Development of an Upper Limb Master-Slave Robot for Bimanual Rehabilitation

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***Abstract*—Most activities in daily life involve the use of both hands. Post-stroke patients lose inter-limb coordination and require intensive rehabilitation therapy for a faster recovery. Robot based rehabilitation is preferred to traditional rehabilitation methods due to precise repeatability and the accurate measurements it provides. Bimanual rehabilitation robots can help the patient to keep the position symmetry. Most studies in rehabilitation robots have overlooked the necessity of accurate resistance training. Conventional rehabilitation methods cannot ensure position synchronization during rehabilitation. In order to realize resistance training with maximum efficiency, the resistance should be varied with a reference to a strength profile of a healthy person. This paper presents a master slave robot system designed for bimanual rehabilitation training. Disturbance OBservers (DOB) are implemented to make the system robust. Accurate force sensing is achieved using the Reaction Torque OBserver (RTOB). The paper also presents a method for seamless transfer between the resistance and assistance modes. The proposed methods were validated by experiments.**

***Keywords*—Rehabilitation; Medical Robotics; Torque Control; Disturbance Observer; Reaction Torque Observer**

I. Introduction

Stroke is one of the major causes which results in long term disabilities [1]. Prolonged rehabilitation is essential for the patients to regain functional abilities. Studies suggest that early rehabilitation has the benefit of early recovery [2]. However, the therapists' attention to the patients vary depending on the number of the patients that they may handle simultaneously. Rehabilitation robots are becoming popular as they help the therapists to reduce their fatigue and could give more attention for patients compared to the conventional rehabilitation process. It is said that robots could improve patients' motor control better than conventional therapy [3]. They also provide greater repeatability of the motion exercises and also provide measurable data for reviewing the patient's progress [4]. Research studies mention that 30%-66% stroke patients are able to walk again but unable to recover the functionality of the arm [5].

Bimanual coordination is used in many situations where the brain controls both sides of the body simultaneously to accomplish a task. Coordination between arms is an effortless activity which is done by everyone in everyday life. However, the loss of functionality in one arm is considered significant as human body is naturally designed to handle objects bimanually with inter-limb coordination. Stroke survivors often end up with one sided paralysis (hemiparesis) or lose motor control and find simple day to day tasks very difficult to do. A patient with hemiparesis may find it more challenging to maintain balance when lifting an object with both arms or to drive a car. Research studies suggest that bimanual rehabilitation therapy has potential benefits in upper limb recovery [6], [7]. Bimanual rehabilitation requires increased brain activity. Symmetrical movements in bimanual training may activate the unimpared hemisphere and help the activation of the impaired hemisphere [8]. Therefore it boosts neuroplasticity.

Resistance training is one of the important rehabilitation exercise method for stroke patients. Studies with chronic stroke patients suggest resistance training for early and robust enhancement of the muscle function and performance [9]. In another study it has been shown that high intensity resistance training in the non paretic limb induces muscle activation and gains in strength of the untrained limb [10]. In traditional resistance training the patient is asked to hold a dumbbell by his hemiparetic arm and the therapist will assist as needed. The main disadvantage of this approach is that the patient gets to use the bio-mechanical advantage at some angles and therefore rehabilitation is not efficient. Several studies suggest that high intensity training does improve both paretic and nonparetic limbs of post-stroke patients [11]. The maximum torque that elbow can generate vary throughout the range of motion of the elbow [12]. The resistance cannot be varied with the joint angle in traditional rehabilitation. Variable cam exercise machines are designed to match the human torque profile, but they are not matched effectively [13].

Usually the rehabilitation robots designed for bimanual rehabilitation allows the patient to move the hemiparetic arm using the non paretic arm and feel the torque response of the hemiparetic arm through the non paretic arm using a master slave robot system [14]. This provides the patient extra confidence and safety. These robots can assist and resist patient's motion. It may also help to improve brain neuroplasticity. However, non of the rehabilitation robots are designed to improve the patients' elbow strength profile similar to healthy person. If the resistance torque profile is similar to a healthy human elbow joint torque profile, the maximum resistance torque will be applied at each angle leading to an effective rehabilitation.

Therefore the best option is to program a robot to change impedance according to the human torque profile which is a

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TABLE I. NOMENCLATURE

Parameter	Description
J_n	Nominal inertia of the robot
J	Actual inertia of the robot
J_m	Nominal inertia of the master robot
J_s	Nominal inertia of the slave robot
k_{tn}	Nominal torque constant
k_t	Actual torque constant
I_m^{ref}	Master current reference
I_s^{ref}	Slave current reference
B	Viscous friction coefficient of the robot
F_S	Static friction of the robot
$\widehat{t}_{dis}$	Estimated disturbance torque
$\widehat{t}_{rec}$	Estimated reaction torque
g_{dis}	Disturbance torque observer gain
g_{rec}	Reaction torque observer gain
θ_m	Master robot angle
θ_s	Slave robot angle
$G(\theta_m)$	Gravity torque of the master robot
$G(\theta_s)$	Gravity torque of the slave robot
P	Proportional gain
k_s	Spring constant

function of the elbow angle. To accomplish effective bimanual rehabilitation, it is intuitive for the bimanual robot system to simultaneously provide high impedance elbow strength profile when the patient is able to perform the movement and to reduce the impedance when the patient absolutely necessitates assistance in order to keep the positions of the arms coordinated.

In this paper, a novel bimanual rehabilitation robot is developed to rehabilitate the elbow with a reference to a healthy human torque profile. Therefore the generated elbow torque of the patient will vary similar to a healthy person. When the patient is unable to provide the resistance torque the robot will reduce the impedance to assist the patient. The whole process is implemented to be autonomous with a simple method. Accurate force sensing is achieved by using a sensorless method called the Reaction Torque OBserver (RTOB) [15]. The use of RTOB is advantageous since it has a higher bandwidth compared to conventional force sensors. Using RTOB does not add weight to the system whereas conventional force sensors does add weight which is usually not accounted for during design of the system. Conventional force sensors also use soft materials and therefore has a limited bandwidth whereas bandwidth of the RTOB can be set high and it's accuracy is a function of the sampling time.

II. MODELLING

A. Overview

The bimanual rehabilitation system presented in this work consists of two 1-DOF (Degree of Freedom) robots configured as a master-slave system. The CAD models of the robots are shown in Figure 1. The master robot is used by the patient's non-paretic arm and the slave exoskeleton is used by his/her hemiparetic arm. Both robots are designed with adjustable length mechanisms to accommodate various patients. The system is actuated with Permanent magnet DC (PMDC) motors. The nomenclature is presented in Table I. The subscripts m and s denotes the master and slave robots respectively.

The elbow torque profile data presented in [12] was modelled with polynomials for flexion and extension motions as shown in (1) and (2) respectively where θ is the angle in

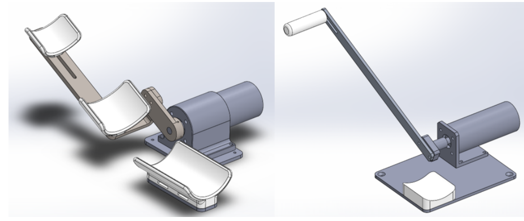

Fig. 1. CAD model of the system. Left-Slave, Right-Master

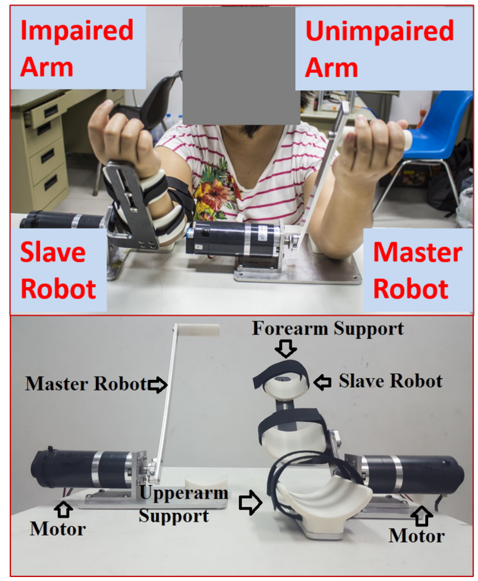

Fig. 2. Bimanual training system with patient

degrees. The torque profile polynomials are plotted in the Figure 3.

$$f_F(\theta) = -0.00006\theta^3 + 0.0045\theta^2 + 0.3899\theta + 65.208 \quad (1)$$

$$f_E(\theta) = 0.00002\theta^3 - 0.0161\theta^2 + 1.7082\theta + 68.921 \quad (2)$$

B. Sensorless Force Sensing

The classic DC motor model is shown in Figure 4. T_{dis} is the total disturbance torque acting on the system. It consists of the external torque applied to the robot, friction forces of

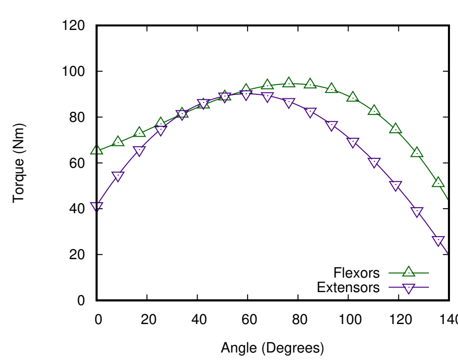

Fig. 3. Elbow strength profile

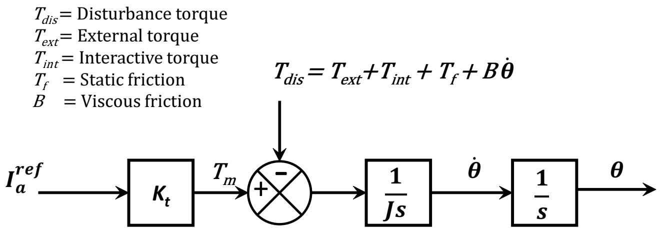

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Fig. 4. DC motor model

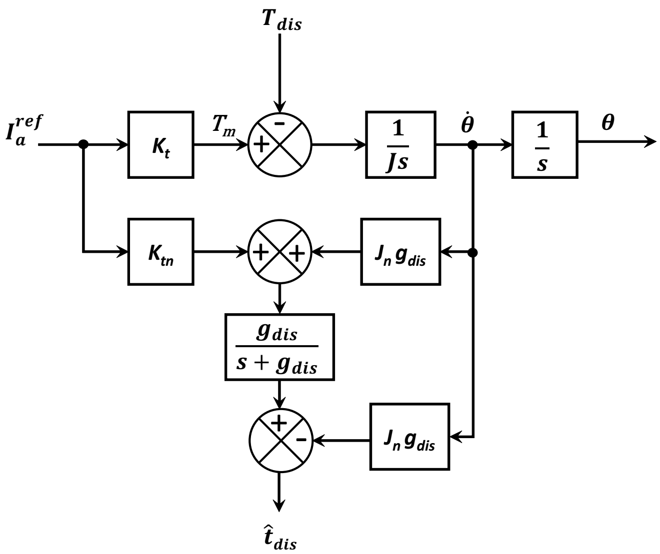

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Fig. 5. Disturbance Observer

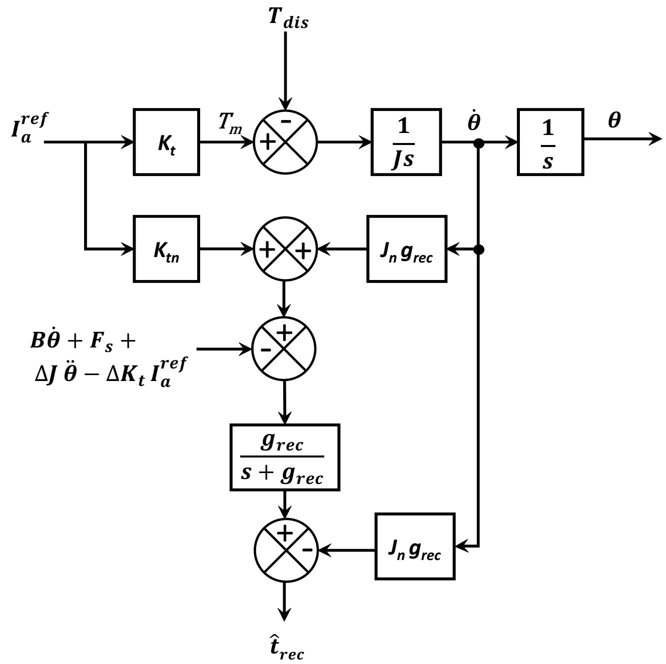


Fig. 6. Reaction Torque Observer

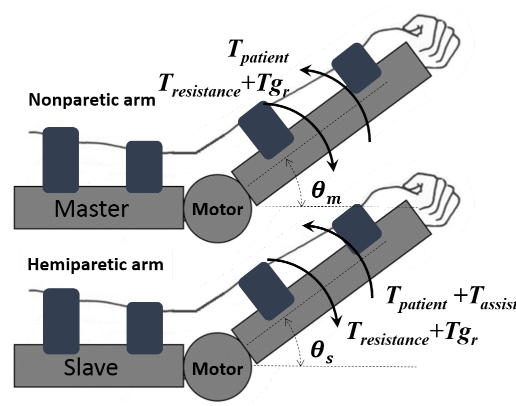


Fig. 7. Bimanual rehabilitation system

the robot and the interactive torque. The external torque is the torque that patient will apply to the robot. The interactive torque T_{int} is zero for single degree of freedom robots [16]. T_{dis} can be estimated using a disturbance observer as shown in Figure 5. During the flexion exercise, the disturbance torque of the master robot estimated by the DOB can be modelled as in (3).

$$t_{dis_m} = T_{patient} - Tg_m + B\dot{\theta} + F_S \quad (3)$$

Using the disturbance observer, the disturbances can be rejected and the robustness of the control system can be improved [15]. The estimated disturbance torque is converted to current and supplied to the motor to compensate for the disturbance.

The RTOB, which is a variation of the DOB is implemented for torque sensing. The reaction torque can be measured by removing the static friction and viscous friction from the DOB as shown in Figure 6. Friction forces of the robot are identified by experiments [17]. The reaction force for the master robot estimated by the RTOB during the flexion exercise, can be modelled as in (4). Similarly, the DOB and RTOB outputs of the slave robot can be also modelled.

$$t_{rec_m} = T_{patient} - Tg_m \quad (4)$$

C. Control System

The resistance torques that should be applied for the master and slave robots are depicted in (5) and (6) where Tg_m and Tg_s correspond to the gravity torques of the master and slave robots respectively.

$$T_m = T_{profile} - Tg_m \quad (5)$$

$$T_s = T_{profile} - Tg_s - T_{assist} \quad (6)$$

The position coordination error θ_e is taken as the difference between the angles of master and slave robots as shown in (7). The switching between resistance and assistance is achieved by integrating the system with a Relative Torsional Spring (RTS) model based on the position error between the master and slave robots as shown in (8). The spring constant k_s is selected experimentally.

$$\theta_e = \theta_m - \theta_s \quad (7)$$

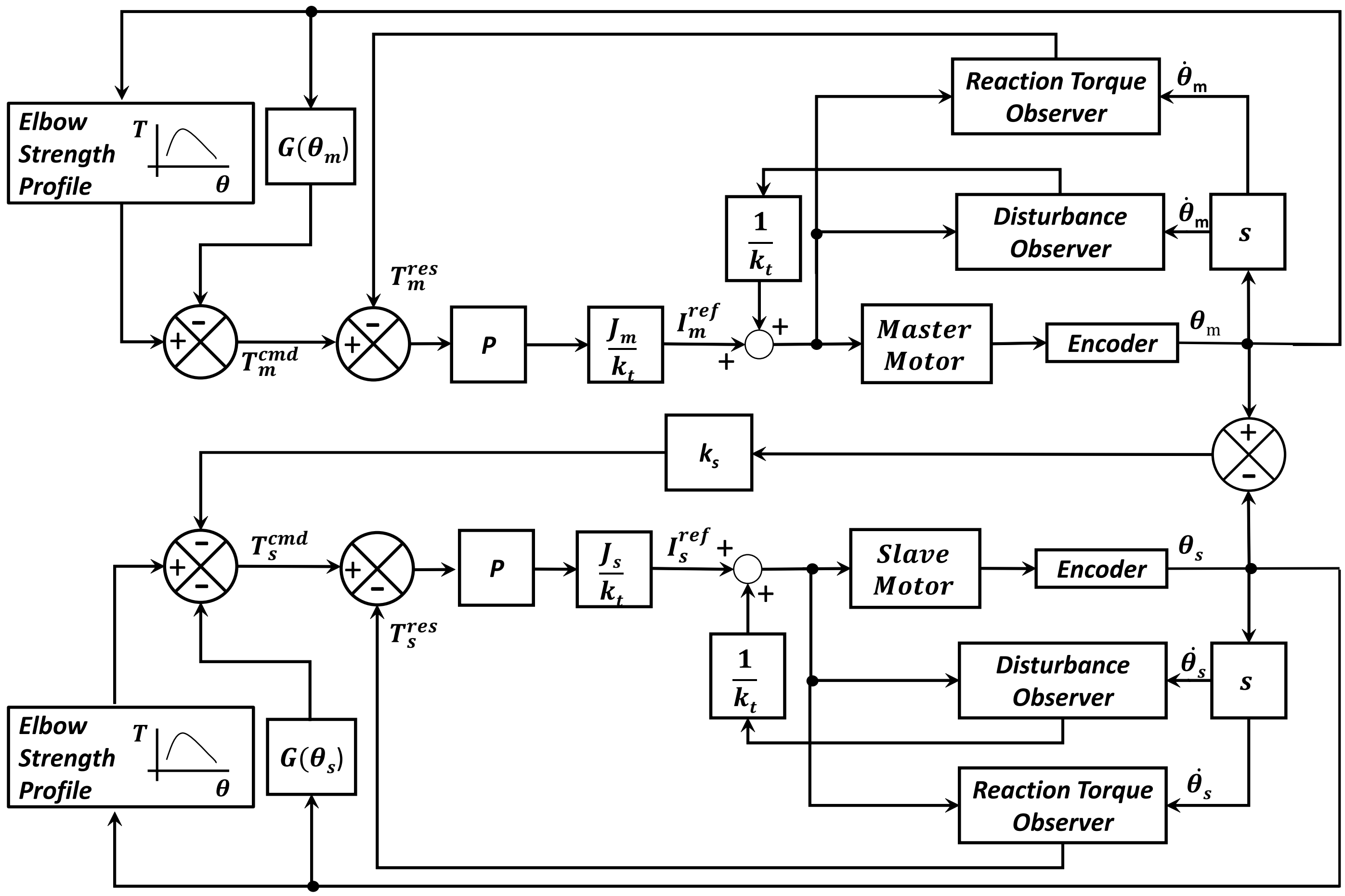


Fig. 8. Control system

$$T_{assist} = k_s \theta_e \tag{8}$$

The control system for the bimanual robot which is derived according to equations (5), (6), (7) and (8) is shown in Figure 8. DOB is implemented for both master and slave robots for disturbance rejection. RTOB is implemented for torque sensing. The elbow strength profile changes with angles of the robots according to (1) and (2).

D. Compensation of Gravity Torque

Ideally, the patient has to work against the pure resistance torque. However, if the effect of the gravity is not considered in the design of the control system, the patient has to work against both the resistance torque and the weight of the rehabilitation robot. This issue is resolved by estimating the gravity torque in advance. The gravity torque of the robot can be modelled as a function of the joint angle and it can be identified using the CAD model [18] as well. The reaction torque observer was used to identify the gravity torque of the robot. The gravity terms of master and slave robots are denoted as $G(\theta_m)$ and $G(\theta_s)$ as shown in Figure 8.

TABLE II. HARDWARE

Component	Part number
Microcontroller	STM32F746ZG
Motor Drivers	Elmo Cel A10/100
Actuators	100 RPM Zheng PMDC Gear Motors

III. RESULTS

The experimental system is shown in Figure 2. The actuators are capable providing maximum torque of 13 Nm. The selected hardware for the experiment is shown in Table II. The motor drivers are current controlled. Simultaneous execution of control and data acquisition algorithms were achieved using multithreading on Real Time Operating System (RTOS). The bimanual control algorithm was running at 10 kHz with real time priority while the data was collected approximately at 1 kHz sampling rate with normal priority.

The results show the differences between the conventional bimanual rehabilitation (without RTS assist) and RTS assisted bimanual rehabilitation. Figure 9 shows the torque response of a healthy person performing the bimanual exercises without the RTS assist. The master and slave torque responses are well matched to the reference elbow strength profile throughout the range of motion. Master and slave torque responses are consistent throughout the motion. However when a patient tries

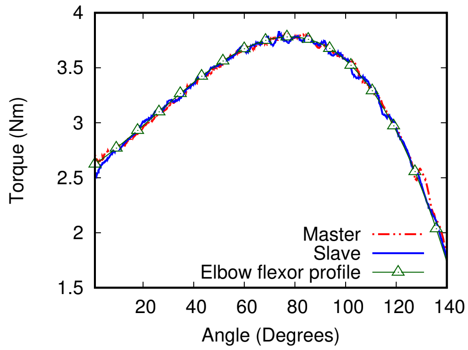


Fig. 9. Conventional bimanual rehabilitation of a healthy person - Torque angle response

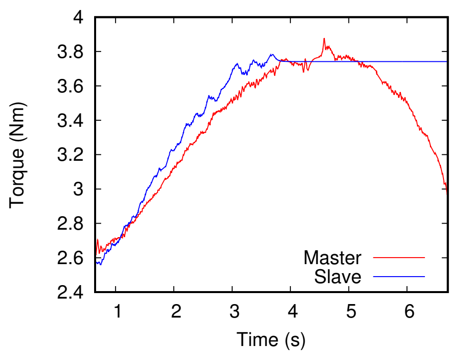


Fig. 10. Conventional bimanual rehabilitation of a patient - Torque time response

to perform bimanual training with the conventional method, the patient was unable to complete the movement as shown in Figures 10-11. The patient's impaired limb could not apply the necessary resistance torque at about 75 degrees.

Figure 13 shows torque angle responses of RTS assisted bimanual training for different spring constant values. The results of the proposed method show that the patient is now able to continue the exercise since the robot is programmed to give priority to the inter-limb coordination rather than

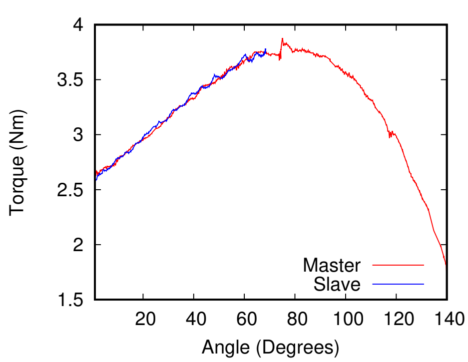


Fig. 11. Conventional bimanual rehabilitation of a patient - Torque angle response

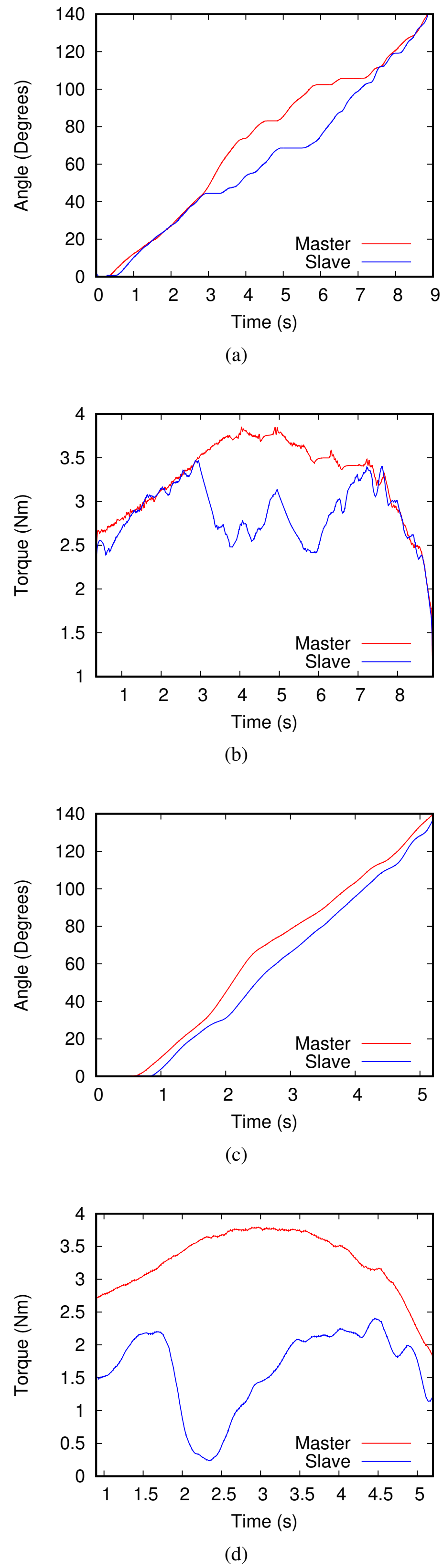
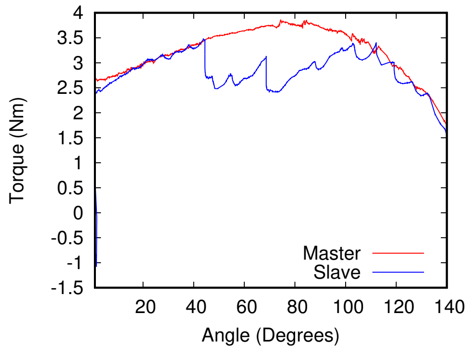
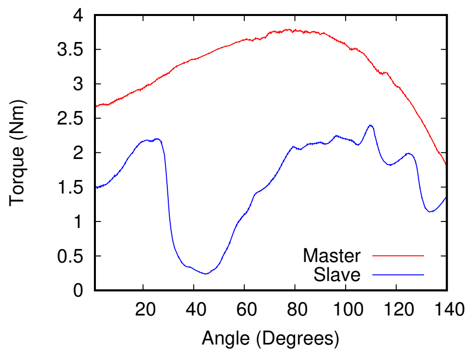


Fig. 12. RTS assisted bimanual rehabilitation. (a) Angle time response k_s = 2.5 (b) Torque time response k_s = 2.5 (c) Angle time response k_s = 10.5 (d) Torque time response k_s = 10.5



(a)



(b)

Fig. 13. RTS assisted bimanual rehabilitation.
(a) Torque angle response k_s = 2.5 (b) Torque angle response k_s = 10.5

maintaining the resistance torque. When the spring constant is low, ($k_s = 2.5$) the assistance is also low. When the spring constant is high ($k_s = 10.5$), the significance of a small position error increases. Therefore the assistance is also high. The angle time responses depicted in Figure 12a and 12c, shows the position coordination of the patient's arms. When the coordination is lost, the change of torque profile of the slave robot can be seen in the corresponding torque time responses as shown in Figures 12b and 12d.

IV. Conclusion

A bimanual rehabilitation robot was developed and programmed to assist with coordination of the human arms and to resist the motion with reference to a elbow strength profile. For seamless transfer between resist and assist modes, a relative torsional spring was modeled based on the error between master and slave robots. The spring constant can be chosen to suit the patient's level of coordination. Using the robot developed in this paper the patients are able to continue resistance training at the level that they are comfortable. If the position error is persistent, it indicates that the patient is unable to move his paretic limb. System reduces the resistance torque and assists the patient. Therefore it is expected that the patient is capable to regain position coordination using the proposed method.

References

[1] K. M. Iburg, "Global, regional, and national disability-adjusted life-years (dalys) for 315 diseases and injuries and healthy life expectancy (hale), 1990–2015: a systematic analysis for the global burden of disease study 2015," *Lancet*, vol. 388, no. 10053, pp. 1603–1658, 2016.

[2] G. Stucki, M. Stier-Jarmer, E. Grill, and J. Melvin, "Rationale and principles of early rehabilitation care after an acute injury or illness," *Disability and rehabilitation*, vol. 27, no. 7-8, pp. 353–359, 2005.

[3] G. B. Prange, M. J. Jannink, C. G. Groothuis-Oudshoorn, H. J. Hermens, and M. J. IJzerman, "Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke," *Journal of rehabilitation research and development*, vol. 43, no. 2, p. 171, 2006.

[4] B. Volpe, H. Krebs, N. Hogan, L. Edelstein, C. Diels, and M. Aisen, "A novel approach to stroke rehabilitation robot-aided sensorimotor stimulation," *Neurology*, vol. 54, no. 10, pp. 1938–1944, 2000.

[5] G. Kwakkel, B. J. Kollen, and R. C. Wagenaar, "Therapy impact on functional recovery in stroke rehabilitation: a critical review of the literature," *Physiotherapy*, vol. 85, no. 7, pp. 377–391, 1999.

[6] M. E. Stoykov, G. N. Lewis, and D. M. Corcos, "Comparison of bilateral and unilateral training for upper extremity hemiparesis in stroke," *Neurorehabilitation and neural repair*, vol. 23, no. 9, pp. 945–953, 2009.

[7] J. J. Summers, F. A. Kagerer, M. I. Garry, C. Y. Hiraga, A. Loftus, and J. H. Cauraugh, "Bilateral and unilateral movement training on upper limb function in chronic stroke patients: a tms study," *Journal of the neurological sciences*, vol. 252, no. 1, pp. 76–82, 2007.

[8] J. H. Cauraugh and J. J. Summers, "Neural plasticity and bilateral movements: a rehabilitation approach for chronic stroke," *Progress in neurobiology*, vol. 75, no. 5, pp. 309–320, 2005.

[9] R. Fernandez-Gonzalo, C. Nissemark, B. Åslund, P. A. Tesch, and P. Sojka, "Chronic stroke patients show early and robust improvements in muscle and functional performance in response to eccentric-overload flywheel resistance training: a pilot study," *Journal of neuroengineering and rehabilitation*, vol. 11, no. 1, p. 150, 2014.

[10] K. Dragert and E. P. Zehr, "High-intensity unilateral dorsiflexor resistance training results in bilateral neuromuscular plasticity after stroke," *Experimental brain research*, vol. 225, no. 1, pp. 93–104, 2013.

[11] C. Patten, J. Dozono, S. G. Schmidt, M. E. Jue, and P. S. Lum, "Combined functional task practice and dynamic high intensity resistance training promotes recovery of upper-extremity motor function in post-stroke hemiparesis: A case study," *Journal of Neurologic Physical Therapy*, vol. 30, no. 3, pp. 99–115, 2006.

[12] I. Kanelov, G. Koroleova, P. Milanov, and N. Pencheva, "Impact of the joint angular position on the peak torque of elbow flexors and extensors in healthy males." *Research in Kinesiology*, vol. 44, no. 1, 2016.

[13] J. Folland and B. Morris, "Variable-cam resistance training machines: Do they match the angle–torque relationship in humans?" *Journal of sports sciences*, vol. 26, no. 2, pp. 163–169, 2008.

[14] N. Alavi, G. Herrnstadt, B. Randhawa, L. Boyd, and C. Menon, "Bimanual elbow exoskeleton: Force based protocol and rehabilitation quantification," in *Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE*. IEEE, 2015, pp. 4643–4646.

[15] A. H. S. Abeykoon and R. M. Ruwanthika, "Remote gripping for effective bilateral teleoperation," in *Handbook of Research on Human-Computer Interfaces, Developments, and Applications*. IGI Global, 2016, pp. 99–134.

[16] M. Mizuochi, T. Tsuji, and K. Ohnishi, "Improvement of disturbance suppression based on disturbance observer," in *9th IEEE International Workshop on Advanced Motion Control, 2006*. IEEE, 2006, pp. 229–234.

[17] M. D. Chinthaka, R. Punchihewa, and A. H. S. Abeykoon, "Disturbance observer based friction compensator for a dc motor," in *Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2014 11th International Conference on*. IEEE, 2014, pp. 1–6.

[18] F. Just, K. Baur, R. Riener, V. Klamroth-Marganska, and G. Rauter, "Online adaptive compensation of the armin rehabilitation robot," in *Biomedical Robotics and Biomechatronics (BioRob), 2016 6th IEEE International Conference on*. IEEE, 2016, pp. 747–752.