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Robot-aided therapy on the upper limb of subacute and chronic stroke patients: a biomechanical approach

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Abstract—**The goal of this study is to propose a methodology for evaluating recovery mechanisms in subacute and chronic post-stroke patients after a robot-aided upper-limb therapy, using a set of biomechanical parameters.**

Fifty-six post-stroke subjects, thirteen subacute and forty-three chronic patients participated in the study. A 2 dof robotic system, implementing an "assist-as-needed" control strategy, was used.

Biomechanical parameters related (i) to the speed measured at the robot's end-effector and (ii) to the movement's smoothness were computed. Outcome clinical measures show a decrease in motor impairment after the treatment both in chronic and subacute patients.

All the biomechanical parameters show an improvement between admission and discharge.

Our results show that the robot-aided training can contribute to reduce the motor impairment in both subacute and chronic patients and identify neurophysiological mechanisms underlying the different stages of motor recovery.

Keywords-Robotics; rehabilitation; motor recovery; upper limb

I. INTRODUCTION

Stroke is a leading cause of movement disability in USA and Europe, and World Health Organization (WHO) estimates that approximately 5 million people worldwide remain permanently disabled after a stroke [1]. Recently, the American Heart Association has estimated that each year approximately 700,000 people in the USA experience a new or recurrent stroke; of these, approximately 500,000 are first attacks [2]. Approximately 80% of stroke patients experience long-term reduced manual dexterity and half of all patients show functional limitations of the upper limbs, usually more frequent than walking deficits, which are responsible for the reduction in the survivor's quality of life [3].

Several studies concerning robot-aided rehabilitation treatment in subacute and chronic stroke patients have shown a reduction of the upper limb impairment [4], but till now an evidence of the advantage in the use of robotic therapy compared to traditional standard treatment is still lacking [5]. Recent systematic reviews showed that upper limb robot-aided rehabilitation treatments in post-stroke subjects improve short- and long-term motor control, even if no consistent influence on functional abilities was found [4], [6] and evidence of better results providing an intensive treatments, both administered using robotic systems and by therapists, was found [5].

In most studies only clinical scales (i.e. Fugl-Meyer, Ashworth Scale) were used as outcome measures and few studies have analysed the different mechanisms underlying motor recovery.

Applying this intensive approach to patients in subacute phase of stroke may led to better results in terms to clinical outcome, mainly due to the fact that the brain has added capacity for plasticity earlier after stroke [7].

Robot-aided rehabilitation after stroke has been studied primarily in motor re-learning and recovery of the upper-limbs. Their relationship has received little attention, but it seems to be relevant because motor recovery shares many mechanisms with motor learning and it could explain phenomena like true recovery versus compensation.

The analysis of mechanisms of recovery in subacute and chronic stroke patients, currently based on the use of clinical scales only, assumes great importance in the rehabilitation area, as it can support the clinical decision process.

Robotic systems let to record several biomechanical variables, such as speed and trajectories, which can be used to differentiate the motor recovery mechanisms in different groups of patients based on the impairment's severity and evaluate the effects of early and late treatment, supporting the hypothesis of a wider neuroplasticity in early stages after the acute event.

The primary aim of this study is to propose a biomechanical approach in order to evaluate the difference of recovery mechanisms in subacute and chronic post-stroke patients, by evaluating the trend of different parameters, before and after the robot-aided treatment.

The biomechanical parameters which were computed are the following: 1) mean speed, 2) jerk metric, 3) number of speed peaks, 4) speed metric, 5) normalized reaching speed, and 6) acceleration metric.

The different metrics are related to the smoothness of planar movements [8], which is a fundamental characteristic of coordinated human movement. Such parameter has been already proposed as a measure of motor performance of both healthy subjects and post-stroke patients.

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II. METHODS

A. Participants

Thirteen subacute stroke subjects, age range 18-82 (mean age 61.6±17.7) years, six men and seven women, were recruited for the study. Six were resulted in right hemiparesis, and seven in left hemiparesis. They had experienced the acute event 25±7 days prior to the study.

Forty-three chronic subjects, age range 17–86 (mean age 53.9±13.5) years, twenty-eight men and fifteen women, were recruited for the study. Seventeen were resulted in right hemiparesis, and twenty-six in left hemiparesis.

They had experienced the acute event at least one year prior to the study (mean time from onset of neurological damage 24 months). Inclusion criteria for both groups 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, (iv) inability to provide informed consent and (v) other current severe medical problems. All subjects were right-handed. 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 [9]. Seven subacute stroke subjects received a CM value of 2, four of them received a value of 4, and two of them received a value of 5.

Six chronic stroke subjects received a CM value of 2, thirty-three received a CM value of 3 or 4, and four chronic subjects received a CM value of 5.

B. Experimental Setup

The InMotion2.0 robotic system (Interactive Motion Technologies, Inc., Watertown, MA, USA), a robot designed for clinical and neurological applications [10], was used for this study. The 2 dof robotic system (Figure 1) supports the execution of reaching movements in the horizontal plane through an "assist as needed" control strategy.

Figure 1. The shoulder/elbow robotic system

A monitor in front of the subject displays the exercises to be performed. A second monitor is dedicated to the operator. The workstation is mounted on a custom-made adjustable chair, which allows the chair to be rotated 360° and translated 0.5 m toward a table-top, specially designed to facilitate transfer of wheelchair-bound patients. The robot can guide the movement of the upper limb of the subjects and record end-effector physical quantities such as the position, velocity, and applied forces. The subject's arm was placed in a customized arm support attached to the robot's end-effector.

C. Intervention

Each subject was asked to perform goal-directed, planar reaching tasks, which emphasized shoulder and elbow movements, moving from the centre target to each of 8 peripheral targets (Figure 2).

Each subject performed five sessions per week for 6 weeks, based on 8 targets equally spaced in a circumference around a central target.

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*).

Biomechanical data were recorded from the robotic system before starting and at the end of therapy, during the *Record* series of exercises.

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

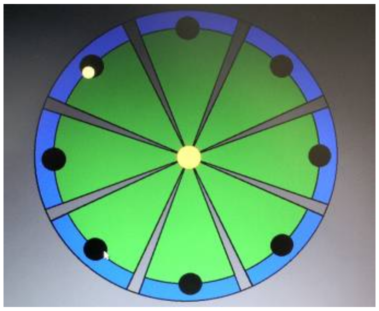

Figure 2. The "clock-like" robot-aided therapy scenario

D. Outcome measures

Each subject underwent an upper limb evaluation by an experienced physiatrist using the following scales:

- the upper limb impairment of seventeen chronic stroke patients was assessed using the shoulder and elbow section of Motor Status Scale (MSS-SE) (maximum score=40) [11].
- the upper limb impairment of all subacute patients and

twenty-six chronic patients was assessed using the Fugl-Meyer (FM) Assessment Scale (maximum score=58) [12].

The same evaluation tools were used for each subject before (Pre-treatment) and after (Post-treatment) the robotic therapy.

E. Data Analysis

A) Velocity

All the gathered recordings represent a large amount of raw biomechanical data that should be processed in order to capture relevant characteristic features with respect to stroke patient recovery. Every recording contains discrete-time trajectories of velocities 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 speed data was sampled at 200 Hz.

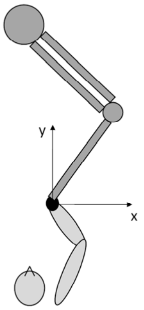

Figure 3. The robot's reference coordinate system

Among the 16 directions, two of them were considered in this study; South back (*Sb*), from the bottom target to the centre, and North toward (*Nt*), from the centre to the top target. These directions allow maximizing extension movements, an important feature to be recovered for post-stroke patients, in which the flexor component is strongly developed. The speed of movements exerted by each subject along the parallel ($v_x[k]$) and orthogonal ($v_y[k]$) axis to the planar movement direction on the sagittal plane (shoulder flexion/elbow extension) were computed for each Record series. The mean speed vectors $\overline{v_x}$ and $\overline{v_y}$ are defined as follows:

$$\overline{v_x} = \frac{1}{N}\sum_{k=1}^{N} \mathrm{v_x[k]}$$

$$\overline{v_y} = \frac{1}{N}\sum_{k=1}^{N} \mathrm{v_y[k]}$$

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

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

The mean speed vector is defined as follows:

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

B) Movement Smoothness

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

These parameters were analyzed to evaluate and quantify the smoothness of movements: jerk metric, number of speed peaks, speed metric, normalized reaching speed, and acceleration metric. Impaired voluntary movements of paretic arm in post-stroke patients are characterized by the loss of smoothness in the movement trajectory. In healthy subjects movement trajectories are smooth, with single-peaked, bell-shaped velocity profiles: single acceleration phase followed by a single deceleration phase [13].

1) Jerk metric

The jerk metric (*JM*) characterizes the mean rate of change of acceleration in a movement. We computed such parameter using a slightly different formula compared to [13]. It is calculated by dividing the mean jerk magnitude by the peak speed, as follows:

$$JM = \frac{\left|\overline{J_{xy}}\right|}{v_{xy_{max}}}$$

The jerk J_{xy} was defined as the third derivative of the position in the x-y plane. The *JM* has units of 1/s^2. Low values associated to *JM* correspond to smooth movements.

2) Number of speed peaks

Number of speed peaks (*NSP*) in the velocity profile is another metric used to quantify smoothness of movement in stroke patients [14]. A speed peak was identified in the acceleration profile as the point where the trajectory crossed the zero line and the sign of acceleration changed from positive (accelerating phase) to negative (decelerating phase) [15]. The acceleration data were calculated by the first derivative of speed data recorded during each Record series. Smooth movements are characterized by few periods of acceleration and deceleration, therefore by low values of NSP.

3) Speed Metric

The speed metric (*SM*) represents the normalized mean speed and is computed as the mean speed divided by the peak speed [13]. Post-stroke patients typically present movements 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 mean speed of such movements is much lower than its peak: in this case the *SM* is relatively low.

4) Normalized Reaching Speed

The normalized reaching speed (*NRS*) is computed as the ratio between the peak speed and mean speed difference, and the peak speed:

$$NRS = \frac{v_{xy_{max}} - \overline{v_{xy}}}{v_{xy_{max}}}$$

Low values of the parameter indicate smooth movements.

5) Acceleration Metric

The Acceleration Metric (*AM*) is defined as the ratio between the mean acceleration and the peak acceleration. We considered the acceleration in the x-y plane. As the *SM* parameter, *AM* should be lower at the admission and higher at the end of robot-aided treatment due to the increase of the movement smoothness.

III. RESULTS

The robot-aided therapy was well accepted and tolerated by all patients. The results from outcome measures show a significant decrease in motor impairment in the paretic upper limb after the robot-aided treatment both in chronic and subacute patients (Table I). Student's t-test was performed to verify the statistical significance of change of clinical scales at post-treatment compared to pre-treatment values. Statistically significant improvements were found on the MSS-SE ($p<0.001$) and FM ($p<0.001$), measured before and after the robotic treatment. Table I summarizes the results obtained using the clinical scales, before and after the robotic treatment.

TABLE I. PRE- AND POST-TREATMENT VALUES OF CLINICAL SCALES

	FM (subacute)	**MSS-SE (chronic)**	**FM (chronic)**
PRE	25.69 ± 10.78	14.50 ± 7.02	22.7 ± 11.8
POST	35.46 ± 13.19	16.56 ± 7.18	31.7 ± 13.7
Change	9.77 ± 8.11	2.06 ± 1.12	8.6 ± 5.3
p	< 0.001	< 0.001	< 0.001

In chronic patients, FM change score is higher than the corresponding MSS-SE change as the scales are comparable [11], even if FM is more sensitive than MSS-SE in the chronic stage. All the biomechanical parameters show an improvement in both groups, chronic and subacute patients, in both directions (*Sb* and *Nt*). Values of mean velocity increase after the robot-aided treatment in both groups, in both directions (Figure 4), particularly in subacute patients. At the end of robotic treatment patients execute movements at higher speed than at the beginning. *JM* improves at the end of treatment (Figure 5): it decreases after the robot-aided treatment, in both groups, in both directions. The *NSP* parameter decreases at the end of the robot-aided treatment (Figure 6). The velocity profile is more regular, therefore movements performed by stroke patients are smoother than at the beginning of treatment.

In particular, *NSP* presents a greater improvement in subacute patients than in chronic, in fact the reduction percentage of *NSP* in subacute is about 60%, whereas in chronic patients about 45%. *SM* increases at the end of the robotic therapy (Figure 7): the movement's smoothness is increased at the end of treatment. After the robot-assisted therapy the speed profile become smoother, with swallower valleys between peaks; indeed, the *SM* for these movements is higher. *NRS* decreases at the end of robot-aided treatment in both groups (Figure 8). This parameter further confirms the improvement of movement smoothness after the upper limb robotic treatment, particularly in subacute patients along direction *Nt*.

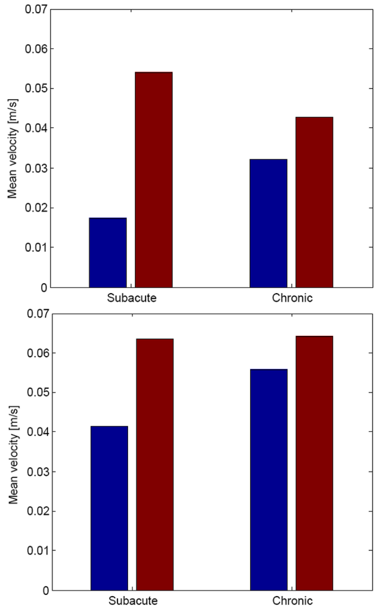

Figure 4. Mean velocity ($\overline{v_{xy}}$) in subacute and chronic patients for directions *Nt* (top) and *Sb* (bottom)

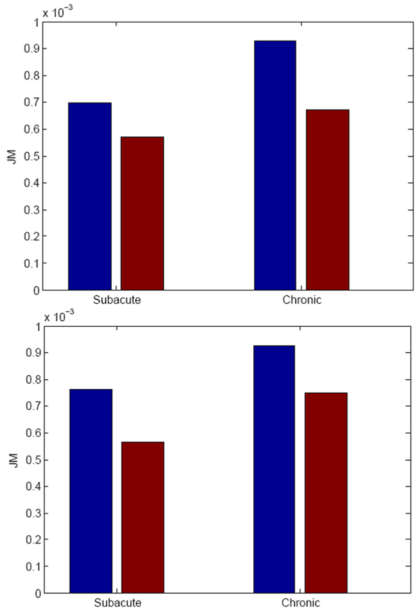

Figure 5. *JM* in subacute and chronic patients for directions *Nt* (top) and *Sb* (bottom)

AM is higher at the end of robotic treatment for both groups of patients and directions, therefore the movements performed by patients result smoother if compared to the start of the treatment (Figure 9).

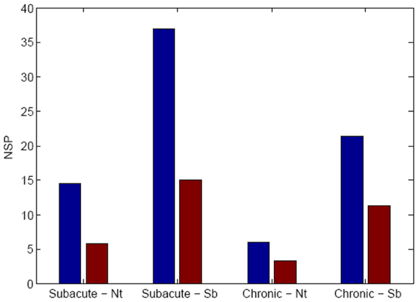

Figure 6. *NSP* in subacute and chronic patients for directions *Nt* and *Sb*

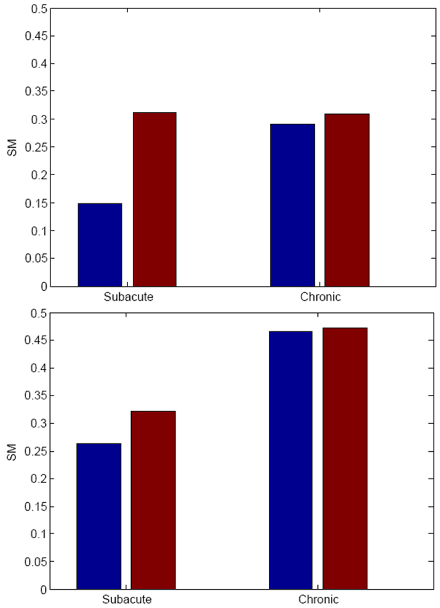

Figure 7. *SM* in subacute and chronic patients for directions *Nt* (top) and *Sb* (bottom)

IV. DISCUSSION

The primary goal of this study was to evaluate the effects on robot-aided treatment in upper limb rehabilitation of subacute and chronic post-stroke patients, not only by the evaluation of clinical scales score, but through the computation and analysis of different biomechanical parameters.

Our study confirms the motor improvement in upper limb impairment of post-stroke patients after the treatment based on a robot-aided therapy training both in chronic and subacute patients, as demonstrated also by previous studies [16]-[19].

This study demonstrates that the velocity and smoothness of movements, fundamental characteristics of coordinated and voluntary human movement, present a significant improvement after the robotic training.

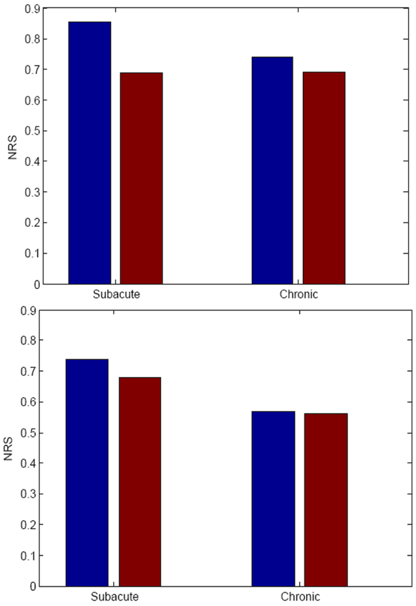

Figure 8. *NRS* in subacute and chronic patients for directions *Nt* (top) and *Sb* (bottom)

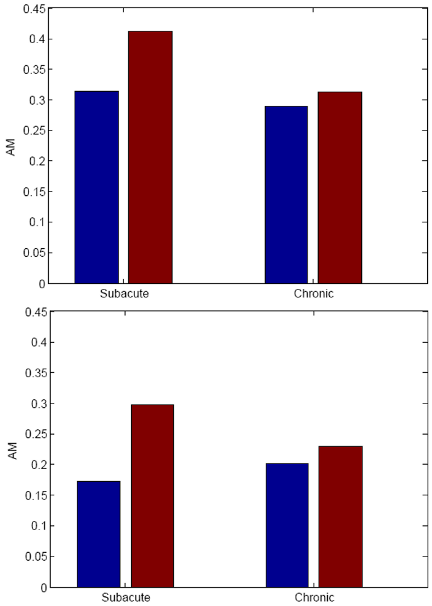

Figure 9. *AM* in subacute and chronic patients for directions *Nt* (top) and *Sb* (bottom)

The recovery of smoothness of movement in chronic and subacute post-stroke patients is demonstrated by five different metrics. Both groups significantly improved the velocity of the arm movement, in the horizontal plane.

Such improvement determines a reduction of movement duration. Moreover, all five metrics used to evaluate smoothness present an improvement after the robotic treatment: the movement smoothness increases after the robot-aided training.

The method based on the analysis of biomechanical parameter related to the velocity and smoothness of movement, recorded during the robot-aided rehabilitation can contribute to understand if, in post-stroke patients, a rehabilitative intervention could be effective in order to reduce the impairment and improve the quality of the movements as well.

V. CONCLUSION

Our results demonstrate that the robotic therapy can significantly improve motor abilities of upper limb movements in post-stroke patients, both in subacute and chronic stage.

Several biomechanical parameters can be computed starting from kinematic variables recorded through robotic systems without using markers, typical of systems for the motion analysis, or other complex tools for data collection, and without any interference with the rehabilitative procedure. Furthermore, the data collection can be performed during every rehabilitative session: the changes of such biomechanical parameters can be monitored along the whole rehabilitation period.

Clinical outcomes and proposed biomechanical parameters are significantly improved after the upper limb robotic training, suggesting that the motor recovery can be positively influenced by repetitive, intensive and goal-oriented movements. However the demonstration of better outcomes when using a robot-aided therapy, if compared to the traditional treatments, is still to be clarified.

This study demonstrates that velocity and smoothness of movements present a significant improvement after the upper limb robotic training. In particular, the improvement seems to be greater in subacute patients than in chronic patients: this finding suggests that the robotic treatment provides greater benefits on motor recovery and reduction of disability, if delivered at an earlier stage.

The analysis of velocity and smoothness of movement during the robot-aided treatment can contribute to identify the neurophysiological mechanisms underlying the different stages of motor recovery and tailor the rehabilitation treatment to each patient. If the pathological pattern is not yet structured, rehabilitative interventions have to be addressed toward the use of motor re-learning procedures; on the other hand, when a strong pathological pattern is observed, mechanisms of compensation must be encouraged.

REFERENCES

[1] World Health Organization, The atlas of heart disease and stroke. Available from: http://www.who.int/cardiovascular_diseases/resources/atlas/en/.

[2] American Heart Association, heart disease and stroke statistics – 2007. Available from: http://www.americanheart.org/.

[3] D. S. Nichols-Larsen, P. C. Clark, A. Zeringue, A. Greenspan, and S. Blanton, "Factors influencing stroke survivors' quality of life during sub-acute recovery," *Stroke*, vol. 36, pp. 1480–1484, 2005.

[4] G. Kwakkel, B. J. Kollen, and H. I. Krebs, "Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review," *Neurorehabil Neural Repair,* vol. 22, no. 2, pp. 111-21, 2008.

[5] A. C. Lo, P. D. Guarino, L. G. Richards, J. K. Haselkorn, G. F. Wittenberg, D. G. Federman, "Robot-assisted therapy for long-term upper-limb impairment after stroke," *N Engl J Med.* Vol. 362, no. 19, pp. 1772-83, 2010.

[6] G. B. Prange, M. J. Jannink, C. G. Groothuis-Oudshoorn, H. J. Hermens, and M. J. Ijzerman, "Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke," *J Rehabil Res Dev.*,vol. 43, no. 2, pp. 171-84, 2006.

[7] S. Masiero, E. Carraro, C. Ferraro, P. Gallina, A. Rossi, and G.Rosati, "Upper limb rehabilitation robotics after stroke: a perspective from the University of Padua, Italy," *Journal of Rehabilitation Medicine*, vol. 41, no. 12, pp. 981-85, 2009.

[8] L. E. Kahn, M. L. Zygman, W. Z. Rymer, and D. J. Reinkensmeyer, "Effect of robot-assisted and unassisted exercise on functional reaching in chronic hemiparesis," In Proc. of the 23rd Annual International Conference of the Institute of Electrical and Electronics Engineers/Engineering in Medicine and Biology Society, Istanbul, Turkey, October 2001, vol. 2, pp. 1344 – 47.

[9] C. Gowland, P. Stratford, M. Ward, J. Moreland, W. Torresin, S. Van Hullenaar, J. Sanford, S. Barreca, B. Vanspall, and N. Plews, "Measuring physical impairment and disability with the Chedoke-McMaster Stroke Assessment," *Stroke,* vol. 24, pp. 58–63, 1993.

[10] H. I. Krebs, N. Hogan, M. L. Aisen, and B. T. Volpe, "Robot-aided neurorehabilitation," *IEEE Trans Rehabil Eng,* vol. 6, no. 1, pp. 75-87, 1998.

[11] M. Ferraro, J. H. Demaio, J. Krol, C. Trudell, K. Rannekleiv, L. Edelstein, P. Christos, M. Aisen, J. England, S. Fasoli, H. I. Krebs, N. Hogan, and B. T. Volpe, "Assessing the motor status score: a scale for the evaluation of upper limb motor outcomes in patients after stroke," *Neurorehab Neural Re,* vol. 16, no. 3, pp. 283-9, 2000.

[12] A. R. Fugl-Meyer, L. Jääskö, I. Leyman, et al, "The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance," *Scand J Rehabil Med* 1975;7(1):13-31.

[13] B. Rohrer, S. Fasoli, H. I. Krebs, R. Hughes, B. Volpe, W. R. Frontera, J. Stein, and N. Hogan, "Movement smoothness changes during stroke recovery," *The Journal of Neuroscience*, vol. 22, no. 18, pp. 8297-8304, September 2002.

[14] G. Kamper, A. N. McKenna-Cole, L. E. Kahn, and D. J. Reinkensmeyer, "Alterations in reaching after stroke and their relation to movement direction and impairment severity," *Arch Phys Med Rehabil*, vol. 83, no. 5, pp. 702-7, May 2002.

[15] C. Tsao, and M. M. Mirbagheri, "Upper limb impairments associated with spasticity in neurological disorders," *Journal of NeuroEngineering and Rehabilitation,* 4:45, 2007.

[16] F. Posteraro, S. Mazzoleni, S. Aliboni, B. Cesqui, A. Battaglia, P. Dario, and S. Micera.. "Robot-mediated therapy for paretic upper limb of chronic patients following neurological injury," *Journal of Rehabilitation Medicine*, vol. 41, no. 12, pp. 976-80, 2009.

[17] M. Ferraro, J. J. Palazzolo, J. Krol, H. I. Krebs, N. Hogan, and B. T. Volpe, "Robot-aided sensorimotor arm training improves outcome in patients with chronic stroke," *Neurology*, vol. 61, no. 11, pp. 1604–7, 2003.

[18] S. E. Fasoli, H. I. Krebs, J. Stein, W. R. Frontera, R. Hughes, and N. Hogan, "Robotic therapy for chronic motor impairments after stroke: follow-up results," *Arch Phys Med Rehabil,* vol. 85, no. 7, pp. 1106–11, 2004.

[19] P. S. Lum, C. G. Burgar, M. Van der Loos, P. C. Shor, M. Majmundar, and R. Yap, "MIME robotic device for upper-limb neurorehabilitation in subacute stroke subjects: a follow-up study," J Rehabil Res Dev, vol. 43, no. 5, pp. 631-42, 2006.