

Since 1989, she has been a Programmer at the Bioengineering Department, the Fondazione Salvatore Maugeri, Rehabilitation Institute of Veruno (NO), Italy. Her research interests include robot-aided neurorehabilitation, cardiovascular control assessment by spectral analysis of heart rate variability signals, and respiratory mechanics assessment.

Carmen Delconte received the Diploma in neurophysiological techniques from the University of Pavia, Pavia, Italy, in 1989.

She is currently with the Clinical Neurophysiology Unit, Scientific Institute of Veruno “Salvatore Maugeri” Foundation, Rehabilitation Institute, Veruno, Italy. Her research concerns the quantification of muscle tone, eng-biomechanical studies, and the robotic rehabilitation of upper limb in cerebrovascular diseases. She has been published in the clinical and electrophisiological field of neuromuscular diseases and on the topic of stroke patients rehabilitation. Her current research is focused on the evaluation and treatment of upper limbs disorders like spasticity and paraparesis.

Dr. Delconte is a Member of the Italian Neurophysiology Technician Society.

M. Chiara Carrozza (M’00) received the Laurea degree in physics from the University of Pisa, Pisa, Italy, in 1990.

Since 2001, she has been an Associate Professor of biomedical robotics at the Scuola Superiore Sant’Anna, Pisa, Italy. She is the co-director of the Advanced Robotics Technology and Systems Laboratory where she is responsible for some national and international projects in the fields of biorobotics. Her research interests are in the fields of biorobotics (artificial hands, upper limb exoskeletons), rehabilitation engineering (neurorehabilitation, dornotic, and robotic aids), and biomedical microengineering (microsensors, tactile sensors). She is an author of several scientific papers and international patents.

Paolo Dario (M’88–SM’01–F’03) received the Dr. Eng. degree in mechanical engineering from the University of Pisa, Pisa, Italy, in 1977.

He is currently a Professor of Biomedical Robotics at the Scuola Superiore Sant’Anna, Pisa, Italy. He also teaches courses at the School of Engineering of the University of Pisa, and at the Campus Biomedico University, Rome, Italy. He has been a Visiting Professor at Brown University, Providence, RI, at the Ecole Polytechnique Federale de Lausanne (EPFL), Lausanne, Switzerland, and at Waseda University, Tokyo, Japan. He was the founder of the Advanced Robotics Technologies and Systems (ARTS) Laboratory and is currently the co-director of the Center for Research in Microengineering (CRIM) Laboratory of the Scuola Superiore Sant’Anna, where he supervises a team of about 70 researchers and Ph.D. students. He is also the Director of the Polo Sant’Anna Valdara and a Vice-Director of the Scuola Superiore Sant’Anna. His main research interests are in the fields of medical robotics, mechatronics, and micro/nanoeengineering, and specifically in sensors and actuators for the above applications. He is the coordinator of many national and European projects, the editor of two books on the subject of robotics, and the author of more than 200 scientific papers (75 in ISI journals). He is Editor-in-Chief, Associate Editor, and Member of the Editorial Board of many international journals.

Prof. Dario served as President of the IEEE Robotics and Automation Society during 2002–2003, and he is currently Co-Chair of the Technical Committees on Bio-robotics and of Robo-ethics of the same society. He is a Fellow of the European Society on Medical and Biological Engineering, and a recipient of many honors and awards, such as the Joseph Engelberger Award. He is also a Member of the Board of the International Foundation of Robotics Research (IFRR).

Giuseppe Minuco received the Dr. Eng. degree in mechanical engineering from the Politecnico Milano, Milan, Italy, in 1972, and a postgraduate degree in biomedical engineering from the Faculty of Medicine, Bologna, Italy, in 1975.

He is currently Head of the Bioengineering Department, “Salvatore Maugeri” Foundation, IRCCS, Pavia, Italy. He is Chair of the Technical Scientific Committee of “CBIM” (Medical Informatics and Bioengineering Consortium) Pavia, Italy. He is Member of the Editorial Board of The Monaldi Archives for Chest Disease and of Giorrnale Italiano di Medicina del Lavoro ed Ergonomia. Has taught several courses in healthcare management. His main interests are in the fields of rehabilitation engineering, clinical engineering, medical informatics, and telemedicine.