2014 5th IEEE RAS & EMBS International Conference on
Biomedical Robotics and Biomechatronics (BioRob)
August 12-15, 2014. São Paulo, Brazil

Upper limb robot-assisted therapy in subacute and chronic stroke patients: preliminary results on initial exposure based on kinematic measures

S. Mazzoleni, *Member, IEEE*, L. Buono, P. Dario, *Fellow, IEEE*, and F. Posteraro

Abstract— **The goal of this study is to evaluate the effects of robot-assisted upper limb therapy in subacute and chronic stroke patients using a set of kinematic parameters evaluated during each of the first 15 rehabilitation sessions.Twenty-four post-stroke subjects, twelve subacute and twelve chronic, participated in the study. A 2 DOFs robotic system was used for upper limb training. Kinematic parameters related to the speed and smoothness measured at the robot's end-effector were computed.**

Outcome clinical measures show a decrease in motor impairment at half-treatment both in chronic and subacute patients. Significant improvements in kinematic parameters within the first 15 sessions were observed only in subacute patients.

I. Introduction

The 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 and 200,000 occur in people who have had previously a stroke [2].

The rehabilitation goal in post-stroke subjects is to promote recovery of lost function, to allow independence and early reintegration into social and domestic life.

The number of people that require rehabilitation after stroke is growing rapidly [3], with increasing costs and pressure on healthcare budgets.

Post-stroke patients require continuous medical care and intensive rehabilitation but unfortunately, current demands and budget restrictions do not allow this intensive rehabilitation.

Therefore, the use of robotic systems in order to improve the efficacy and effectiveness of post-stroke rehabilitation is increasingly growing.

Several studies on robot-assisted rehabilitation treatment in subacute and chronic stroke patients have shown a reduction of the upper limb impairment, but till now evidence on the advantage of the use of robotic therapy compared to other types of intervention (i.e., electrical stimulation) is still lacking [4], even if robotic therapy can provide novel methods for improving upper limb coordination and function also in children with moderate to severe impairments due to cerebral palsy [5].

The optimal choice of rehabilitation treatments is based on the deep knowledge of mechanisms underlying motor recovery after stroke. Currently the main assessment tool is represented by clinical outcome measures. On the other hand robotic systems are able to provide quantitative assessment measures and performance metrics which can contribute to highlight the different recovery processes in subacute and chronic patients [6]-[11].

The main goal of this study is to evaluate the effects of the first 15 sessions of upper limb robot-assisted therapy in subacute and chronic stroke patients by using kinematic parameters and clinical outcome measures.

II. Methods

A. Participants

Twelve subacute stroke subjects, age range 49-77 (mean age 67.1±10.2) years, four men and eight women, were recruited for the study. Five suffered right hemiparesis, and seven from left hemiparesis. They had experienced the acute event 25±7 days prior to the study.

Twelve chronic subjects, age range 31-86 (mean age 60.9±13.6) years, six men and six women, were recruited for the study. Eight were resulted in right hemiparesis, and four in left hemiparesis. They had experienced the acute event at least one year prior to the study.

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 patients at admission was assessed using the Stage of Arm section of the Chedoke-McMaster (CM) Stroke Assessment Scale [12]. One subacute stroke subjects received a CM value of 1, five a CM value of 2 or 3, and six a CM score of 4 or 5. Eight chronic patients received a CM value of 2 or 3 and four a CM value of 4 or 5.

S. Mazzoleni is with the Biorobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy and the Laboratory of Rehabilitation Bioengineering, Volterra, Italy (corresponding author: phone: +39 050 883132; fax: +39 050 883101; e-mail: s.mazzoleni@sssup.it).

L. Buono is with the Biorobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy and the Laboratory of Rehabilitation Bioengineering, Volterra, Italy (e-mail: l.buono@sssup.it)

P. Dario is with the Biorobotics Institute, Scuola Superiore Sant'Anna, Pisa, Italy (e-mail: p.dario@sssup.it)

F. Posteraro is with Rehabilitation Department, Versilia Hospital - AUSL12, Lido di Camaiore, Italy and the Laboratory of Rehabilitation Bioengineering, Volterra, Italy (e-mail: f.posteraro@riabilitazione-volterra.it)

978-1-4799-3127-9/6/14/$31.00 ©2014 IEEE

B. Experimental setup

The InMotion Arm (Interactive Motion Technologies, Inc., Watertown, MA, USA), a 2 DOFs robotic system designed for neurological applications [13]-[14], was used for this study (Figure 1).

The robotic system allows subjects to execute reaching movements in the horizontal plane, through an "assist as needed" control strategy based on impedance algorithm.

Figure 1. A stroke patient during the robot-assisted upper limb rehabilitation treatment.

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 to facilitate the transfer from and to a wheelchair.

The robot can guide the movement of the upper limb of the subjects and record end-effector physical quantities such as 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 five sessions per week (6 weeks for subacute, 4 weeks for chronic) of 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 session was 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 was asked to perform a further series of 16 unassisted clockwise movements (Record).

Kinematic data were computed starting from physical variables recorded at the robot's end-effector during the Record series of each of the first 15 sessions.

The main motivation for analysing only 15 sessions is based on the plateau value reached on each of the kinematic parameters in both groups.

The targets sequence was not randomized as our focus is on repetitive movements.

D. Outcome measures

Each subject underwent an upper limb evaluation by an experienced physical therapist using the following outcome measures:

- Stage of Arm section of the Chedoke-McMaster (CM) Stroke Assessment Scale: it was compiled only before the treatment for classifying the patients according to different degrees of severity of the upper limb impairment [12].
- Upper Extremity subsection of the Fugl-Meyer (FM-UE) Assessment Scale [15].
- Modified Ashworth Scale: to assess muscle spasticity by rating resistance to passive stretch. It was evaluated on the shoulder (MAS-S) and the elbow (MAS-E) [16].
- Passive range of motion (pROM) in 11 different muscle groups (7 for the shoulder and 4 for the elbow)
- Motricity Index (MI): to assess the motor impairment in a patient who has had a stroke [17].

The evaluation tools were used for each patient before the first session (T0) and at half-treatment (T1) of the robotic therapy.

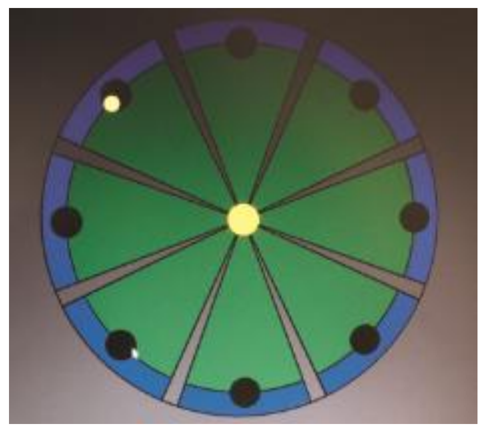

Figure 2. The "clock-like" robot-assisted therapy scenario

E. Kinematic parameters

The following kinematic parameters were computed: 1) normalized reaching speed, 2) number of speed peaks and 3) jerk metric.

The velocities of movements performed by each subject along x and y axis ($v_x[k]$, $v_y[k]$) 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 only; this variable is defined 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 this study considers also the peak velocity ($v_{xy}max$) defined as the maximum value reached by $v_{xy}[k]$. The Normalized Reaching Speed (NRS) defined as follows:

$$NRS = \frac{v_{xy}max - \overline{v_{xy}}}{v_{xy}\,max} \qquad (5)$$

was computed as well.

In addition to NRS, other two measures were analyzed to evaluate and quantify the smoothness of movements: number of speed peaks and jerk metric. Healthy subjects are characterized by smooth movement trajectories described 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[18].

1) Number of Speed Peaks

Number of Speed Peaks (NSP) in the xy-plane velocity profile is a metric used to assess smoothness of movement in stroke patients [19], [20]. Smooth movements are characterized by few periods of acceleration and deceleration, therefore by low values of NSP.

2) Jerk Metric

Jerk is the rate of change of acceleration with respect to time (third time derivative of the position).

The data obtained after computing the time derivative of acceleration data were then digitally low-pass filtered forward and backward in time at 5 Hz with a 10th-order Butterworth filter.

Jerk metric (JM) is calculated by dividing the mean jerk magnitude by the peak speed, as follows:

$$JM = \frac{|\overline{J_{xy}}|}{v_{xy\,max}} \qquad (6)$$

Low values associated to JM correspond to smooth movements.

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 outcomes measures, a one way repeated measures ANOVA was computed.

A one-way ANOVA was used for the statistical analysis of differences of kinematic parameters during each of the first 15 session of the treatment.

All pairwise multiple comparison procedures using Tukey Test $p<0.05$.

III. RESULTS

The robot-assisted therapy was well accepted and tolerated by all patients and no patients dropped out. The results from clinical outcome measures showed a decrease in motor impairment in the paretic upper limb after the robot-assisted treatment.

In subacute patients, statistically significant improvement were found on FM-UE ($p<0.05$), ROM ($p<0.001$) and MI ($p<0.05$). In chronic patients, statistically significant improvement were found on FM-UE ($p<0.05$) and ROM ($p<0.001$).

Table I and Table II summarize the results of clinical outcome measures at T0 and T1 in subacute and chronic patients, respectively.

TABLE I. FM-UE, MI, MAS-S, MAS-E, ROM values at T0 and T1 in subacute patients

	T0 (mean±sd)	T1 (mean±sd)	Change	p
FM-UE	27.17±12.24	33.58±13.69	6.42±5.88	<0.05
MI	40.17±25.29	51.83±28.84	11.67±12.66	<0.05
MAS-S	0.42±0.67	0.08±0.29	-0.33±0.78	N.S.
MAS-E	0.67±0.89	0.42±0.90	-0.25±0.62	N.S.
pROM	747.92±123.70	786.25±109.11	38.33±31.50	<0.001

Kinematic parameters recorded in subacute patients show significant improvements (Figure 3-Figure 5). On the other hand, significant improvements on kinematic parameters within the first 15 sessions of therapy were not observed in chronic patients (Figure 6- Figure 8).

TABLE II. FM-UE, MI, MAS-S, MAS-E, ROM values at T0 and T1 in chronic patients

	T0 (mean±sd)	T1 (mean±sd)	Change	p
FM-UE	22.75±7.48	27.33±9.46	4.58±4.34	<0.05
MI	36.83±18.77	42.17±21.12	5.33±6.70	N.S.
MAS-S	1.92±1.24	1.50±1.24	-0.42±0.79	N.S.
MAS-E	2.33±1.15	1.83±1.19	-0.50±0.52	N.S.
pROM	641.25±79.23	689.58±74.18	48.33±27.33	<0.001

The evaluation of kinematic parameters shows significant improvements only in subacute patients. Chronic patients require a longer exposure to the robot-assisted therapy to achieve significant improvements [11].

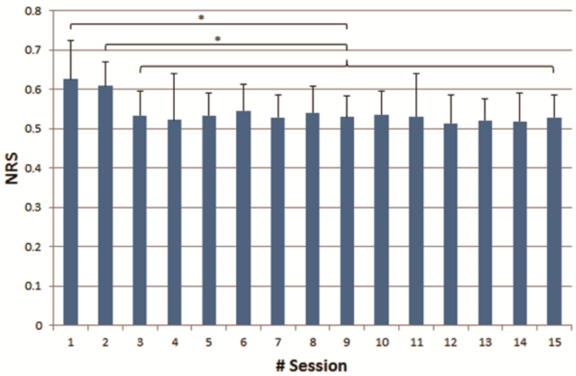

Figure 3. NRS values in subacute patients during the first 15 sessions of robot assisted training (*indicates p<0.05).

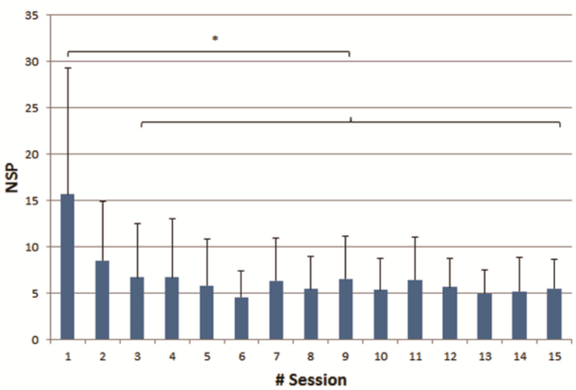

Figure 4. NSP values in subacute patients during the first 15 sessions of robot assisted training (* indicates p<0.05).

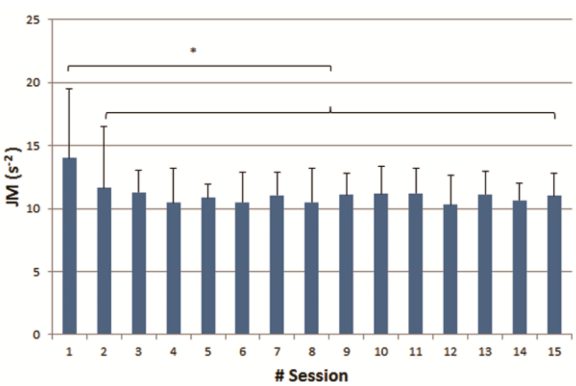

Figure 5. JM values in subacute patients during the first 15 sessions of robot assisted training (*indicates p<0.05).

IV. Discussion and Conclusion

Table I and Table II show a significant decrease in motor impairment of subacute and chronic stroke patients following upper limb robot-assisted treatment (FM-UE and pROM) at T1.

In subacute patients statistically significant improvements were found in MI at T1 as well (Table I).

The values of kinematic parameters in subacute patients show significant improvements in the movement quality (Figure 3-Figure 5). On the other hand, any significant improvements on kinematic parameters within the first 15 sessions were not observed in chronic patients (Figure 6-Figure 8).

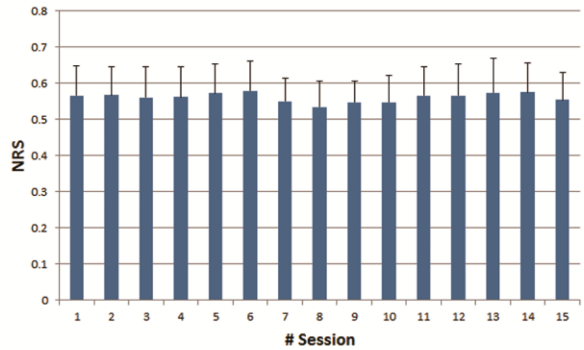

Figure 6. NRS values in chronic patients during the first 15 sessions of robot assisted training.

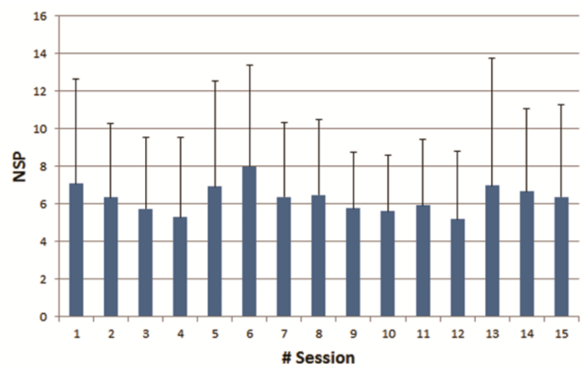

Figure 7. NSP values in chronic patients during the first 15 sessions of robot assisted training.

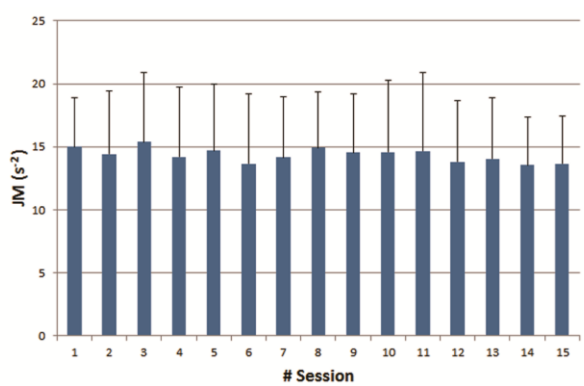

Figure 8. JM values in chronic patients during the first 15 sessions of robot assisted training.

Changes on MAS-S and MAS-E in subacute patients are rather small as values at T0 are low as spasticity is not already developed.

The significant improvement of upper limb impairment in chronic patients (i.e., FM-UE) occurs without any evident improvement in the quality movement as detected by kinematic parameters. This finding is confirmed by values of MAS-S and MAS-E higher than those observed in subacute patients.

Initial values of NRS and NSP in chronic patients are lower than those in subacute patients as the latter are characterized by a more severe impairment and the former underwent a rehabilitation treatment.

The plateau value of NRS in subacute patients corresponds to the NRS initial value observed in chronic patients.

NSP significantly decreases in subacute patients achieving a plateau value lower than that found in chronic patients.

Chronic stage seems to be characterized by reaching movements performed at the same velocity as that detected in the subacute stage, although the movements smoothness worsens.

In conclusion, the evaluation of kinematic parameters shows significant improvements only in subacute patients. Chronic patients require a longer exposure to the robot-assisted therapy to achieve significant improvements [21].

ACKNOWLEDGEMENT

This work was partly funded by Regione Toscana, under the Regional Health Research Program 2009 ("Telerehabilitation and Robotics" research project) and Fondazione Cassa di Risparmio di Volterra, Italy.

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] World Health Organization. World Health Statistics 2008. Geneva, Switzerland: WHO Press; 2008.

[4] S. Hesse, C. Werner, M. Pohl, J. Mehrholz, U. Puzich, and H.I. Krebs, "Mechanical arm trainer for the treatment of the severely affected arm after a stroke: a single-blinded randomized trial in two centers", *Am J Phys Med Rehab.*, vol. 87, pp. 779-88, 2008.

[5] S.E. Fasoli, M. Fragala-Pinkham, R. Hughes, N. Hogan, H.I. Krebs, and J. Stein, "Upper limb robotic therapy for children with hemiplegia", *Am J Phys Med Rehab*., vol. 87, pp. 929-36, 2008.

[6] S. Balasubramanian, R. Colombo, I. Sterpi, V. Sanguineti, and E. Burdet, "Robotic assessment of upper limb motor function after stroke," *Am J Phys Med Rehab*., vol. 91, pp. 255-269, 2012.

[7] R. Colombo, F. Pisano, S. Micera, A. Mazzone, C. Delconte, and M. C. Carrozza, "Assessing mechanisms of recovery during robot-aided neurorehabilitation of the upper limb," *Neurorehabil Neural Repair*, vol. 22, pp. 50-63, 2008.

[8] H. I. Krebs, J. J. Palazzolo, L. Dipietro, M. Ferraro, J. Krol, and K. Rannekleiv, "Rehabilitation robotics: performance-based progressive robot-assisted therapy," *Auton Robot*, vol. 15, pp. 7-20, 2003.

[9] L. Zollo, E. Gallotta, E. Guglielmelli, and S.Sterzi, "Robotic technologies and rehabilitation: new tool for upper-limb therapy and assessment in chronic stroke," *Eur J Phys Rehab Med*., vol. 47, pp. 223-36, 2011.

[10] R. Colombo, I. Sterpi, A. Mazzone, F. Pisano, and C. Delconte, "Modeling upper limb clinical scales by robot-measured performance parameters," In Proc. IEEE *Int Conf Rehabil Robot*, 1-5, 2011.

[11] S. Mazzoleni, F. Posteraro, F. Forte, S. Micera, P. Dario and M. C. Carrozza, "Biomechanical assessment of reaching movements in post-stroke patients during a robot-aided rehabilitation," *Applied Bionics and Biomechanics*, vol. 8, pp. 39-54, 2011.

[12] 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.

[13] H. I. Krebs, N. Hogan, M.L. Aisen, and B.T. Volpe, "Robotaided neurorehabilitation," *IEEE Trans Rehabil Eng*., vol. 6, pp. 75-87, 1998.

[14] 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, pp. 976-80, 2009.

[15] A. R. Fugl-Meyer, L. Jääskö, I. Leyman, S. Olsson and S. Steglind, "The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance" *Scand J Rehabil Med*., vol. 7, pp. 13-31, 1975.

[16] R. W. Bohannon and M. D. Smith, "Interrater reliability of a modified Ashworth scale of muscle spasticity" *Phys Ther*., vol. 67, pp. 206–207, 1987.

[17] G. Demeurisse, O. Demol and E. Roboy, "Motor evaluation in vascular hemiplegia", *Eur Neurol*., vol. 19, pp. 382–89 , 1980.

[18] 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" *J Neurosci*., vol. 22, pp. 8297-8304, 2002.

[19] C. Tsao and M.M. Mirbagheri, "Upper limb impairments associated with spasticity in neurological disorders" *J Neuroeng Rehabil*, 4:45, 2007.

[20] D.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, pp. 702-7, 2002.

[21] S. Mazzoleni, L. Puzzolante, L. Zollo, P. Dario, F. Posteraro, "Mechanisms of motor recovery in chronic and subacute stroke patients following a robot-aided training", *IEEE Transactions on Haptics*, 99, no. PrePrints, p. 1, 2013.