Effects of upper limb robot-assisted therapy on motor recovery of subacute stroke patients: a kinematic approach

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***Abstract*—The goal of this study is to evaluate the effects of upper limb robot-assisted treatment in a group of 25 subacute post-stroke patients using clinical outcome measures and kinematic parameters. Fugl-Meyer (FM) Assessment scale and Motricity Index (MI) were used for clinical assessment, and a set of kinematic parameters was computed. A significant decrease in motor impairment after the robot-assisted treatment (FM p<0.05 and MI p<0.05) was found. Significant improvements of upper limb motor performance was found after 2 weeks (p<0.001); subsequently, no further significant improvements were observed. Our results confirm that robotic treatment is effective to reduce upper limb motor impairment in subacute stroke patients. Kinematic parameters can provide important information on mechanisms underlying motor recovery and the frequent assessment of their values can contribute to identify an appropriate number of robotic therapy sessions as to reach soon substantial improvements.**

Keywords*—robotics; rehabilitation; upper limb; stroke; kinematics

I. INTRODUCTION

Robotic systems for upper limb motor rehabilitation programs have already demonstrated to provide safe and intensive treatment to persons with neurological impairment: several studies showed the advantages of robotic therapy [1]-[5] on chronic post-stroke patients, even if no consistent influence on functional abilities was found [6], [7] and evidence of better results providing intensive treatments, both robotic and conventional rehabilitative techniques, was found [8]. Until now, only few studies have been carried out on subacute stroke patients [9]-[13].

Improvement in functional performance after stroke can result from compensatory adaptations, which can occur by using abnormal patterns of movement to accomplish a particular task (e.g. to help stabilize an object with the paretic arm), as well as from recovery of movement and normal muscle activation synergies.

The goal of rehabilitation is to maximize the patient's functional outcome, through both compensation and true recovery processes [5], [14].

The relationship between motor recovery and motor learning is receiving growing attention as relevant issue in neurorehabilitation [15]: motor recovery seems to share several mechanisms with motor learning and could explain phenomena such as true recovery versus compensation.

Motor learning is likely mediated by different modifications in function (synaptic strength) and structure of neural circuits in different brain regions and motor recovery is based on neural circuits not affected by injury which learn to compensate for lost cells and connections thereby re-enabling effective movements (i.e., neuroplasticity) [16]-[19].

The analysis of mechanisms of recovery in subacute and chronic stroke patients, which is now mainly based on the use of clinical scalesin the clinical practice, assumes great importance in the rehabilitation domain, as it can support the clinical decision process, although differences about the motor recovery in chronic and subacute stroke patients can be hypothesized, but are still to be demonstrated.

As regards this issue, robotic systems, which allow recording and monitoring of several biomechanical data (speed, forces, etc.), represent useful tools to investigate motor recovery mechanisms in subacute stroke patients and evaluate the effects of early and late treatment supporting the

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hypothesis of a wider neuroplasticity in early stages after the acute event.

The most common clinical assessment scales used as outcome measures in rehabilitation [20] are able to provide merely quantitative information on the patient's motor performance, but are unable to provide qualitative information, which could be useful to differentiate the mechanisms underlying motor recovery.

Some robotic systems are capable of controlling and quantifying the intensity of practice and objectively measuring changes in terms of biomechanical parameters representing kinematical variables and forces, which can be used as quantitative and repetitive assessment of the effects of rehabilitation treatment, allowing the use of robotic devices not only in terms of delivery of motor rehabilitation treatment, but also as evaluation tools [21], as proposed in previous studies where different kinematic and kinetic measures for assessing motor performances of post-stroke subjects during robot-aided rehabilitation treatment were computed [22]-[25], [30].

The aim of this work is to analyse the effects of upper limb robot-assisted therapy on motor recovery of subacute post-stroke patients through clinical assessment scales and kinematic parameters, computed starting from physical variables recorded by the robotic device.

II. METHODS

A. Patients

A group of twenty-five subacute stroke subjects, age range 44-82 years (mean age 70.2±9.4), sixteen men and nine women, was recruited for the study. Ten were resulted in right hemiparesis, and fifteen in left hemiparesis. They had experienced the acute event 25±7 days prior to the study. The level of the upper limb impairment for each stroke patient at admission was assessed using the "Stage of Arm" section of the Chedoke-McMaster (CM) Stroke Assessment Scale [26]. One subacute stroke subject had a CM score of 1, thirteen a CM score of 2 or 3, and eleven a CM score of 4 or 5.

Inclusion criteria were: (i) unilateral paresis as result of first stroke, (ii) ability to understand and follow simple instructions, (iii) ability to remain in a sitting posture, even through seat belts for trunk fixation. Exclusion criteria were: (i) bilateral impairment, (ii) severe sensory deficits in the paretic upper limb, (iii) cognitive impairment or behavioural dysfunction that would influence the ability to comprehend or perform the experiment (i.e., aphasia, frontal syndrome) assessed by clinical evaluation, (iv) inability to provide informed consent and (v) other current severe medical problems. All subjects were right-handed. The local ethics committee approved the experimental protocol and each subject signed a consent form.

B. Experimental setup

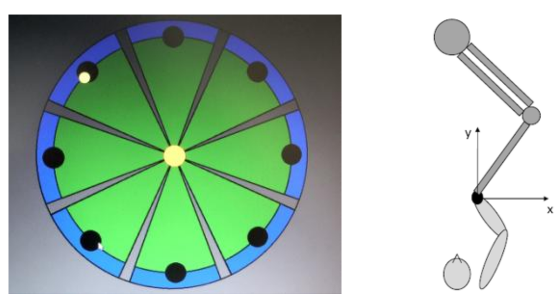
The InMotion 2.0 robotic system (Interactive Motion Technologies, Inc., Watertown, MA, USA), a robot designed for clinical and neurological applications [27], was used for this study. The robotic system (Figure 1) supports the execution of reaching movements in the horizontal plane through an "assist as needed" control strategy. The robot can guide the movement of the upper limb of the patients and record end-effector physical quantities such as the position, velocity, and applied forces.

Figure 1. Stroke patient during robot-assisted shoulder/elbow rehabilitation

C. Intervention

Each subject was asked to perform 5 sessions for 6 weeks goal-directed, planar reaching tasks, which emphasized shoulder and elbow movements, moving from the centre target to each of 8 peripheral targets equally spaced on a 0.14 m radius circumference around a centre target (Figure 2). During the 6 weeks period patients underwent a standard rehabilitation treatment on the lower limbs.

Each session is formed by (i) a series of 16 assisted clockwise repetitions to each robot target (training test); (ii) a series of 16 unassisted clockwise repetitions to each robot target *(Record)*; (iii) 3 series of 320 assisted clockwise repetitions *(Adaptive)*. At the end of each *Adaptive* series, the patient is asked to perform a further series of 16 unassisted clockwise movements *(Record)*. Kinematic data were recorded from the robotic system during the *Record* series of first, tenth (after 2 weeks), twentieth after (4 weeks) and thirtieth (after 6 weeks) session , at a self-pace velocity. The low impendence of the system facilitates the residual movement of more severely impaired patients: if the patient is not able to reach the target, after an adjustable time threshold, here set at t=5 sec., the blinking cursor to be reached, automatically moves from one target to another. Kinematics parameters are recorded even if the patient performs partially the movement, without reaching the target.



(a) (b)

Figure 2. a) "Clock-like" robot-assisted therapy scenario; b) reference coordinate system

Upon demonstration of competency and understanding by the patient, minimal feedback was provided. Verbal encouragement and environmental distraction was kept to a minimum.

D. *Clinical outcome measures*

Each subject underwent an upper limb evaluation by an experienced blinded physical therapist not involved in rehabilitation treatment team using the Upper Extremity subsection of the Fugl-Meyer (FM-UE) Assessment Scale (maximum score = 66) [28], and the upper limb component of the Motricity index (MI) for Motor Impairment after Stroke [29]. The same evaluation tools were used for each subject immediately before the first session (Pre-treatment) and after the last session (Post-treatment) of robotic therapy. CM was compiled only before the treatment for classifying the patients according to different degrees of severity in the upper limb impairment.

E. *Kinematic parameters*

The recordings collected during the robotic therapy represent a large amount of raw biomechanical data that have be processed in order to capture relevant characteristic features with respect to stroke patient recovery [30]. Every recording contains discrete-time trajectories of speed with respect to two perpendicular directions in the horizontal plane. These data were then digitally low-pass filtered forward and backward in time at 5 Hz with a 10th-order Butterworth filter. The velocities $v_x[k]$ and $v_y[k]$ are defined as the discrete-time velocity signals along the axes x and y, respectively. The velocity reference coordinate system is shown in Figure 3. The velocities of movements performed by each subject along x and y axes ($v_x[k]$, $v_y[k]$) were computed for *Record* series. The mean speed vectors $\overline{v_x}$ and $\overline{v_y}$ are defined as follows:

$$\overline{v_x} = \frac{1}{N}\sum_{k=1}^{N} v_x[k] \qquad (1)$$

$$\overline{v_y} = \frac{1}{N}\sum_{k=1}^{N} v_y[k] \qquad (2)$$

where N represents the number of samples for each recording. In this study the resultant velocity in the xy-plane is considered; this variable is defined by its components $v_x[k]$ and orthogonal $v_y[k]$, as follows:

$$v_{xy}[k] = \sqrt{(v_x[k])^2 + (v_y[k])^2} \qquad (3)$$

The mean velocity vector is defined as follows:

$$\overline{v_{xy}} = \frac{1}{N}\sum_{k=1}^{N} v_{xy}[k] \qquad (4)$$

In addition to the mean velocity, three measures of smoothness were computed starting from the kinematic data acquired during reaching movements.

TABLE I

PRE- AND POST- TREATMENT VALUES OF OUTCOME MEASURES

	PRE (mean ± sd)	POST (mean ± sd)	Change (mean ± sd)	p
FM-UE	26.28 ± 12.10	35.66 ± 12.34	9.50 ± 7.83	< 0.05
MI	40.42 ± 26.35	56.37± 26.25	15.95 ± 12.49	< 0.05

Legend: PRE, pre-treatment; POST, post-treatment; FM/se, Fugl-Meyer shoulder/elbow subsection

These parameters were analysed to evaluate and quantify the smoothness of movements: number of speed peaks, speed metric and acceleration metric. Movement trajectories of healthy subjects are smooth, characterized, in theory, by single-peaked and bell-shaped velocity profiles. In contrast, impaired voluntary movements of paretic arm in post-stroke patients are characterized by the loss of smoothness in the movement trajectory [31].

1) Number of Speed Peaks

Number of Speed Peaks (NSP) in the xy-plane velocity profile is a metric used to quantify smoothness of movement in stroke patients [32], [33]. Low values of NSP indicate few periods of acceleration and deceleration, resulting in a smooth movement.

2) Speed Metric

The Speed Metric (SM) represents the normalized mean speed and is computed as the mean speed divided by the peak speed [33]. Post-stroke patients typically present movements appearing composed of a series of short and rapid sub-movements, and the resulting speed profile has a series of peaks with deep valley in between. The value of mean speed for such a movement is rather lower than the peak speed, resulting in relatively low value of SM.

3) Acceleration Metric

The Acceleration Metric (AM) is defined as the ratio between the mean acceleration and the peak acceleration. The acceleration data were calculated by the first derivative of speed data recorded during each Record series. We considered the acceleration in the xy-plane. Like the SM parameter, AM value should be lower at the admission and higher at the end of robot-aided treatment due to the increase of the movement smoothness. Data were processed using custom routines developed under Matlab environment (Mathworks Inc., Natick, MA, USA).

F. *Statistical analysis*

In order to evaluate statistical significance of the difference before and after the treatment on clinical outcome measures (i.e., FM-UE and MI) in the group of subacute patients, a one-way Analysis of Variance (ANOVA) was computed. The post-hoc pairwise multiple comparison procedure was performed using the Holm-Sidak method, and Tukey test in case of failure of normality test.

A Student’s t-test was used for the statistical analysis of differences of kinematic parameters during different weeks of treatment as well.

III. RESULTS

Statistically significant improvements were found on FM-UE (p<0.05) between pre- and post-treatment. Statistically significant improvements were found on MI between pre- and post-treatment (p<0.05). Table 1 summarizes the results on FM-UE and MI, before and after the robotic treatment.

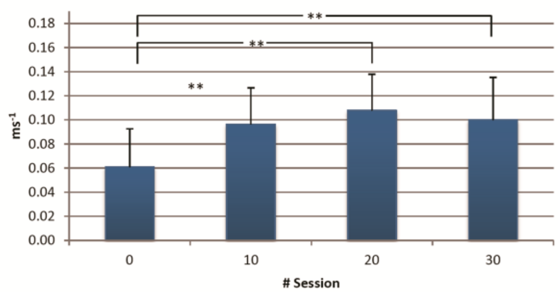


Figure 3. Mean velocity values at pre-treatment (0), after 10, 20 and 30 sessions of robot-assisted training (** indicates p<0.001)

Kinematic parameters (Figure 3-6) show statistically significant improvements after 2 weeks of robotic treatment (p<0.001); subsequently, no further significant improvements were observed.

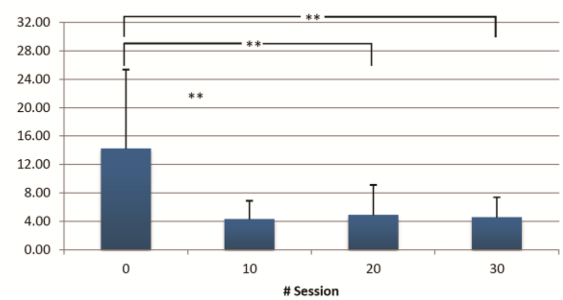


Figure 4. NSP values at pre-treatment (0), after 10, 20 and 30 sessions of robot-assisted training (** indicates p<0.001)

IV. DISCUSSION AND CONCLUSION

Due to ethical reasons it is hard to distinguish spontaneous from robot-assisted therapy recovery in the post-stroke subacute stage. Anyway, our results confirm that robotic systems for upper limb motor rehabilitation can be used to provide effective and safe treatments to reduce functional impairment in subacute stroke patients as showed

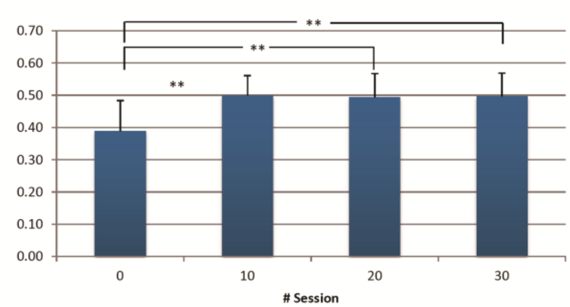


Figure 5. SM values at pre-treatment (0), after 10, 20 and 30 sessions of robot-assisted training (** indicates p<0.001)

by clinical evaluation scales scores before and after treatment. The use of kinematic parameters for assessment purposes proposed in this study represents a challenging approach in order to provide further information on the pathophysiology of motor disorders, the mechanisms of recovery and, especially, it is crucial for optimizing the timing of rehabilitative intervention.

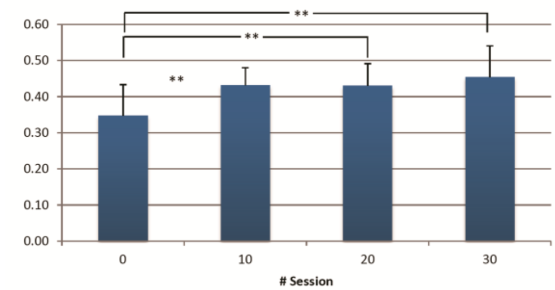


Figure 6. AM values at pre-treatment (0), after 10, 20 and 30 sessions of robot-assisted training (** indicates p<0.001)

Clinical evaluation scales are able to detect changes of quantitative aspects of movements without any identification of pathological compensation mechanisms used for performing the motor action. Indeed, kinematic parameters are able to quantify features of qualitative movements providing information on mechanisms underlying motor recovery.

In our study subacute stroke patients show an upper limb motor recovery characterized by changes of kinematic parameters. The evaluation of kinematic parameters after 10, 20 and 30 sessions showed that all parameters significantly improved, even though a plateau after the first 10 sessions was observed.

In conclusion, although it is well know that changes in kinematic measures of movement do not represent the same changes in motor performance as evaluated by clinical scales and high correlation between the two factors is not observed, our study suggests that frequent measurements should be recorded and analysed during the robotic therapy.

Such approach would let to identify an appropriate number of robotic therapy sessions as to reach soon substantial improvements: it would also support the clinical decision to provide different types of rehabilitation treatments. Consequently, the entire rehabilitation treatment can be tailored on the specific needs of each patient optimizing the cost-benefit ratio as well.

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