Comparison of Robotic and Clinical Motor Function Improvement Measures for Sub-Acute Stroke Patients

Ozkan Celik, Marcia K. O'Malley, Corwin Boake,
Harvey Levin, Steven Fischer, Timothy Reistetter

Abstract— In this paper, preliminary results in motor function improvement for four sub-acute stroke patients that underwent a hybrid robotic and traditional rehabilitation program are presented. The therapy program was scheduled for three days a week, four hours per day (approximately 60% traditional constraint induced therapy activities and 40% robotic therapy). A haptic joystick was used to implement four different operating modes for robotic therapy: unassisted (*U*), constrained (*C*), assisted (*A*), and resisted (*R*) modes. A target hitting task involving the positioning of a pointer on twelve targets was completed by the patients. Two different robotic measures were utilized to quantify the motor function improvement through the sessions: trajectory error (TE) and smoothness of movement (SM). Fugl-Meyer (FM) and Motor Activity Log (MAL) scales were used as clinical measures. Analysis of results showed that the group demonstrates a significant motor function improvement with respect to both clinical and robotic measures. Regression analyses were carried out on corresponding clinical and robotic measure result pairs. A significant relation between FM scale and robotic measures was found for both of the analyzed modes. Regression of robotic measures on MAL scores resulted in no significance. A regression analysis that compared the two clinical measures revealed a very low agreement. Our findings suggest that it might be possible to obtain objective robotic measures that are significantly correlated to widely-used and reliable clinical measures in considerably different operating modes and control schemes.

Index Terms— Rehabilitation robotics, stroke measures, motor function recovery, haptic assistance.

I. Introduction

Stroke is the third most frequent cause of death in the United States. Direct and indirect costs due to stroke are estimated as $57.9 billion for 2006 [1]. The current rehabilitation process for recovery of motor function after stroke consists of physical therapy, which requires a therapist to administer the training and evaluation procedures for each patient. The repetitive and intensive nature of the rehabilitation program makes it a suitable area of application for robotics [2], [3].

O. Celik and M. K. O'Malley are with the Department of Mechanical Engineering and Materials Science, Rice University, Houston, TX 77005 (e-mails: {celiko, omalleym}@rice.edu)

Corwin Boake is with University of Texas Health Science Center, 1333 Moursund, Houston, TX 77030 (e-mail: Corwin.Boake@uth.tmc.edu)

Harvey Levin is with Cognitive Neuroscience Laboratory, Baylor College of Medicine, 1709 Dryden Road, Suite 725, Houston, TX 77030 (e-mail: hlevin@bcm.edu)

Steven Fischer is with The Institute for Rehabilitation Research (TIRR), 1333 Moursund, Houston, TX 77030

Timothy Reistetter is with Department of Occupational Therapy, East Carolina University, Health Sciences Building, 3305C Greenville, NC 27858 (e-mail: reistettert@ecu.edu)

Robotic rehabilitation for stroke patients has been an active field of research since the 1990s. Studies on robotic rehabilitation concentrate on mechanical design of robotic devices, design of software and interfaces for the patients and therapists, identifying quantitative and objective measures for motor improvement, and developing different operating modes/scenarios for the devices. Studies conducted with MIT-MANUS [3] and MIME [4] robotic devices have found that robot assisted therapy can match therapist administered therapy and might even supply greater motor improvement gains. MIT-MANUS and MIME systems are capable of providing movements mostly concentrated on shoulder and elbow, i.e. on proximal joints. Given the success of systems that focus on the elbow and shoulder, there has been interest in developing robotic devices for the more distal joints of the upper extremity. Examples of devices that focus on the wrist include the RiceWrist [5], [6], the wrist extension of the MIT-MANUS [7] and the wrist rehabilitation device developed by Hesse et al. [8].

In this study, a haptic joystick (IE2000 by Immersion Inc.) was used to implement four different operating modes in a robotic therapy protocol. A simple target hitting task was completed repetitively by the patients during the sessions, while the operating mode for each session was determined by the therapist according to the patient's progress and capability. Collected position data was later processed to obtain daily average values of the smoothness of movement (SM) and trajectory error (TE) measures. The primary purpose of the study is to obtain and relate clinical and robotic improvement measures for stroke patients.

An important advantage of robot assisted therapy is that it makes obtaining objective motor function measures possible. Movement smoothness [9], [10], average movement speed [11], movement percentage voluntarily achieved by the patient without robot's assistance [11] and different error values indicating the difference between the desired target/trajectory and the target/trajectory achieved by the patient [10], [11] are among these measures. These measures can be directly calculated from the data recorded by the robotic devices' sensors and displayed on-line during the sessions or used for analysis off-line. Such measures are not vulnerable to subjective human interference during evaluation unlike many clinical measures. The measures can capture the quality of movement, or can ensure independence from factors such as time. They can also be used to provide patients with immediate feedback on their progression after each therapy session, as opposed to the lengthy evaluation procedures

conducted by a therapist that typically occur at only the beginning and end of therapy.

There have been a few studies on the correlation between clinical and robotic stroke measures in upper extremities. Colombo et al. [11] conducted a study with two stroke patient groups; for a three week therapy period, seven patients were assigned to a 1-DOF wrist rehabilitation device and nine patients were assigned to a 2-DOF shoulder-elbow rehabilitation device. Motor improvement of the patients was assessed by various clinical and robotic measures. Correlation between pre- and post-treatment Fugl-Meyer (FM) scores and three robotic scores defined in the study (namely: robot score, mean velocity and active movement index) of the patients in the second group were examined using regression analysis. A moderate and significant correlation was observed. Regression analysis for the same set of robotic measures and Motor Status Score and Medical Research Council measures did not produce significant results.

A study by Hester et al. [12] aimed to develop a method for predicting clinical measure scores for stroke patients using a wearable set of accelerometers on the arm. Numerous features extracted from the accelerometer data collected from twelve patients were used to obtain linear regression models. Models were found to be successful in predicting the FM shoulder-elbow scores of the patients.

Although robotic measures are objective and can be readily calculated at each robotic therapy session, they do not have the reliability, validity and widely accepted use of clinical measures. More research is needed to reveal the correlation between the two types of measures and establish commonly accepted and reliable robotic measures.

In this pilot study conducted with four sub-acute stroke patients, correlations between various clinical and robotic measures are investigated. Motor recovery of the patients was assessed using Fugl-Meyer (FM) upper extremity scale and Motor Activity Log (MAL) scale. The patients underwent a one-month treatment program that consisted of robotic therapy and traditional constraint induced movement therapy (CIMT) activities.

In this paper, the specifications and capabilities of the haptic joystick used for robotic therapy sessions are introduced, including operating modes and task descriptions in Sections II-A and II-B. Then the profiles of the patients, the therapy period and program and details of the CIMT activities are explained in Section II-C. Calculation methods for SM and TE measures are explained in Section II-D. Results based on the mentioned robotic measures in two operating modes and according to clinical measures (MAL, FM) are summarized in Section III. Correlations between clinical and robotic measures are investigated using regression analyses. The paper concludes with a discussion of results.

II. METHODS

A. Haptic Joystick

An Impulse Engine 2000 joystick from Immersion Inc. was used as the device to deliver the robotic therapy and
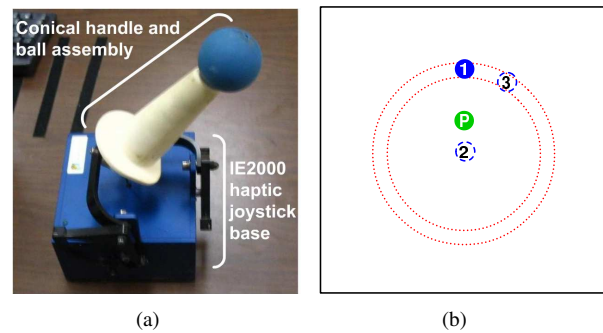

Fig. 1. IE2000 haptic joystick with the replaced handle. (b) Graphical interface showing the active target (1), the pointer (P), and the next two active targets (2 and 3) that will appear upon successful hits.

record movements of the patients. The IE2000 is a back-drivable 2-DOF device having a workspace of $\pm45° \times \pm45°$. It has high resolution optical encoders for position sensing that provide a rotational resolution of $0.036°$. The maximum torque value that can be reflected with the device is 493.5 mNm. The loop rate for haptic feedback based on impedance control was 1 kHz. In order to enable easier grasping and strapping of the patient to the handle of the IE2000, the original handle was replaced by a conical handle-ball assembly shown in Fig. 1(a).

2-DOF movements of the joystick provided pronation/supination and abduction/adduction of the wrist, since the forearms of the patients were fixed. However, since the rotation axes for of the wrist did not perfectly align with the joystick's two rotational DOF, minor movements of the forearm were inevitable. Movements to hit the targets required a range of approximately $\pm27°$ of rotation on the joystick.

B. Task and Operating Modes

The task assigned to the patients was to control the position of a pointer in a 2D workspace to hit targets around a circle. The pointer's position was directly determined by the joystick's position. Twelve targets were positioned equidistantly on a circle that was centered on the workspace, resembling the positions of numbers on a round clock, as illustrated in Fig. 1(b). OpenGL was used to implement the graphical interface. The active target was displayed until it was successfully hit by the pointer, after which the active target became the center point. Once it was hit, the target became the next one on the circle in a clockwise direction. The defined task resembles the task configuration in [9]. Position data of the cursor were recorded at a sampling frequency of 20 Hz for further analyses. The duration of a typical session was eight minutes.

Four operating modes were implemented, namely unassisted (U), constrained (C), assisted (A), and resisted (R). In U mode, no force is generated by the joystick. In this mode, the movement of the pointer is solely determined by the movement of the patient. U mode is suitable for gathering and analyzing data that represents a patient's free movement with no external interference.

In *C* mode, the patients' movement is allowed only in a neighborhood of the desired trajectory (the line between the last target and the next) and is constrained by virtual fixtures [13] when the patient moves out of the determined neighborhood. In this mode patients are passively assisted due to the constraint keeping them approximately following the desired trajectory.

A mode involves an active assistance scheme. A virtual linear spring between the current position of the pointer and the target is simulated. The spring has a static equilibrium point at the position that makes the displacement between the target and the pointer zero, hence a force pulling the joystick towards the target is generated. The virtual fixtures of *C* mode are also active in *A* mode.

In contrast, *R* mode utilizes a spring simulated between the active target and the pointer such that the spring is in static equilibrium when the target and the pointer are a radius apart from each other. This makes the task more difficult and requires the patient to use more motor power to compress the spring as he/she moves the pointer towards the target. In this mode, the virtual fixtures are again also active, in order to help the patient in following the desired trajectory.

In this paper, robotic measure results in *U* and *R* modes are presented since the data in *C* and *A* modes are limited. This is mainly due to the preferences of the therapist on selecting the mode during therapy sessions.

C. Patient Profiles and Therapy Program

Four sub-acute stroke patients were involved in the study. For inclusion in the study, the patient was required to demonstrate enough wrist range of motion to move the joystick and reach the targets. Characteristics of the patients are summarized in Table I. The therapy was conducted for four weeks, three days (Monday, Wednesday, Friday) per week for all patients except Patient 1 who underwent the therapy for eighteen days. The total duration of each daily therapy session was four hours consisting of approximately 60% traditional CIMT activities and 40% robotic tasks.

In the robotic therapy program, patients completed one to four sessions on each therapy day. A session typically consisted of eight minutes of work with a therapist-determined operating mode, however deviations in duration occurred due to patients' preferences or therapist's decisions. A follow-up session involving only *U* mode was also conducted approximately one month after the last therapy session for all patients. For Patient 1, the follow-up session was conducted three months after the last therapy session.

The CIMT component had three parts: (1) Shaping tasks delivered by therapist with immediate feedback of performance to the patients. (2) Behavioral techniques to promote transfer that included administration of the MAL tasks. (3) Constraint of the unaffected upper-extremity by wearing a protective safety mitt for six waking hours per day.

D. Clinical and Robotic Measures

Fugl-Meyer (FM) upper limb component and Motor Activity Log (MAL) scales are the clinical measures used in this

Patient Number	Gender	Age (years)	Months Since Stroke	Side Affected	Stroke Type
1	M	62	24	R	Left BS
2	F	63	12	L	Right BG
3	M	62	121	R	Left MCA
4	M	65	50	R	Left Hem

study. The 66-point upper limb component of the FM scale is administered by the therapist. The therapist uses a 3-point ordinal scale (0: can not perform, 1: can perform partially, 2: can perform fully) to rate each of 32 items completed by the patient in the test. The FM measure is the sum of all ratings with score of reflex activity item doubled [14]. MAL has two components: a 6-point scale for amount of use and another 6-point scale for quality of movement. Patient and caregiver independently rate in both components each item in a list of activities of daily living. The result is an average of all ratings [15].

Two different robotic measures were calculated using the data files: trajectory error (TE) and smoothness of movement (SM). The trajectory error measure is the difference between the desired trajectory and the patient's trajectory from one point in the workspace to another. Desired trajectory is always a straight line from the last target to the current target. Absolute values of the deviations from this straight line trajectory during the movement were summed to obtain the TE value. The edge length of the square workspace was normalized to 1 prior to the TE calculations.

The smoothness of movement (SM) measure gives the percent match value between the patient's speed profile and a speed profile utilizing the minimum jerk principle. SM in the minimum jerk sense was one of the measures tested in [9]. Tangential speed of patients' movements was used as the speed profile of the patients. The minimum jerk speed profile on a straight line for each target hit movement was calculated by the equation

$$v_{mj}(t) = \frac{\Delta}{T}\left(\frac{30t^4}{T^5} - \frac{60t^3}{T^4} + \frac{30t^2}{T^3}\right) \quad (1)$$

where t is time, Δ is distance traveled and T is the duration of the movement. Patients' speed profiles were shifted so as to have the minimum speed value at the initiation of each movement match the zero time of the minimum jerk speed profile. This is the same method mentioned in [10] with some minor differences in calculation of T. The correlation coefficient ρ is calculated by

$$\rho = \frac{\Sigma[(V_{norm} - \overline{V}_{norm})(V_{mj} - \overline{V}_{mj})]}{\sqrt{\Sigma(V_{norm} - \overline{V}_{norm})^2 \Sigma(V_{mj} - \overline{V}_{mj})^2}} \quad (2)$$

where V_{norm} is the normalized movement speed, $\overline{V}_{norm}$ is the

TABLE II

THERAPY RESULTS IN MAL AND FM MEASURES (ABBREVIATIONS:
PRE, PRE-TREATMENT; POST, POST-TREATMENT; F/U, FOLLOW-UP; W,
WEEK)

P#	FM			MAL					
	Pre	Post	f/u	Pre	W1	W2	W3	Post	f/u
1	36	41	40	0.50	1.09	1.52	2.03	2.52	2.20
2	23	39	43	1.81	2.69	2.90	3.40	3.52	3.24
3	36	49	49	1.12	2.00	3.03	3.45	3.63	3.08
4	50	58	57	1.09	1.52	2.62	3.29	4.05	3.38

mean normalized movement speed, V_{mj} is the normalized minimum jerk speed profile, $\overline{V}_{mj}$ is the mean normalized minimum jerk speed profile again following [10].

Both measures serve as an objective assessment of movement quality. The TE measure assesses the patients' performance of tracking straight line target trajectories, while the SM measure compares the speed profile of the patients' movements with the speed profiles observed in healthy people's movements. Both measures demonstrate how stroke patients' movements deviate from healthy people's movements. Based on sampled data collected from the movements, they provide practical, fast, direct and objective evaluations of movement quality.

E. Statistical Analyses

In order to see whether patients demonstrated significant improvements with respect to the robotic measures, daily average values of SM and TE measures of all patients in U and R modes were regressed on the number of days. The absolute number of days instead of the number of therapy days was preferred by taking the CIMT activities on the off-therapy days into consideration. The regression line's slope (β) and p values were identified.

To scrutinize the correlation between the clinical and the robotic measures, another regression analysis was carried out. The pre-treatment, post-treatment and follow-up evaluations of all patients in the FM measure were paired with the corresponding robotic measure results (the ones that were temporally the closest to the FM evaluations). Similar data pairs were formed for the MAL measure. Regression analyses are carried out using the paired data sets, with the same set of parameters summarized.

A final regression analyses was run using the corresponding FM and MAL measures to reveal the concordance between the two clinical measures.

III. RESULTS

Clinical measure results in FM and MAL scales are summarized in Table II. The mean difference between post- and pre-treatment FM scores is found to be significant ($p = 0.012$) on a one tailed t-test. The result of the same analysis for MAL scores was also found to be significant ($p = 0.002$). Hence the motor recovery gains were more pronounced in MAL scores.

TABLE III

RESULTS OF THE REGRESSION ANALYSES OF TE AND SM MEASURES
VS. DAYS IN U AND R MODES. * DENOTES SIGNIFICANT RESULTS
($p < 0.05$). ABBREVIATIONS: P#, PATIENT NUMBER; N, NUMBER OF
DATA POINTS USED FOR REGRESSION; β, SLOPE OF THE REGRESSION
LINE; p, p VALUE OF THE REGRESSION

Mode	P#	N	TE		SM	
			β	p	β	p
U	1	8	-0.006	0.679	0.137	0.523
	2	10	-0.040	0.059	0.291	0.034*
	3	13	-0.039	0.001*	0.713	0.000*
	4	15	-0.012	0.000*	0.730	0.000*
R	1	9	-0.014	0.000*	0.354	0.003*
	2	6	-0.068	0.074	0.393	0.064
	3	12	-0.026	0.000*	0.679	0.000*
	4	7	-0.008	0.001*	1.302	0.002*

Regression analysis results for TE and SM measures vs. days in U and R modes are summarized in Table III. The number of data points used in each regression analysis is designated as N.

In U mode, a significant decreasing trend with a significant slope was observed in TE for Patients 3 and 4. The results were not significant for Patients 1 and 2. A significant positive slope in SM emerged for Patients 2, 3 and 4. All slopes for the TE regression were negative (decreasing error) while they were all positive for SM (increasing smoothness), as expected. The steepest slopes in TE trends were observed for Patients 2 and 3 while the salient positive trend in SM was observed for Patient 4. Daily average SM values for all patients in U mode are depicted in Fig. 2 together with the regression lines.

In R mode, excluding Patient 2's results, all slopes were found to be significant for both TE and SM regressions. A counterintuitive result was observed for Patient 1; both TE and SM regressions were significant in R mode while they were not in U mode.

Among the four clinical measure vs. robotic measure regression analyses for each mode, FM-TE and FM-SM regressions in both U and R modes demonstrated significant results. None of the regressions that utilized MAL clinical measure was significant. Correlated pairs of FM and TE measures in both modes are plotted with the regression line in Fig. 3. Similar results and plots for FM-SM regression are depicted in Fig. 4. Results of the statistical analyses for the data are also given on the plots.

Since none of the MAL scores were significantly correlated to the robotic measures while FM scores were found to have significant correlation, analysis of the correlation of FM and MAL clinical measures is also of interest. Regressed line to the MAL-FM data pairs had a nonsignificant slope of $\beta = 0.066$ and a low R^2 value of 0.31.

IV. DISCUSSION

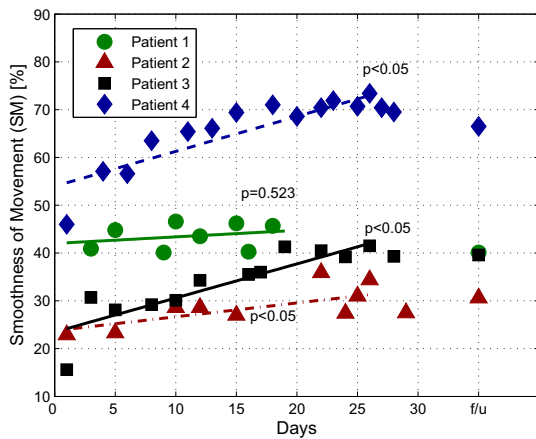An important feature that emerged with robotic rehabilitation technology has been the robotic motor assessment

Fig. 2. Average SM results for unassisted (*U*) mode. Day 1 corresponds to the first therapy day. f/u denotes the follow-up session.
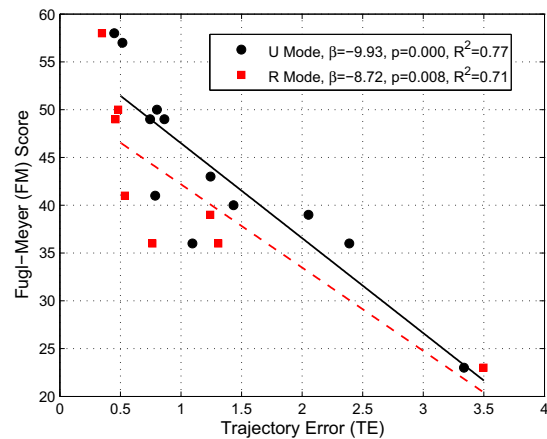

Fig. 3. Correlated pairs of Fugl-Meyer (FM) and trajectory error (TE) scores in *U* and *R* modes. Regression lines and regression statistics are also given.

measures. Robotic measures are entirely objective and can be directly calculated using the data being captured by the robot, thus allowing fast assessment and feedback to patients. Yet an important drawback of robotic measures is lack of a set of agreed-upon measures that are applicable to all robotic therapy systems/schemes. Rather each study on robotic rehabilitation defines its own measures that might be specific and limited to that system. In order to establish reliable and common robotic measures, a consensus between robotic and clinical measures needs to be formed.

This study aims to address this need by examining the relations between different robotic and clinical measures. In this section, the overall significance of the motor improvement results in both types of measures is discussed. Agreement between clinical and robotic measures is discussed for overall improvement and follow-up results. The regression results of FM scale on robotic measures are highlighted. Agreement with prior studies, contributions and possible implications of presented analyses are outlined. Nonsignificant results that utilized MAL scale are discussed in light of the regression analysis on two clinical measures. Finally, topics that are planned to be addressed in future work are given.

A. Motor Improvement

A significant motor function improvement was observed for all patients with respect to both clinical measures. This is found to be in agreement with the significant trends demonstrated by all patients (except Patient 1 in *U* mode and Patient 2 in *R* mode) in SM measure results in *U* and *R* modes. Significant negative TE measure trends for both modes and all patients are also in agreement with clinical measure results. Exception to this are Patient 1's results in *U* mode and Patient 2's results in both modes. It should be noted that Patient 1 had left the study after two weeks. It is interesting to observe that although Patient 2 showed the greatest improvement in FM scale, her TE trends are not significant in both modes, however they have the steepest slopes. Insignificance is caused by the large scatter of the

data along the fit line and this can be attributed to the specific stroke type (Basal Ganglia) of the patient [16].

When the robotic measures vs. days regressions are examined, it can be said that in general, *R* mode pushed the robotic measure evaluations towards significance when compared to *U* mode results, except for Patient 2. The most pronounced effect is for Patient 1. These results are thought to be related to the passive assistance provided to the patients by the virtual fixtures in *R* mode.

An interesting observation in the results is that Patient 3, who is approximately ten years past stroke, showed a fair amount of increase in FM scale from 36 to 49 which was completely preserved until the follow-up session. The same result was observable in both robotic measures.

Follow-up session results in clinical measures show that the achieved motor recovery by all patients was generally preserved after the follow-up period. There are some exceptions to this for Patients 3 and 4 in MAL measure. SM and TE results in *U* mode on the follow-up days are in accordance with the clinical measures.

B. Regression Analyses

The significance of the regression of FM measure results on the robotic measures are encouraging and in agreement with the findings of Colombo et al. [11]. Our study presents relevant data for motor recovery in the wrist, which had not been studied in the literature. It also extends the previously demonstrated validity of correlation between the robotic and clinical measures to a very different and relatively complex operating mode: *R* mode that includes both a resisting force applied to the patients' hand movements and a pair of virtual fixtures that passively assist the patients. Also, existence of significant correlation for a different robotic measure, the SM measure, was shown. These results are considered an indication of the feasibility of establishing a set of robotic parameters that will bear a significant accordance with reliable clinical measures for considerably different robotic therapy
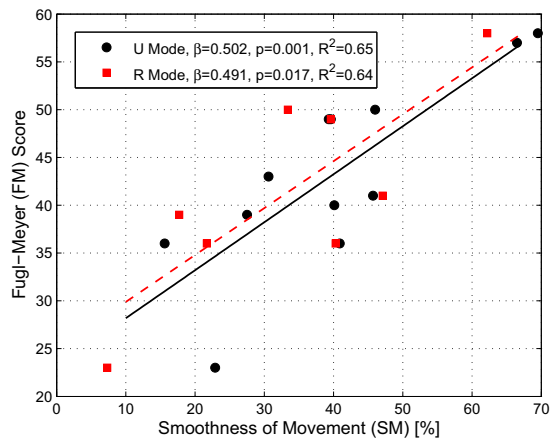
Fig. 4. Correlated pairs of Fugl-Meyer (FM) and smoothness of movement (SM) scores in *U* and *R* modes. Regression lines and regression statistics are also given.

programs, control strategies and operating modes.

Lack of significant results in correlations between our robotic measures and the MAL measure is considered a limitation of the study. However, the more subjective properties of the MAL measure are thought to have caused these results. This is more clearly revealed by examining the correlation between the MAL and FM measure results which also is insignificant. The low R^2 value implies that the two clinical measures are in considerable disagreement, hence looking for a significant correlation between the robotic measures and both clinical measures might be an unrealistic task. Along these lines, it is probable that the robotic measures will not be correlated to both clinical measures, as we note in this study. We feel it is a preferred outcome that our robotic measures are well-correlated to FM rather than MAL, since FM is a well-established, extensively used and studied, reliable and relatively objective measure.

C. Future Work

We plan to extend this pilot study to a clinical trial with more stroke patients. Future analyses will examine the effects of additional operating modes such as *C* and *A* modes and reveal the relation between these additional modes and clinical measures. The set of clinical measures will be expanded to include other tests such as Action Research Arm Test (ARAT), grip-pinch strength, 9-hole peg test and Jebsen Taylor Hand Function Test.

V. CONCLUSION

In this pilot study, a comparison of clinical measures with smoothness of movement (SM) and trajectory error (TE) robotic measures is given for four sub-acute stroke patients. Clear and significant agreement of these measures with the FM clinical measure was observed with moderate R^2 values while the results were inconclusive for the MAL measure.

The therapy group demonstrated a significant improvement with respect to the clinical measures. Regression analysis of the robotic measure results for *U* and *R* modes verified this

improvement. Clinical and robotic measures were found to be mostly in agreement for the follow-up results as well.

These results demonstrate the possibility of establishing objective robotic motor function assessment measures that are in good correlation with the long-used and well-known clinical measures in different operating modes and control algorithms.

REFERENCES

[1] T. Thom *et al.*, "Heart disease and stroke statistics-2006 update. A report from the american heart association statistics committee and stroke statistics subcommittee," 2006.

[2] M. K. O'Malley, T. Ro, and H. S. Levin, "Assesing and inducing neuroplasticity with transcranial magnetic stimulation and robotics for motor function," *Arch Phys Med Rehabil*, vol. 87, pp. S59–66, December 2006.

[3] H. Krebs, N. Hogan, M. Aisen, and B. Volpe, "Robot-aided neurorehabilitation," *IEEE Trans. Rehab. Eng.*, vol. 6, no. 1, pp. 75–87, 1998.

[4] P. Lum, C. Burgar, P. Shor, M. Majmundar, and M. Van der Loos, "Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke." *Arch Phys Med Rehabil*, vol. 83, no. 7, pp. 952–9, 2002.

[5] A. Gupta and M. K. O'Malley, "Design of a haptic arm exoskeleton for training and rehabilitation," *IEEE/ASME Trans. Mechatron.*, vol. 11, no. 3, May 2006.

[6] A. Gupta, V. Patoglu, and M. K. O'Malley, "Design, control and performance of RiceWrist: a force feedback wrist exoskeleton for rehabilitation and training," *International Journal of Robotics Research, Special Issue on Machines for Human Assistance and Augmentation*, 2007, (in Review).

[7] S. Charles, H. Krebs, B. Volpe, D. Lynch, and N. Hogan, "Wrist rehabilitation following stroke: initial clinical results," in *Proc. IEEE International Conference on Rehabilitation Robotics (ICORR'2005)*, Chicago, IL, USA, June–July 2005, pp. 13–16.

[8] S. Hesse, G. Schulte-Tigges, M. Konrad, A. Bardeleben, and C. Werner, "Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects." *Arch Phys Med Rehabil*, vol. 84, no. 6, pp. 915–20, 2003.

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

[10] J. Daly, N. Hogan, E. Perepezko, H. Krebs, J. Rogers, K. Goyal, M. Dohring, E. Fredrickson, J. Nethery, and R. Ruff, "Response to upper-limb robotics and functional neuromuscular stimulation following stroke." *J Rehabil Res Dev*, vol. 42, no. 6, pp. 723–36, 2005.

[11] R. Colombo, F. Pisano, S. Micera, A. Mazzone, C. Delconte, M. Carrozza, P. Dario, and G. Minuco, "Robotic techniques for upper limb evaluation and rehabilitation of stroke patients," *IEEE Trans. Neural Syst. Rehab. Eng.*, vol. 13, no. 3, pp. 311–324, 2005.

[12] T. Hester, R. Hughes, D. Sherrill, B. Knorr, M. Akay, J. Stein, and P. Bonato, "Using wearable sensors to measure motor abilities following stroke," in *Proc. IEEE International Workshop on Body Sensor Networks of the IEEE Computer Society (BSN'2006)*, Washington, DC, USA, April 2006, pp. 5–8.

[13] L. Rosenberg, "Virtual fixtures: perceptual tools for telerobotic manipulation," in *Proc. IEEE Virtual Reality Annual International Symposium (VRAIS'2001)*, 1993, pp. 76–82.

[14] J. van der Lee, "The responsiveness of the action research arm test and the Fugl-Meyer assessment scale in chronic stroke patients," *Journal of Rehabilitation Medicine*, vol. 33, no. 3, pp. 110–113, 2001.

[15] S. Page, S. Sisto, P. Levine, M. Johnston, and M. Hughes, "Modified constraint induced therapy: a randomized feasibility and efficacy study." *J Rehabil Res Dev*, vol. 38, no. 5, pp. 583–90, 2001.

[16] I. Miyai, "Patients with stroke confined to basal ganglia have diminished response to rehabilitation efforts," *Neurology*, vol. 48, no. 1, pp. 95–101, 1997.