The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Evaluation of a Robot-assisted Rehabilitation System with Assist-As-Needed and Visual Error Augmentation Training Methods

Furui Wang[1], Duygun Erol Barkana[2], and Nilanjan Sarkar[1]
[1]*Department of Mechanical Engineering, Vanderbilt University, Nashville, TN, 37212, USA*
[2]*Department of Electrical and Electronics Engineering, Yeditepe University, Istanbul, 34755, TURKEY*
furui.wang@vanderbilt.edu, duygunerol@yeditepe.edu.tr, nilanjan.sarkar @vanderbilt.edu

Abstract: This paper presents the evaluation of a robot-assisted rehabilitation system with assist-as-needed and visual error augmentation training methods. In this robot-assisted rehabilitation system, an assistive controller provides robotic assistance to the participant as and when needed. In addition, the position errors that are visually fed back to the participant are amplified to heighten the participant's motivation to improve tracking accuracy. Experimental results on unimpaired participants are presented to demonstrate the efficacy of the enhanced rehabilitation robotic system.

Keywords: assistive controller, movement tracking training, robot-assisted rehabilitation, assist-as-needed training method, visual error augmentation training method

I. INTRODUCTION

Stroke is a highly prevalent condition [1], especially among the elderly, that results in high costs to the individual and society [2]. According to the American Heart Association (2009), in the U.S., approximately 795 000 people suffer a first or recurrent stroke each year [1]. It is a leading cause of disability, commonly involving deficits of motor function. Recent clinical results have indicated that movement assisted therapy can have a significant beneficial impact on a large segment of the population affected by stroke or other motor deficit disorders. In the last few years, robot-assisted rehabilitation for the stroke patients has been an active research area, which provides repetitive movement exercise and standardized delivery of therapy with the potential of enhancing quantification of the therapeutic process [3]-[6].

The promising results of rehabilitation robotic systems indicate that robots could be used as effective rehabilitation tools. It has been demonstrated that movement tracking training that requires cognitive processing achieved greater gains in performance than that of movement training that did not require cognitive processing [7]. Meanwhile, many models and artificial learning systems such as neural networks suggest that error drives learning, so that one can learn more quickly if the error is large [8]. Such error-driven learning processes are believed to be central to adaptation and the acquisition of skill in human movement [9], [10]. Patton *et al.* [11] have shown that visual error augmentation can improve the rate and extent of motor learning in healthy participants and also suggested that error amplification may facilitate neuro-rehabilitation strategies that restore function in brain injuries such as stroke.

In our previous work, an assistive controller was designed to provide assistance to help the participant track the desired motion accurately. It was an assist-as-needed controller [12]-[14]. In this work, the visual error augmentation training method is integrated to the robot-assisted system in order to improve the training performance. The performances of the participants trained with new training methods are evaluated to demonstrate the efficacy of the enhanced robot-assisted system.

This paper is organized as follows. It first presents the proposed rehabilitation robotic system in Section 2. The methodology section (Section 3) includes task description, the assistive controller, decision logic for robotic assistance and the concept of error augmentation. Experimental results and analysis are presented in Section 4. Section 5 discusses the potential contributions of this work and possible future research directions.

II. THE REHABILITATION ROBOTIC SYSTEM

A PUMA 560 robotic manipulator is used as the main hardware platform in this work. The manipulator is augmented with a force-torque sensor and a hand attachment device (Fig. 1).

In order to record the force and torque applied by the human, an ATI Gamma force/torque sensor is used. The robot is interfaced with Matlab/Real-time Workshop to allow fast and easy system development. The force values recorded from the force/torque sensor are obtained using a National Instruments PCI-6031E data acquisition card with a sampling rate of 1000Hz. The joint angles of the robot are measured using encoder and received through by a Measurement Computing PCIQUAD04 card with a 1000Hz sampling rate. The torque output to the robot is provided by a Measurement Computing PCIM-DDA06/16 card with the same sample rate. A computer monitor is placed in front of the participant to provide visual feedback about his/her motion trajectory during the execution of the task.

We design a hand attachment device where the participant's arm is strapped into a splint that restricts wrist and hand movement. The PUMA 560 is attached to the splint to provide assistance to the upper arm movement using the assistive controller (Fig. 1). Forearm padded aluminum splint (from MooreMedical), which ensures the participant's comfort, is used as a splint in this device. A steel plate is designed with proper grooves that hold two small flat-faced electromagnets (from Magnetool Inc.) that are screwed on it. This plate is also screwed with the force-torque sensor to provide a rigid connection with the robot. A light-weight steel plate is attached under the splint, which is then attached to the electromagnets of the plate. These electromagnets are rated for continuous duty cycle (100%

duty cycle), i.e., they can run continuously at normal room temperature. Pull ratings of these magnets are 40lb. Two electromagnets are used to generate a larger pulling force to keep the splint attached to the hand attachment device. An automatic release (AU) rectifier controller (Magnetool Inc.) has been used to provide a quick, clean release of these electromagnets. A push button, which has been connected to the AU Rectifier Controller, is used to magnetize and demagnetize the electromagnets when the participant wants to remove the hand attachment device from the robotic manipulator in a safe and quick manner.

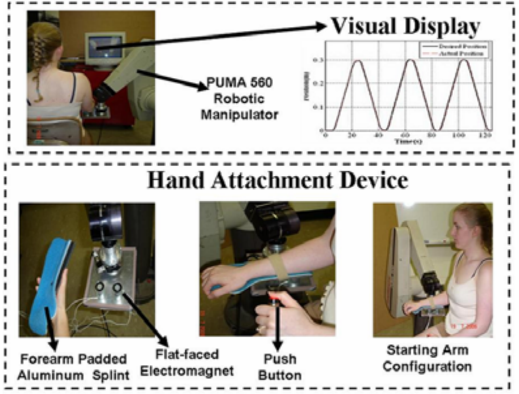

Fig. 1 Participant Arm attached to Robot

Ensuring safety of the participant is a very important issue when designing a rehabilitation robotic system. Thus, in case of emergency situations, therapist can press an emergency button. The patient and/or the therapist can quickly release the patient's arm from the PUMA 560 by using the quick-release hand attachment device to deal with any physical safety related events. In order to release the participant's arm from the robot, the push button is used. When the push button is pressed by patient /therapist electromagnets are demagnetized instantaneously and the participant is free to remove the splint from the robot.

III. METHODOLOGY

The objectives of the current work are to: i) design an upper arm movement rehabilitation task that requires cognitive processing as well as could contribute to a variety of functional daily living activities; ii) design a controller to provide robotic assistance to help participants perform the designed movement rehabilitation task; iii) integrate the controller with visual error augmentation training method to amplify the participant' tracking errors. We present the basic design of the task, the assistive controller and the concept of visual error augmentation training method in this section.

A. Task Design

We choose a reaching task that is commonly used to increase the active range of motion (AROM) in shoulder and elbow in preparation of later functional reaching activities in rehabilitation of upper extremity after stroke. In this task, participants are asked to move their arms in the forward direction to reach a desired point in space and then bring it back to the starting position in a repetitive manner. We ask the participants to follow a visually presented desired position trajectory which is likely to command their concentration. The motion of the arm is constrained in the horizontal plane and in one direction (along the Y-axis), moving forward and backward. The idea here is to improve the ability of participant's arm movement in one direction at a time by helping him/her improve his/her ability to complete a desired reaching task, which is an important everyday activity. The position trajectory that the participant is required to track is a minimum-jerk trajectory.

B. Controller Design

The assist-as-needed controller designed in this work is responsible for providing robotic assistance to a participant to complete the movement tracking task in the task-space in an accurate manner. In this controller, an outer force feedback loop is designed around an inner position loop (Fig. 2). The tracking of the reference trajectory is guaranteed by the inner motion control [15]. The desired force, which is given as a force reference to the controller, is computed by a planner. The proposed controller is similar to an impedance controller; however it allows specifying the reference time-varying force directly.

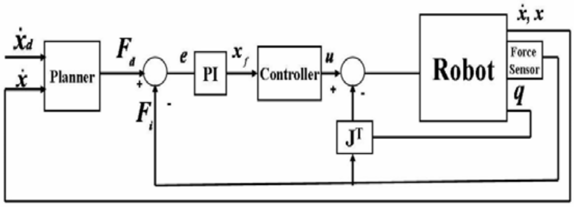

Fig. 2 Robotic Assistive Controller

The control input u to the manipulator is designed as follows:

$$u = M(q)y + V(q,\dot{q}) + G(q) + J^T F \tag{1}$$

where $M(q)$ represents the inertia matrix, $V(q,\dot{q})$ is the summation of the matrix of Coriolis torques $Co(q)(q,\dot{q})$ and centrifugal torques $Ce(q)\left|\dot{q}^2\right|$, $G(q)$ is the vector of gravity torques, $J(q)$ is the Jacobian matrix and F is the contact force exerted by the manipulator. $\mathrm{y} = \ddot{q}$ represents a new input. The new control input y is designed so as to allow tracking of the desired force F_d. To this purpose, the control law is selected as follows:

$$y = J(q)^{-1} M_d^{-1}(-K_d\dot{x} + K_p(x_f - x) - M_d\dot{J}(q,\dot{q})\dot{q}) \tag{2}$$

where x_f is a suitable reference to be related to force error. M_d (mass), K_d (damping) and K_p (stiffness) matrices specify the target impedance of the robot. x and $\dot{x}$ are the position and velocity of the end-effector in the Cartesian coordinates, respectively. The relationship between the joint space and the Cartesian space acceleration is used to determine position control equation.

$$\ddot{\mathrm{x}} = J(q)\ddot{q} + \dot{J}(q,\dot{q})\dot{q} = J(q)y + \dot{J}(q,\dot{q})\dot{q} \tag{3}$$

By substituting (2) into (3), we obtain

$$M_d\ddot{x} + K_d\dot{x} + K_p x = K_p x_f \tag{4}$$

Equation (4) shows the position control tracking of x with dynamics specified by the choices of K_d, K_p and M_d matrices. Impedance is attributed to a mechanical system characterized by these matrices that allows specifying the dynamic behavior. Let F_d be the desired force reference, which is computed using a PID velocity loop:

$$F_d = P_d(x_d - x) + I_d \int (x_d - x)dt + D_d(d(x_d - x)/dt) \tag{5}$$

where x_d , x , P_d , I_d and D_d are the desired position, actual position, the proportional, integral and derivative gains of the PID position loop, respectively. The relationship between x_f and the force error is expressed in (6) as:

$$x_f = P(F_d - F_i) + I\int (F_d - F_i)dt \tag{6}$$

where P and I are the proportional and integral gains, respectively, and F_i is the force applied by the human. Equations (4) and (6) are combined to obtain below equation:

$$M_d\ddot{x} + K_d\dot{x} + K_p x = K_p(P(F_d - F_i) + I\int (F_d - F_i)dt) \tag{7}$$

From (8), the desired force response is achieved by controlling the position of the manipulator.

C. *Decision of Robotic Assistance during Task Execution*

During the tracking task, friction and gravity compensation are always activated in order for the participant to move the robot along with his/her arm in an effortless way. The activation of the controller to provide robotic assistance is decided based on the participant's actual position *x(t)*. First, the desired trajectory x_d is decided and then the acceptable position band (Fig. 3) with the upper bound x_{upper} and the lower bound x_{lower} are calculated as

$$x_{upper} = x_d + (x_d * percentage),\ x_{lower} = x_d - (x_d * percentage) \tag{8}$$

where *percentage* is a predefined value used to increment and decrement the desired position to define the upper and lower bounds for the selected position trajectory. In order to define the position trajectories x_d, a generator block using Matlab/Simulink Blockset is developed. This block generates minimum-jerk position and velocity trajectories with a specified distance, maximum velocity and acceleration using user defined function. If the actual position *x(t)* lies within the acceptable band, then the participant is considered to be able to track the trajectory without robotic assistance. If the actual position x is not between the upper bound x_{upper} and the lower bound x_{lower} , then the assistive controller is activated to provide assistance to bring the participant's position back into the desired range. However, note that any participant will require a certain amount of time (settling time) to generate the desired motion, so the controller should not be activated until it is determined that the participant is not able to generate the required motion by his/her own effort. Thus, we calculate the average values of the participant's actual position x_{ave} (as opposed to instantaneous position), the upper bound x_{upper}, and lower bound x_{lower} in a given time interval (which are used to decide if the robotic assistance is needed) as

$$x_{ave} = \frac{t_s}{(t_f - t_i)}\sum_{t=t_i}^{t_f} x(t),\ \ x_{lower\_ave} = \frac{t_s}{(t_f - t_i)}\sum_{t=t_i}^{t_f} x_{lower}(t),$$
$$x_{upper\_ave} = \frac{t_s}{(t_f - t_i)}\sum_{t=t_i}^{t_f} x_{upper}(t) \tag{9}$$

where t_f , t_i and t_s are the final time, starting time and sampling time, respectively. x_{ave} is the participant's actual position at time *t*.

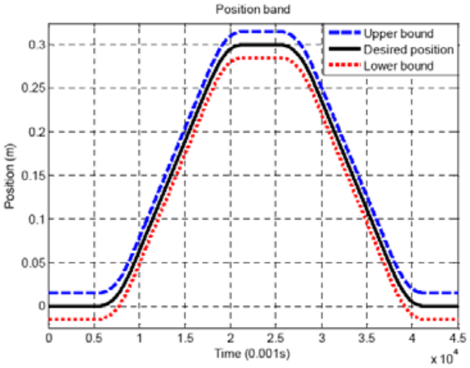

Fig. 3 Position Trajectory band

If Condition I: $x_{lower\_ave} < x_{ave} < x_{upper\_ave}$ is satisfied, then the assistive controller is not activated and participant continue the tracking task without robotic assistance. If condition is not satisfied, then the controller is activated to provide robotic assistance.

D. *Switching Mechanism*

Note that the assistive controller will be switching on and off to provide robotic assistance. In order to ensure smooth switching, a switching mechanism that we have previously presented to guarantee bumpless switching for satisfactory force response [12]-[14] is used in this work. This mechanism modifies the position reference, which is the input for the inner loop of the assistive controller, at the time of the switching in such a way that it is equal to the position reference at the time before switching occurs. The control action in (6) can be modified as below:

$$x_{fp}(t) = x(t),\ x_{ff}(t) = P * e(t) + I * (x_i(t) + x_{io}) \tag{10}$$

where $x_{fp}(t)$ is the position reference when the assistive controller is not active, which is equal to the current position of the human/robot *x(t)*. $x_{ff}(t)$ is the position reference determined using the *P* and *I* gains when controller is active. $x_i(t)$ represents the integral action $\int (F_d - F_i)dt$, and x_{io} is the initial condition of the error integrator. *e(t)* is the force error defined as $F_d - F_i$. If t_s is the time of switching, the position reference just before and after the time of switching can be found using (11), respectively:

$$x_{fp}(t_s^-) = x(t_s^-),\ x_{ff}(t_s^+) = P * e(t_s^+) + I * (x_i(t_s^+) + x_{io}) \tag{11}$$

where t_s^- is moment just before the switching occurs, t_s^+ is the moment just after the switching occurs. The integral action associated with the assistive controller is reset during the switching so $x_i(t_s^+) = 0$. The initial condition of the integrator is set as $x_{io} = x(t_s^-)/I$. The force error $e(t_s^+)$ is set to zero just after the time of the switching so $P * e(t_s^+) = 0$. When these conditions are substituted in (11), we get (12). (12) ensures that the position reference is indeed continuous during switching, which guarantees bumpless activation and deactivation of the controller.

$$x_{ff}(t_s^+) = x_{fp}(t_s^-) \tag{12}$$

E. *Visual Error Augmentation*

In the literature, it has been shown that visual error augmentation method makes small errors more noticeable to the participant, which will motivate the participant and trigger him/her to make faster response to correct the error. Faster response may lead to larger changes in performance. Additionally, amplified error can also increase signal-to-noise ratios which may improve cognitive processing and self-evaluation. It has been previously verified that training performance of the patients had been improved only when the original errors had been magnified, but not when the errors were reduced or absent [11]. Hence error amplification training may be an effective way to promote functional motor recovery for people after stroke. However, it is important to select the proper gain K in error amplification. If the gain is too small, the effect of error augmentation will be quite limited; if the gain is too large, it is possible that the motor-sensory learning will become unstable, which may cause sensor inaccuracy, over-correction and other uncertainties, and even draw frustration and anxiety in the participants.

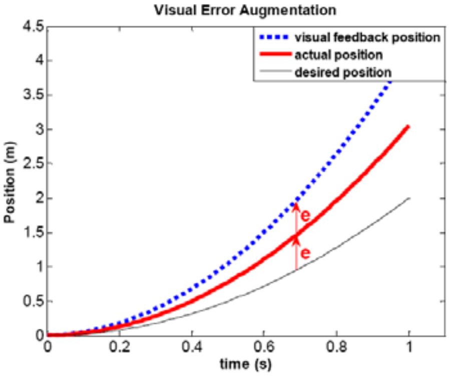

Fig. 4 Illustration of the Visual Error Augmentation

In this work, the gain is selected as *2,* which is shown to lead the best experimental result in [11]. A gain of 2 means any deviation from the desired trajectory will be displayed twice as much distance from the desired trajectory (Fig. 4). The participant's performance is expected to be better when visual error augmentation method is used. However, for stroke patients, it may still happen that the patient is not capable of completing the task by himself/herself. In this case, the assistive controller described in the previous section will be activated so that robot will help the patient back into to the acceptable band and continue the task. Note that the errors fed back to the assistive controller are not amplified, which guarantees the robotic system works in an accurate manner.

IV. EXPERIMENT AND RESULTS

In this section we present the experimental procedure and the results of the experiments with unimpaired participants.

A. *Experiment Procedure*

Participants were seated in a height adjustable chair as shown in Fig. 1 (top left) and asked to place their forearm on the hand attachment device as shown in Fig. 1 (bottom left) when the starting arm configuration was fixed. The height of the PUMA 560 robotic manipulator was adjusted for each participant to start the tracking task in the same arm configuration. The starting arm configuration was selected as shoulder at neutral 0º position and elbow at 90º flexion position. The task required moving the arm in forward flexion to approximately 60º in conjunction with elbow extension to approximately 0º and then coming back to starting position. The release button of the hand attachment device was given to the participants in case of emergency situations during the task execution (Fig. 1- bottom middle). The participants received visual feedback of the task trajectories and their own position trajectories on a computer monitor in front of them (Fig. 1-top right).

We conducted two experiments to evaluate the proposed robot-assisted rehabilitation system with the enhanced assistive controller. In both experiments, the participants used their non-dominant arms to perform the task. It was done in order to create imperfect tracking condition so that the robotic training has some room to effect improvement. In the first experiment, the aim was to evaluate the efficacy of the system with the assist-as-needed training method only. Participants were required to perform the tracking task with the robotic assistance but without the visual error augmentation training. In the second experiment, the aim was to evaluate the efficacy of the system when the visual error augmentation training method was integrated. As our purpose of this research is to apply the robot-assisted rehabilitation system to stroke patients who are not likely to complete the task by their own effort, robotic assistance was also made available in the second experiment.

For safety consideration, we chose relatively small PI gains (*0.0001* for P, *0.0004* for I) for the assistive controller, which gave a conservative amount of force to the participant, avoiding jerk motion and rough push in his/her arm. These gains had been tested in our previous paper [16].

B. *Results and Data Analysis*

Two female and four male participants within the age range of 25-35 years took part in the two experiments described in above. All of them were right-handed persons. The total distance and the maximum velocity of the task were customized to meet each participant's motor ability and physical configuration. The maximum acceleration was *0.008*m/s^2. These task parameters were chosen in consultation with a physical therapist who works with stroke patients at the Vanderbilt Stallworth Rehabilitation Hospital. Table 1 showed task parameters which were used to generate an appropriate tracking task for each participant.

Table 1 Task Parameters for Each Participant

Participant	Gender	Distance (m)	V_{max} (m/s)
P1	Male	0.25	0.02
P2	Male	0.3	0.02
P3	Female	0.25	0.02
P4	Male	0.25	0.025
P5	Female	0.25	0.02
P6	Male	0.3	0.025

Once these task parameters were defined, x_d, $\dot{x}_d$, x_{upper} and x_{lower} trajectories were generated by reference blocks. The acceptable error band range was set as $\pm 5\,\%$. The position information x_{ave}, x_{upper_ave}, and x_{lower_ave} were calculated every 4 seconds using (9). Condition I was checked to decide the activation of the assistive controller. The idea of the assistive controller was to assist the participants as and when the patients were out of the position band, and bring them back into the acceptable position band.

For each experiment, participants were asked to execute the tracking task 25 times, which were grouped into 5 training groups. Thus the participant performed the required task 5 times in each training group without break. Between two training groups, the participant took a 3-5 minutes break. Additionally, two experiments were conducted with at least 7 days interval to wash out participants' motor adaptation to the task and any other habituation effect. Before each experiment, the participant took part in a trial practice to get a basic understanding of the task. After the second experiment, the participant took part in an extra practice without error augmentation to wash out the possible sensory-motor distortion.

Fig. 5 showed a segment of the position error trajectory of Participant 4 in Experiment 1. It could be seen that when the average of position error in a period (*4s*) was out of band, the controller trigger was turned on, robotic assistance was activated and brought the participant's position back into the acceptable range within one period time.

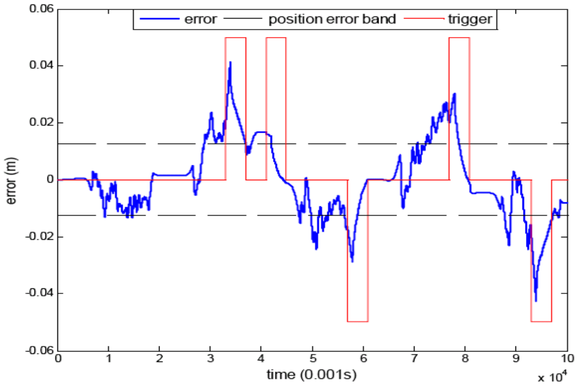

Fig. 5 Position Error during Robotic Assistance for Participant 4

We recorded the number of times that each participant needed robotic assistance to complete the task in two experiments. Fig. 6 demonstrated the number of assistance participant needed when robotic assistance was provided without visual error augmentation training method. Fig. 7 demonstrated the number of assistance participant needed during the execution of the task when both robotic assistance and visual error augmentation training method were used. It could be seen from Fig. 6 and 7 that the number of times of assistance needed for each participant decreased from Training 1 to Training 5, which implied that the participant was getting better in completion of the task by himself/herself after trainings. Thus both training methods were efficient in improving participants' tracking performance.

When the two experiments were compared, it was clear that in Experiment 2, the participant needed less assistance compared to Experiment 1, which indicated that the visual error augmentation training method had greatly improved the performance of the participants (Fig. 8). The decrease was statistically significant (p-value<0.001, paired t-test).

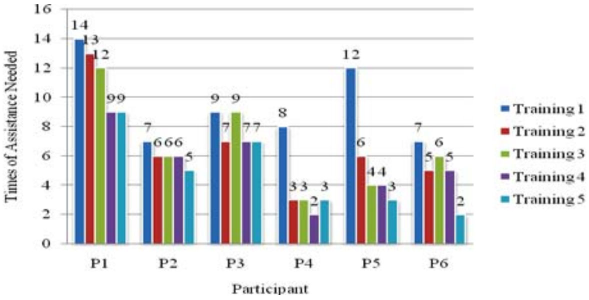

Fig. 6 Results of Experiment 1

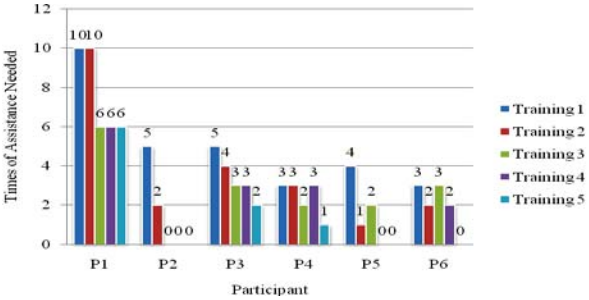

Fig.7 Results of Experiment 2

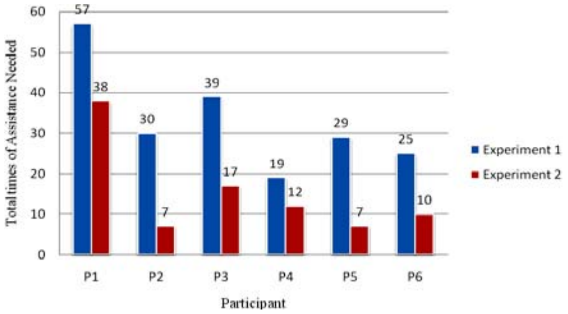

Fig. 8 Results Comparison of Two Experiments

We also calculated the means and standard deviations (S.D.) of absolute position error values for each participant in two experiments (Table 2). The mean errors and standard deviations in Experiment 2 were much smaller than those in Experiment 1 (p-value<0.004, paired t-test), which meant that more accurate tracking performances were achieved by participants in Experiment 2. These results demonstrated that visual error augmentation in conjunction with assist-as-needed training method could enhance the efficacy of the robotic rehabilitation system.

Table 2 Mean and Standard Deviation (S.D) in Position Errors

	Original		Experiment 1		Experiment 2	
	Mean (m)	S.D. (m)	Mean (m)	S.D. (m)	Mean (m)	S.D. (m)
P1	0.011069	0.009511	0.011291	0.009816	0.009495	0.009530
P2	0.00610	0.003934	0.008272	0.008279	0.004616	0.005251
P3	0.00892	0.008818	0.009019	0.009153	0.005772	0.005943
P4	0.00664	0.006302	0.006616	0.006508	0.004729	0.005304
P5	0.00514	0.004111	0.007617	0.007409	0.004433	0.004840
P6	0.00619	0.005548	0.006382	0.007152	0.005282	0.006905

It should be noted that Participant 2 and Participant 5's performance in Experiment 1 with robotic assistance were not as good as their original performance. This was because the gains chosen for the assistive controller were relatively conservative to avoid jerky motion and rough pushing force in the participant's arm when considering the safety of stroke patients in future application. However, participants in the experiments were healthy people and they might be more capable to correct their own position errors than what the robot could with low control gains. In other words, their original performance might be better than the performance with the help of robotic assistance. To improve the efficacy of robotic assistance for Participant 2 and Participant 5, PI control gains were selected as 0.0002 for P, 0.0007 for I and the experiments were conducted again. The results showed that robotic assistive controller with new control gains could provide sufficient assistance to these participants to achieve a good task performance (Table 3). The proper PI gain selection for the assistive controller for different participants was presented in our previous work [16].

Table 3 Position Errors with Assistive Controller with New PI Gains

Participant	Mean Error (m)	S.D. (m)
P2	0.006214	0.005130
P5	0.005139	0.004370

V. DISCUSSION AND CONCLUSION

In this work, a rehabilitation robotic system with assist-as-needed and visual error augmentation training methods has been presented. Integration of assist-as-needed and visual error augmentation training methods in a robot-assisted rehabilitation system is an important enhancement because recent research reveals that both assist-as-needed training and visual error augmentation training when applied individually can improve the efficacy of robot-assisted movement training [11], [17], [18]. It is of our great interests to develop a robotic system that combines both training methods which may lead to better rehabilitation training performance.

The enhanced robotic system is evaluated with unimpaired participants in two experiments. The results have demonstrated that: 1) the assistive controller can provide robotic assistance to participants as and when needed, and is able to bring the participants' position back to the acceptable range quickly; 2) in both experiments, participants have shown improvements to complete desired tasks after trainings; 3) the total number of times of robotic assistance needed by each participant has significantly decreased in Experiment 2, which means the participant becomes more capable of executing the task, when visual error augmentation training has been integrated in the rehabilitation system; 4) the participants' tracking performances are more accurate (smaller average position errors) after visual error augmentation method has been integrated inside the assistive controller; 5) By choosing proper PI gains, the assistive controller provides smooth and sufficient robotic assistance to different participants. As a result, we could suggest that introducing performance based training methods, such as assist-as-needed and visual error augmentation, will greatly improve the efficacy of robot-assisted rehabilitation system.

As a future work, new technique, which can automatically choose the proper controller gains of the robotic assistive controller, will be developed so that participants can achieve a better training performance in assist-as-needed training method. Different error amplification gains will be tested to obtain a comprehensive understanding of visual error augmentation training method.

ACKNOWLEDGMENT

We gratefully acknowledge the support provided by the following NIH grants to perform this research: R24HD050821 and 5 R21HD055478-02 from the Eunice Kennedy Shriver National Institute of Child Health & Human Development. We also gratefully acknowledge the help of Dr. Thomas E. Groomes, the Medical Director of Spinal Cord and Traumatic Brain Injury Program, and the occupational therapist Sheila Davy of Vanderbilt University's Stallworth Rehabilitation Hospital for their feedback about task design. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

REFERENCES

[1] American Heart Association, "Heart and Stroke Statistical Update", http://www.Americanheart.org/statistics/stroke.htm, 2009.

[2] Matchar D.B., Duncan P.W., "Cost of stroke", *Stroke Clin Updates*, 5, 9-12 (1994).

[3] Kahn L.E., Zygman M.L.Rymer W.Z, Reinkensmeyer D.J, "Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: a randomized controlled pilot study", *J. of NeuroEngineering and Rehabilitation,* 3(12), 1-13 (2006).

[4] Lum, P.S.; Burgar, C.G.; Van der Loos, H.F.M.; Shor, P.C.; Majmundar M.; Yap R. "MIME robotic device for upper-limb neurorehabilitation in subacute stroke subjects: A follow-up study", *J. of Rehab. Research & Development,* 43(5), 631-642 (2006).

[5] Krebs H. I, Ferraro M., Buerger S.P, Newbery M. J., Makiyama A., Sandmann M., et al., "Rehabilitation robotics: pilot trial of a spatial extension for MIT-Manus", *Journal of NeuroEngineering and Rehabilitation*, 1(5), 1-15, (2004).

[6] Loureiro R., Amirabdollahian F., Topping M., Driessen B., Harwin W. "Upper limb mediated stroke therapy-GENTLE/s approach", *Autonomous Robots*, 15, 35-51 (2003).

[7] Carey, J.R.; Bhatt, E. & Nagpal, A., "Neuroplasticity Promoted by Task Complexity", *Exercise and Sport Science Review*, 33, pp. 24-31.

[8] D. E. Rumelhart, G. E. Hinton, and R. J. Williams, "Learning representations by back-propagating errors", *Nature (London)*, vol. 323, pp. 533-536, 1986.

[9] M. Kawato, "Feedback-error-learning neural network for supervised learning", *Advanced neural computers,* R. Eckmiller, Ed. Amsterdam: North-Holland, 1990, pp. 365-372.

[10] D. M. Wolpert, Z. Ghahramani, and M. I. Jordan, "An internal model for sensorimotor integration", *Science*, vol. 269, pp. 1880-2, 1995.

[11] Yejun Wei, Preeti Bajaj, Robert Scheidt, and James Patton, "Visual Error Augmentation for Enhancing Motor Learning and Rehabilitative Relearning", *Proceedings of the 2005 IEEE Intl. Conf. on Rehabilitation Robotics*, 2005

[12] D. Erol and N. Sarkar, "Design and Implementation of an Assistive Controller for Rehabilitation Robotic Systems", *Intl. Journal of Advanced Robotic Systems*, Vol. 4, No. 3 (2007), pp. 271-278

[13] D. Erol and N. Sarkar, "Intelligent Control for Robotic Rehabilitation after Stroke", *Journal of Intelligent and Robotic Systems*, vol. 50, no.4, pp. 341-360, December 2007.

[14] D. Erol and N. Sarkar, "Coordinated Control of Assistive Robotic Devices for Activities of Daily Living Tasks", *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol.16, no.3, pp. 278-285, June 2008.

[15] Sciavicco, L. & Siciliano, B., *Modeling and Control of Robot Manipulators*, McGrawHill, 1996

[16] D. Erol and N. Sarkar, "Smooth Human-Robot Interaction in Robot-Assisted Rehabilitation", *IEEE 10th Intl. Conf. on Rehabilitation Robotics*, ICORR 2007, 11-15 May 2007, pp. 5-12.

[17] Kahn LE, Lum PS, Rymer WZ, Reinkensmeyer DJ. "Robot-assisted movement training for the stroke-impaired arm: Does it matter what the robot does", *J Rehabil Res Dev,* 2006; 43: 619-30.

[18] Hogan N, Krebs HI, "Interactive robots for neuro-rehabilitation. Restor", *Neurol Neurosci,* 2004;22(3–5):349–58.