31st Annual International Conference of the IEEE EMBS
Minneapolis, Minnesota, USA, September 2-6, 2009

Design and Development of a Hand Robotic Rehabilitation Device for Post Stroke Patients

E. Rashedi, A. Mirbagheri, B. Taheri, F. Farahmand, G.R. Vossoughi, M. Parnianpour

Abstract— **Robot-mediated rehabilitation is a rapidly advancing discipline that seeks to develop improved treatment procedures using new technologies, e.g., robotics, coupled with modern theories in neuroscience and rehabilitation. A robotic device was designed and developed for rehabilitation of upper limbs of post stroke patients. A novel force feedback bimanual working mode provided real-time dynamic sensation of the paretic hand. Results of the preliminary clinical tests revealed a quantitative evaluation of the patient's level of paresis and disability.**

I. Introduction

Cerebrovascular disorders and traumatic brain injuries are considered to be the main causes of disability, resulting in partial or complete motor limitation in upper and lower limbs in adults. Stroke is the third cause of death in U.S. following cardiovascular diseases and cancer and about 700,000 people experience it yearly [1]. Rehabilitation of these patients usually requires intensive manual interaction with therapists [2] who perform physical therapy, electrical stimulation, or passive manipulation [3-4]. Recently, new sensory-motor rehabilitation techniques based on the use of robots and mechatronics systems has been proposed for post stroke patients [5-11]. These techniques are claimed to improve the patient's motor performance, provide intensive rehabilitation, shorten the rehabilitation duration, and provide objective data for evaluation of patient's progress [12, 13].

The upper limb rehabilitation robotic systems have usually one to three degrees of freedom (DoFs) and are designed for unilateral or bilateral shoulder and elbow movement or bilateral passive and active practice of forearm and wrist [5-11]. During robotic rehabilitation, a paretic arm is manipulated, similar to a traditional physical therapy exercise, and simultaneously the speed, direction and strength of the residual voluntary activity are measured [5, 7, 8, 11]. Moreover, in some systems, e.g., GENTLE/s [10], the models for human arm movement have been coupled with haptic interfaces and virtual reality technology. A variety of robotic rehabilitation devices have been introduced in the literature. In Driver 's SEAT [5], a one degree of freedom robotic device is used to promote coordinated bimanual movement in post stroke patients. Mirror-Image Motion Enabler (MIME) [6] and MIT-Manus [7] are 2 DoFs robotic manipulators that assist unrestricted and horizontal plane shoulder and elbow movements, respectively, and have shown positive results in clinical practice. The ARM guide [8], on the other hand, is an assistive device that helps the patient to exercise reaching in a straight-line trajectory. Finally, Arm Trainer robot [9] enables bilateral passive and active practices of forearm and wrist movements.

Our research group has developed an upper limb robot-mediated rehabilitation device to provide therapeutic practices for the post stroke patients. The system was aimed to decrease muscles spasticity, increase power and motor control and relieve pain in the arm of chronic hemiparetic patients. Some new features were implemented in the device, namely a force feedback for real-time dynamic sensation of the paretic hand by the patient's healthy hand, and a modular design to facilitate the application of the system in different operational states.

E. Rashedi is a Ph.D. student of Mechanical Engineering at Sharif University of Technology and research assistant at Research Center for Science and Technology In Medicine (RCSTIM), Tehran, Iran (e-mail: rashedi@mech.sharif.edu).

A. Mirbagheri is a Ph.D. candidate of Mechanical Engineering at Sharif University of Technology and a research assistant at Research Center for Science and Technology In Medicine (RCSTIM), Tehran, Iran (e-mail: mirbaghery@mech.sharif.edu).

B. Taheri received his M.Sc. in Mechanical Engineering from Sharif University of Technology, Tehran, Iran (e-mail: taheri_behzad@mech.Sharif. edu).

F. Farahmand is a professor and chairman of School of Mechanical Engineering at Sharif University of Technology, Tehran, Iran (e-mail: farahmand@sharif.edu).

G. Vossoughi is an associate professor of School of Mechanical Engineering at Sharif University of Technology, Tehran, Iran (e-mail: vossough@sharif.edu).

M. Parnianpour is an adjunct professor of School of Mechanical Engineering at Sharif University of Technology, Tehran, Iran and a professor in Department of Information and Industrial Engineering, Hanyang University, Ansan, Gyeonggi-do, Rep. of Korea

II. Method

A. Mechanical Design and Implementation

An apparatus was designed to provide the passive or active unilateral or bilateral therapeutic exercises of the upper limb in two operational states: pronation/supination of forearm and flexion/extension of wrist (Fig. 1). Considering the fact that the axes of rotation for these two movements were perpendicular, an innovative design strategy was employed so that the system could tilt 90° upward to switch between these states. Also, the special form of handles allowed them to be used for both movements with no need to be exchanged. As a result, the angular positions of patient's hands were constant in the two operational states, facilitating the clinical application of the device. The major parts of the apparatus are illustrated in Fig. 1(b). Each handle was

978-1-4244-3296-7/09/$25.00 ©2009 IEEE

connected via an axis, going through two bearings, one coupling and a torque sensor, to an electric DC motor. The brushless servo motor PR 070 (Amtec Robotics Co., Munich, Germany) provided the actuating torque and had a harmonic drive gear head with an incremental encoder for positioning and velocity control. The 1-DoF 10 Nm capacity torque sensor TCN 16 (Dacell Co., Chung-buk, Korea) measured the applied torque at the hand of the patient and provided the required safety alarms. The bearings MUSCP004 (JIB Co., Jiangyin, China) and 2-DoF clamp type coupling HPS-45C (HSK Co., Kaohsiung, Taiwan) were used to prevent transmission of undesired torques to the sensors. A PC was used to collect all the data and control the servo motors. The torque sensor signals were communicated to the PC using a 12-bit, 16-channel A/D converter PCI-1711L (Advantech Co., Taipei, Taiwan). Derivers of motors were connected to the PC through the RS232 serial port. A visual C++ program was developed to provide the communications with torque sensors and motors. Six different plans were considered to guarantee the patient's safety during practicing with the device: (1) a magnetic brake to stop the movement when the torques exceeded 4Nm [9], (2) a stop command in case of applying torques more than 4Nm [9], (3) programmable limits for the angular position range of motors to keep the rotation within the safe range, (4) mechanical stops to restrict the rotation within the safe range, (5) an emergency stop in reach of both patients and physiotherapist, and (6) a ground connection to the frame of the system to avoid electrical shocks.

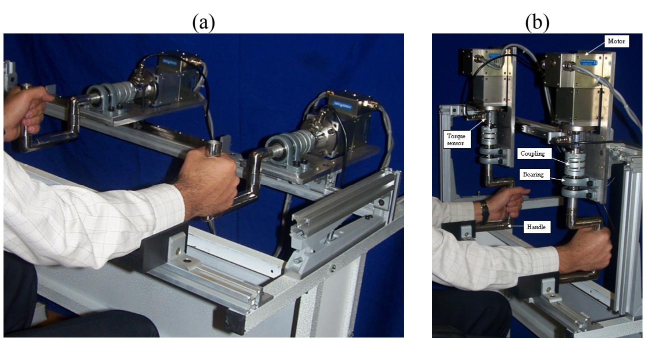

Fig. 1. The rehabilitation device and its major parts while the patient is practicing (a) pronation/supination of the forearm, (b) flexion/extension of the wrist.

B. Control Algorithm

Considering the fact that the therapeutic practices are to be regular and undisturbed, it was decided to use impedance control with real-time position and force registration. Three working modes were programmed for the device: (1) a passive mode in which the velocity and range of motion could be separately controlled, (2) an active bimanual mode in which the unaffected hand moved the paretic extremity in a mirror-image motion pattern (master/slave mode), and (3) an active mode in which each side could move independently against an adjustable resistance.

The control algorithm of the system is presented here for the second and third working modes, as the system's most challenging working modes from the control point of view. In the second working mode, the unaffected hand takes the role of the master of the system and the paretic extremity acts as the slave. The torque at the slave side was recorded and applied to the master side as a force feedback to provide a real-time dynamic sensation of the paretic hand and prevent excessive torques from being applied by the motor. A schematic of the control algorithm for this mode is presented in Fig. 2. The angular position applied by the master hand, θ_m, is registered by the encoder of the master motor, then applied to the slave motor and consequently the paretic hand with a minus sign. In this way, the paretic hand is always moved to the mirror-image angle of the master hand, θ_s. Furthermore, the torque sensor on the slave side indicates the moment exerted to the paretic hand, τ_s. This signal is used as a feedback with the algorithm shown in Fig. 2 to generate a velocity command for the master motor. The algorithm was designed so that if the absolute value of the master moment, $|\tau_m|$, monitored by the torque sensor in the master side, exceeds the absolute value of the feedback signal, $|\tau_s|$, then the master motor receives a velocity command, V_m, with a magnitude proportional to the difference of the moment signals, $|\tau_m|-|\tau_s|$, in the proper direction.

In the third working mode, each hand can practice against an adjustable resistance. Fig. 3 illustrates a schematic of the control algorithm of this working mode. The subject's hands can move only if he exerts the required reference torque, τ_R. A procedure similar to that of the former working mode generates a velocity command for the motor, V_M, while an upper limit, $V_{\max}$, is applied to keep the velocity in the safe range.

III. Results

After ensuring the safety and acceptable technical performance of the device, some preliminary clinical tests were accomplished on a female patient, in the presence of a physical therapy expert. The patient was affected from trauma on her left side with the other side relatively healthy. All the working modes were utilized during the tests; each lasted for about 45 sec. The sample results of the tests for the forearm pronation/supination practices are presented in fig. 4 to 8 with the positive direction considered counterclockwise for angular position (from the reference position of the handle) and clockwise for the torque. Fig. 4 shows the results for the angular position and applied torque of both hands in the bimanual working mode, while the patient used her healthy hand as the master. Considering the fact that

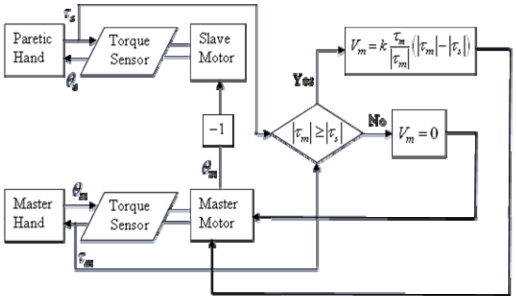

Fig. 2. Schematic diagram of the control algorithm for the bimanual working mode of the device.

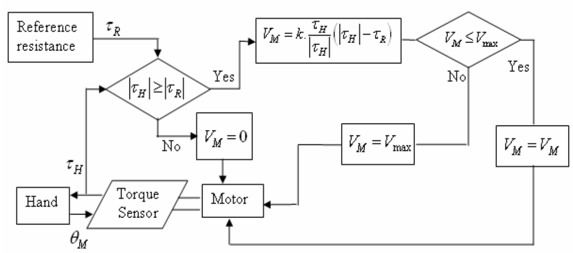

Fig. 3. Schematic diagram of the control algorithm for the active resistive mode of the device.

the rotating torque for a healthy forearm is negligible, the results revealed that the paretic hand of the patient required higher moments to produce supination movement than pronation. This indicates the more spastic pronator and the weaker supinator muscles of the patient's paretic hand. An interesting feature of the control algorithm of the active bimanual working mode of the device is also illustrated in Fig. 4. Whenever the torque sensor of the master side indicated a lower absolute value of moment than that of the slave side, the master motor did not let the master hand to continue its movements. In this way, the master hand had to generate larger torques to keep moving in the desired direction. Using this trend, the master hand could sense the real time dynamics of the slave hand in all instances of practicing with the device.

In another test of the bimanual working mode of the device, the paretic hand of the patient was set as the master and the healthy hand as the slave. The results (Fig. 5) show that the torque applied by the master hand in this situation was much lower than that of the previous test indicating the lower capability of this side to generate torques. On the other hand, the range of motion of the paretic hand was larger during pronation in comparison with supination movement. This is consistent with the results of the first test (Fig. 4) and is thought to be due to the relatively higher spasticity of pronator and the paralysis of supinator muscles. In the third test, the patient was asked to perform the supination exercise with the healthy hand while the corresponding handle was fixed. The results of the torques generated by the two hands (Fig. 6) indicated several unsuccessful efforts by the healthy hand to move the handle. However, during this period, a small torque and angular

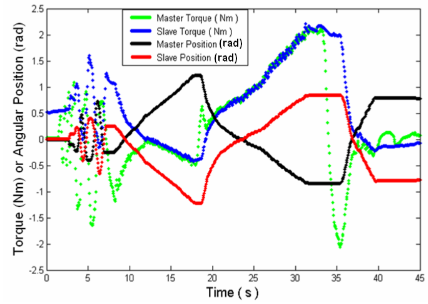

Fig. 4. The angular positions and the generated torques of the healthy (as master) and paretic (as slave) hands while practicing forearm pronation/supination movement in bimanual working mode of the device.

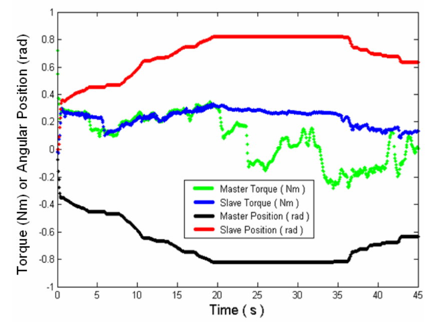

Fig. 5. The angular positions and the generated torques of the paretic (as master) and healthy (as slave) hands while practicing forearm pronation/supination movement in bimanual working mode of the device.

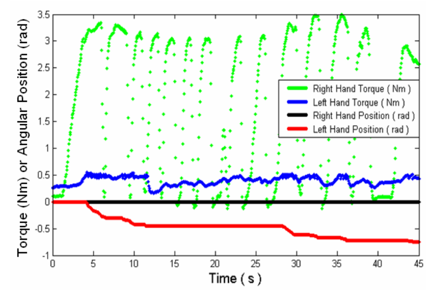

Fig. 6. The angular positions and the generated torques of both hands while patient was trying to perform supination movement with her healthy hand and the corresponding handle was fixed.

movement was observed at the paretic hand. This phenomenon called the brain irradiation effect was due to the fact that the brain signals responsible for activating the healthy hand were irradiated to the neighboring parts of the brain causing some unintentional movements at the paretic hand.

IV. Discussion

Robot-mediated rehabilitation is a rapidly emerging field that seeks to develop improved treatment procedures using new technologies such as robotics, coupled with theories in neuroscience and rehabilitation. The one DoF robotic device developed in the present study could provide unilateral and bilateral passive and active therapeutic practices with force monitoring and feedback for post stroke patients. The system was able to perform exercises in two operational states: pronation/supination of the forearm and flexion/extension of the wrist, and there working modes: passive mode, bimanual active practice, and active exercise. The selection of these working modes was based on a detailed study of the clinical literature. Passive movements without sudden tips are among the conventional mobilization techniques to improve muscle, joint and tendon mobility while reducing muscle tone [14]. Bimanual practice has been suggested to have a facilitatory effect on the paretic extremity. The consensual operation of unaffected upper limb motivates ipsilateral corticospinal projections to the paretic muscles, helping them to recover from hemiplegia. Furthermore, post stroke functional imaging studies have shown an improved activation and blood flow in the ipsilateral sensorimotor area and subsequent motor recovery for the affected extremity [15]. Finally, repetitive voluntary flexion of the affected wrist has been suggested to enhance the upper extremity's overall motor function and improve the biomechanical characteristics of the hand, including grip strength, isometric extension force and rapid isotonic wrist extension [16]. The role of the wrist joint is considered to be more significant than the other parts of the upper extremity during physical therapy process, since the motor recovery after stroke is extended more effectively from distal to proximal joints [14].

In comparison with the previous robot-mediated rehabilitation devices in the literature, e.g., the Arm Trainer robot [9], our system provides some major advantages. The modular design of the system facilitates its manufacturing and provides an appropriate basis for the future more advanced designs. The system configuration could be changed easily with minimal effort to accommodate different arthrometric characteristics of the subjects, as well as between the two operational states for the forearm and elbow rehabilitation exercises. Another main advantage of the system is the force feedback in the second working mode. This allows the level of patient interaction during the therapy tasks to be measured precisely, and his progress to be tracked quantitatively. Moreover, the force feedback provides a real-time dynamic sensation of the paretic hand in the healthy hand and prevents excessive passive manipulations. This capability is unique for our system and has not been reported for any of the previous robot-mediated rehabilitation devices in the literature [5-11].

Our robotic system, however, has only one DoF and is mechanically simpler than the more complicated two or three DoF systems, e.g., MIT-Manus and MIME [6, 7]. With this limitation, only one DoF therapeutic exercises are enabled which are far from the hand's movement patterns during daily activities. Work is in progress to design a device with two DoFs while maintaining the advanced controlling features of the present system. Such devices might be extended in future for use as home-based telerehabilitation systems to provide continuous care and therapy.

REFERENCES

[1] W. Rosamond, K. Flegal, G. Friday, K. Furie, A. Go, K. Greenlund, N. Haase, M. Ho, V. Howard, B. Kissela, S. Kittner, D. Lloyd-Jones, M. McDermott, J. Meigs, C. Moy, G. Nichol, C. J. O'Donnell, V. Roger, J. Rumsfeld, P. Sorlie, J. Steinberger, T. Thom, S. Wasserthiel-Smoller, and Y. Hong, "Heart disease and stroke statistics - 2007 Update: A report from the American Heart Association Statistics Committee and Stroke Statistics Subcommittee," *Circulation,* vol. 115, pp. e69-e171, 2007.

[2] "Post-stroke rehabilitation: assessment, referral and patient management. Post-Stroke Rehabilitation Guideline Panel. Agency for Health Care Policy and Research," *Am Fam Physician,* vol. 52, pp. 461-70, Aug 1995.

[3] H. M. Feys, W. J. De Weerdt, B. E. Selz, G. A. Cox Steck, R. Spichiger, L. E. Vereeck, K. D. Putman, and G. A. Van Hoydonck, "Effect of a therapeutic intervention for the hemiplegic upper limb in the acute phase after stroke: a single-blind, randomized, controlled multicenter trial," *Stroke,* vol. 29, pp. 785-92, Apr 1998.

[4] D. X. Cifu and D. G. Stewart, "Factors affecting functional outcome after stroke: a critical review of rehabilitation interventions," *Arch Phys Med Rehabil,* vol. 80, pp. S35-9, May 1999.

[5] M. J. Johnson, H. F. M. Van der Loos, C. G. Burgar, and L. L. J., "Driver's SEAT: Simulation environment for arm therapy," in *International Rehabilitaion Robotics*, Stanford, 1999, pp. 227–234.

[6] P. S. Lum, C. G. Burgar, and P. C. Shor, "Evidence for improved muscle activation patterns after retraining of reaching movements with the MIME robotic system in subjects with post-stroke hemiparesis," *Neural Systems and Rehabilitation Engineering, IEEE Transactions on,* vol. 12, pp. 186-194, 2004.

[7] H. I. Krebs, M. Ferraro, S. P. Buerger, M. J. Newbery, A. Makiyama, M. Sandmann, D. Lynch, B. T. Volpe, and N. Hogan, "Rehabilitation robotics: pilot trial of a spatial extension for MIT-Manus," *J Neuroeng Rehabil,* vol. 1, p. 5, Oct 26 2004.

[8] D. J. Reinkensmeyer, L. E. Kahn, M. Averbuch, A. McKenna-Cole, B. D. Schmit, and W. Z. Rymer, "Understanding and treating arm movement impairment after chronic brain injury: progress with the ARM guide," *J Rehabil Res Dev,* vol. 37, pp. 653-62, Nov-Dec 2000.

[9] 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, pp. 915-920, 2003.

[10] R. Loureiro, F. Amirabdollahian, M. Topping, B. Driessen, and W. Harwin, "Upper Limb Robot Mediated Stroke Therapy—GENTLE/s Approach," *Autonomous Robots,* vol. 15, pp. 35-51, 2003.

[11] D. J. Reinkensmeyer, C. T. Pang, J. A. Nessler, and C. C. Painter, "Web-based telerehabilitation for the upper extremity after stroke," *IEEE Trans Neural Syst Rehabil Eng,* vol. 10, pp. 102-8, Jun 2002.

[12] H. I. Volpe Bt Fau - Krebs, N. Krebs Hi Fau - Hogan, and N. Hogan, "Is robot-aided sensorimotor training in stroke rehabilitation a realistic option?."

[13] M. J. A. Prange Gb Fau - Jannink, C. G. M. Jannink Mj Fau - Groothuis-Oudshoorn, H. J. Groothuis-Oudshoorn Cg Fau - Hermens, M. J. Hermens Hj Fau - Ijzerman, and M. J. Ijzerman, "Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke."

[14] C. Bütefisch, H. Hummelsheim, P. Denzler, and K.-H. Mauritz, "Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand," *Journal of the Neurological Sciences,* vol. 130, pp. 59-68, 1995.

[15] P. M. Davies, *Steps to follow : a guide to the treatment of adult hemiplegia : based on the concept of K. and B. Bobath*. Berlin; New York: Springer-Verlag, 1985.

[16] S. C. Cramer, G. Nelles, R. R. Benson, J. D. Kaplan, R. A. Parker, K. K. Kwong, D. N. Kennedy, S. P. Finklestein, and B. R. Rosen, "A functional MRI study of subjects recovered from hemiparetic stroke," *Stroke,* vol. 28, pp. 2518-27, Dec 1997.