

# A Novel Rehabilitation System Supporting Bilateral Arm Cooperative Training

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**Abstract**—Numerous rehabilitation robots have been developed to deliver therapy for hemiplegic patients with a unilateral-disabled limb or for aged persons with motor-function degenerated limbs. Recently, much attention has been paid to the development of robots that support bilateral arm training in various patterns. It has been proved that the coordination of two limbs can reduce hypertonia and abnormal synergies compared to unilateral limb training. However, traditional robots realized different modes with the robot providing a corresponding force for the impaired limb. This paper proposes a novel bimanual training system. A subject controls master and slave terminal handles with his/her two limbs. The less impaired limb provides a corresponding force for the more impaired limb to achieve different training patterns. No matter in which mode, the two limbs accomplish symmetric movement. An experimental prototype was built. Frequency response test and training tests on 9 healthy subjects in active-resisted and active-assisted modes were performed. Experimental results confirm that the system can correctly respond a subject's commands if velocity was changed within the frequency range of 30 Hz. For each training mode, the average position error, and RMS (root mean square) values of position errors and velocity errors that between the reference values and actual values of a motion tracking task were reduced after practice. This proves the effectiveness of the system for self-assisted rehabilitation training.

## I. INTRODUCTION

REHABILITATION therapy for motor function recovery and strength enhancement has becoming increasingly necessary due to the increasing number of hemiplegic patients and aged persons, whose limbs are unilaterally disabled or degenerated in motor function. However, the limited physical therapy resources confine the duration that patients spent doing rehabilitation activities, and increase the economic burden on patients and the workload of therapists. This situation stimulates considerable interest in the development of rehabilitation robots.

In order to motivate the initiative of patients in training

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exercises, the development of robots that support both passive and active training has attracted much attention in the last few years. MIME [1], [2] is a representative robot to deliver arm therapy in a three-dimensional workspace. It can support robot-assisted movements in four modes: passive, active-assisted, and active-constrained modes for a unilateral training, and a bilateral mode with the two limbs performing mirror image movements. Clinical trials on MIME have proved that the treatments with patients' active participation can produce larger improvements on a motor impairment scale, and the active-constraint training can achieve a greater strength gains. ARMin [3] is a robot that can deliver patient-cooperative arm therapy. Combining with an audiovisual display, it allows patients to play ball games or perform ADL-related tasks, which can motivate the activity of patients in exercises. A portable tele-rehabilitation system [4]–[6] realizing haptic feel was developed for the treatment and assessment of elbow deformity of stroke patients. A real-time control strategy and a teach-and-replay control method are achieved respectively for slow and fast movement tasks. Torque and position control modes for master and slave devices can be exchanged for passive and active movements. With the system, passive and active movements including slow and fast tasks can be carried out accurately based on haptic feel and visual feedback.

In above systems, operators are therapists rather than patients themselves. Even though the therapists can optimize therapy schemes according to feedback force, the degree of comfort of patients cannot be sensed, as a result, the patients may feel pain in the process of training. Therefore, some self-controlled rehabilitation robots were developed. Colombo and Pisano presented two robots for home-based upper limb rehabilitation training [7], [8]. The robots provide quantitative evaluation of patients' recovery during the course of treatment. This enables therapists to modify rehabilitative strategies promptly. Two groups of post-stroke patients were trained with the two robots respectively plus physical therapy. Results have proved that the robots may be useful for improving patients' movement ability. Whereas the patients were trained with the robots and traditional therapy simultaneously, thus, it is difficult to identify if the robot itself favored the good motor outcome. Some other self-controlled robots are also proposed to support unilateral arm practice, such as the systems introduced in [9]–[11].

Recently, it has been proved that bilateral arm exercise can stimulate ipsilateral corticospinal pathways and enhance recovery. Therefore, much attention has been paid to the

development of robots that can support bimanual training. Guo and Song [12] presented a self-assisted rehabilitation system to support active training based on virtual reality. One limb rotates an MTx inertial sensor to give an assistant force for the other limb, which manipulates the stylus of a haptic device PHANTOM. And then, a virtual stick is moved across a predefined curving route way. However, this system mainly supports rehabilitation training of wrist due to its limited work space. It is suitable for mild stroke patients with active motion capability, but the output torque is not enough to deliver strength enhancement therapy. BATRAC [13], [14] is a robotic device that can deliver bilateral arm therapy for stroke patients. Clinical tests have verified that bimanual movements improved arm function by inducing reorganization of brain regions involved in motor control.

Overall, traditional bilateral arm training is generally realized with a robot providing a resistant/assistant force for the impaired limb, further to complete mirror image movements [2]. Or else, the healthy limb provides an assistant force for the impaired one to accomplish predefined movements [12]–[14]. This paper presents a novel self-assisted system to support bimanual training. One limb of an operator provides a resistant, an assistant, or a driving force for the other limb to realize active-resisted, active-assisted, or passive training. No matter in which mode, the two limbs achieve symmetric movement. Besides, the system realizes force sensing without a force sensor or a force controller. Previous work introduced in [15], [16] has verified that the system can realize force sensing, energy recycling, master-slave motion tracking, and bidirectional controllability. In order to make the system more suitable for hemiplegic patients or aged persons to perform rehabilitation exercises, the preliminary platform was improved in configuration, and a visual interaction was added to the system. Training tests were performed on 9 healthy subjects to verify the effectiveness of the system for bimanual training.

## II. SYSTEM PROTOTYPE

### A. System configuration

The improved test platform is given in Fig. 1. The system supports three training modes: 1) passive mode with the healthy limb driving the impaired limb to move passively; 2) active-assisted mode with the healthy limb providing an auxiliary force for the impaired limb; 3) active-resisted mode with the healthy limb appending a resistant force for the impaired limb. The system contains three major parts including: master and slave units (motor 3863012C, combined with Planetary Gearhead 38/2 A, and Encoder IE2-512, Faulhaber Group, Germany) to be manipulated by a subject, a desktop PC to provide visual feedback for the subject, and a dSPACE control platform (CLP1104) to assure an accurately symmetric movement of the two limbs. Master and slave units are fixed to a height-adjustable and position-adjustable table. Two handles are mechanically

connected with the two motor/ gear units. During the process of training, a subject controls the two handles with two limbs and senses the force of each other, further, coordinates the two limbs to accomplish predefined movements that are displayed in the desktop PC.

Identical gearboxes with the gear ratio of 66 are selected for increasing the system's driving power, and meanwhile, acquiring a symmetric structure. The consecutive maximum output torque of the motor is 110 mNm, considering the gearbox efficiency as the theoretical value of 0.7, the corresponding maximum output torque of the system is 5.082 Nm. The torque caused by the gravity of a forearm is estimated for a human person with a weight of 65 kg and a height of 175 cm [17], the result is 1.519 Nm. Therefore, the system has enough driving power for a forearm to perform flexion/extension movements passively. The distance from the two handles to the rotational axes of the motor/gear units is 14 mm, thus the allowable maximum force actively exerted on the handles is 36.3 N.

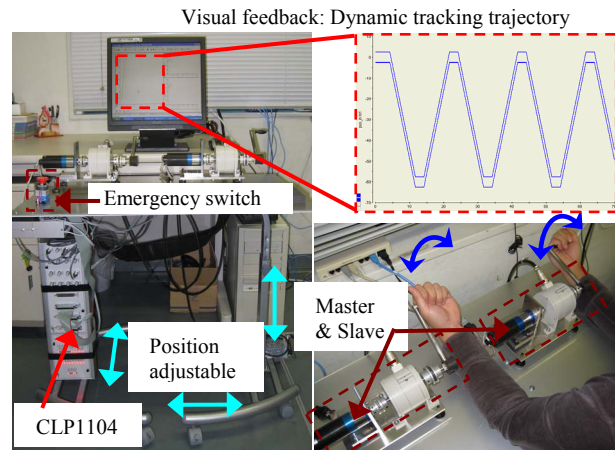


Fig. 1. Self-assisted master-slave robot system

The master and the slave motors are wired connected with an H-bridge driver to construct a closed-loop circuit. The master motor generates electrical energy and powers the slave motor. Meanwhile, the H-bridge driver compensates energy for the circuit to offset energy losses. The energy generated by the master, together with the compensatory energy, ensures the slave motor to drive the connected limb to reproduce the movement of the contra-lateral limb accurately. In addition, two torque transducers and a torque signal amplifier are applied to measure the torques attached to the two terminals and verify force sensing capability, whereas they are not needed in real applications. The transducers are located at the handle bases near the motor shaft connections.

In order to insure safety throughout the training process, position limit can be regulated by setting parameters according to the motor capacity of patients. If the slave terminal is moved beyond the position limit, the H-bridge driver stops compensating energy for the circuit and disconnects the master and the slave motors. As a result, the slave unit stops movement immediately. In addition, if the actual current of the motors is larger than the allowable

maximum value, the H-bridge driver also stops working to ensure the normal operation of the system. Since the driving force in passive mode or the assistant/resistant force in active-assisted/resisted mode is exerted by the healthy limb, patients can regulate the force according to force sensation and the feel of the impaired limb. Therefore, there is no need to set a torque limit based on the residual motor function of patients. Besides, a push-button can be manipulated by the trainee to switch off the power of the system in case of emergency.

The system realizes force sensing and energy recycling based on the closed-loop current (refer to [15], [16]). This working mechanism makes the two limbs can sense the force of each other. That is, the system has bilateral force sensing capability. In addition, each motor can behave as the slave and track the movement of the other motor (master). Actual working states of the two motors are determined from the magnitudes of the forces that attached to the two terminals: the motor attached with a larger force works in generating state and acts as the master, accordingly, the other motor acts as the slave. Thus, the system has bidirectional controllability (right to left or left to right) and is capable of delivering treatment for patients no matter which limb is impaired, and without any demand for hardware reconfiguration. Besides, the symmetric structure ensures the same operation performance for two energy transmission directions.

### B. Information flow

Information flow of the system is explained with Fig. 2. A subject controls the two handles to track desired movements that displayed in the PC. Simultaneously, the actual motion information of two terminals is transmitted to the PC through CLP1104. The subject regulates the forces of the two limbs based on force sensation and visual feedback. During this process, CLP1104 collects velocity and position information through incremental encoder interfaces. A motion tracking controller, which is realized in CLP1104, works out the duty cycles of pulse-width-modulated signal (PWM, 20 KHz) and the direction of compensation voltage in terms of the sampled motion information. The PWM and direction signals are sent to the H-bridge driver through a DAC module and a PWM generator module, respectively. Then, the H-bridge driver compensates a proper amount of energy for the system. The supplementary energy, along with the energy generated by the master, powers the slave to actuate the contra-lateral limb in motion imitation. Torque information is collected through the ADC modules of CLP1104 for testifying the relationship between terminal forces in different modes. This information is not required in real applications and thus it is drawn with dashed lines. All the information is sampled at 1 KHz.

### C. System stability test

1) *Method:* This test was aimed at investigating the stability of the system and testifying the frequency response range in two control directions when velocity was increased. A subject exerted an increased force to one handle and rotated the master and slave units upward and downward repeatedly.

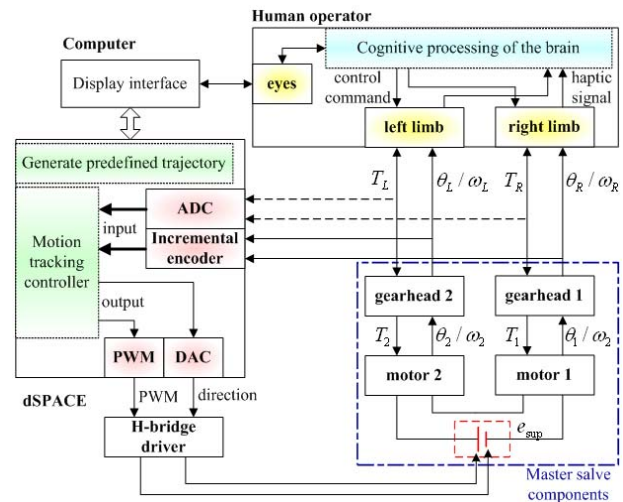


Fig. 2. Information flow of the experimental system

## III. EXPERIMENTS AND RESULTS ANALYSIS

Firstly, the control force was attached to the left handle, and no external force was attached to the right handle. Thus, the left motor acted as the master and the right motor acted as the slave. The slave unit tracked the movement of the master unit with an increased velocity. The control force was increased until the two terminals could not match each other in motion behaviour, then, the subject immediately stopped exerting force. Secondly, the above process was repeated for a reverse control direction: the control force was attached to the right handle and no external force was attached to the left handle. To achieve a reliable result, the above tests were repeated four times. The system's frequency response range was concluded by averaging all the results.

2) *Results:* Frequency response range of the system was analyzed by performing Fast Fourier Transform (FFT) on the velocity of the slave terminal for each test. Since the velocity values obtained after motion fluctuation cannot reflect the response capability of the system, only the velocity values obtained before fluctuation were applied in the FFT analysis. For both control directions, the frequency response results were almost same. Fig. 3 gives a representative result for the case that the control direction was from right to left. The frequency response range of velocity was around 30 Hz. It is enough for a human-controlled rehabilitation application.

When the velocity was increased with a frequency above 30 Hz, the slave can not mirror the movement of the master any more. Because in a sampling period, the velocity/position difference between the two terminals became larger when the velocity was increased. Then, the slave unit had a movement fluctuation. If the velocity had a continuous increase, the two units could not mirror each other in motion behaviour (Fig. 4). When the velocity difference had an obvious increase, as shown in the enlarged subgraph in Fig. 4, the maximum input acceleration was approximately 564 degrees per second<sup>2</sup>. If the external force was not stopped immediately, the system had a serious vibration. In order to avoid vibration, an acceleration limit of 500 degrees per

second<sup>2</sup> was set in the master-slave motion tracking controller. Once the velocity is beyond this limit, the H-bridge driver also disconnects the master and slave motors.

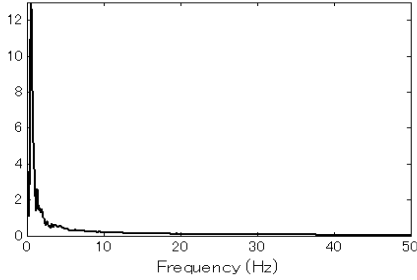


Fig. 3. Frequency response result of velocity: right to left

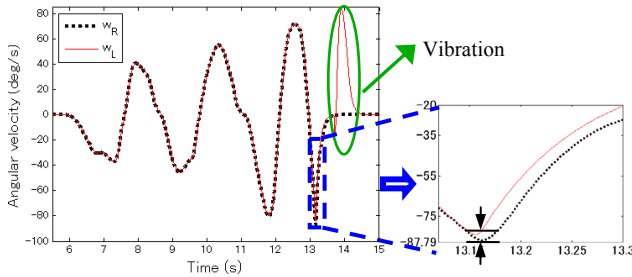


Fig. 4. Velocity tracking results in the system stability test

#### A. Training in different modes

1) *Training process:* Training tests in two training modes were performed on 9 healthy subjects (5 female and 4 male). First was active-resisted training: the left limb started the movement actively while the right limb attached a resistant force. Second was active-assisted training: the left limb provided an active force and the right limb exerted an assistant force. In both modes, the subject regulated the forces of the two limbs based on haptic feel and visual feedback, and controlled the two terminals to track desired movements that displayed in PC. Each training mode included seven motion tracking tasks. Every task lasted 70 seconds. The tracking results in the first and seventh tasks were compared to evaluate the training effect, further to verify the availability of the system for bimanually coordinated training. A score would be presented in the PC to reflect the motion tracking result of each task. This can motivate the subject's interest in exercises and is favorable for improving motor agility. If the score was less than 60 points, the same task should be performed again until the score was not less than 60 points. Before the recorded experiment in each training mode, the subject practiced the first motion tracking task three times to get familiar with the operation. Then, the tracking tasks were performed. Meanwhile, the motion information and torque information were collected for the first and seventh tasks. The torque information was used to confirm the relation between the terminal forces in the two training modes. Before the training, the subject did not know which tasks would be used to evaluate the training effect. This can avoid that the subject pays more effort for the seventh tracking task and obtain an objective result.

2) *Reference trajectory:* Reference trajectories were displayed in the form of trapezoid curve with the height denoting maximum rotational angle, as shown in Fig. 5. Two synchronously dynamic reference trajectories were displayed to define a motion fluctuation range ( $d$  and  $d \cdot \cos \alpha$ ). At the moment of changing rotational direction, a transmit time was given to avoid a sharp variation of velocity. In all the tasks, the motion velocity was same with a magnitude of eight degrees per second. The first and seventh tasks had a same reference trajectory with identical maximum rotational angles in all the reciprocating periods. Whereas the reference trajectories in the other tasks were different: 1) the maximum rotational angles were varied in different periods; 2) the varying amplitude and order were different. That is, the tracking tasks were not only the repetition of the same movement. This was aimed at activating the subject's much attention during the training. In order to further concentrate the subject's attention, before the test, the subject was informed that the reference trajectories had a varying height in different periods, whereas the concrete values were not imparted. In the test, the reference trajectories and the actual motion trajectories of two terminals were displayed in the PC in real-time. The subject coordinated the forces of the two limbs and tried to keep the actual trajectories in the center of two reference trajectories.

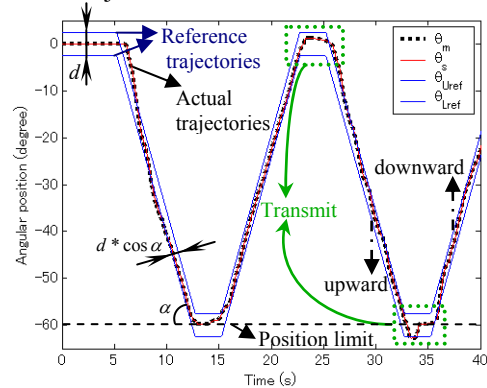


Fig. 5. Schematic diagram of movement tracking

3) *Evaluation metrics:* For each task, a score was calculated based on the difference between the actual positions of two terminals and the ideal position, which was defined as the central position of two reference trajectories. Since the two terminals realized symmetric movement accurately, here, the position of the slave terminal was used to denote the actual position. The calculation formula is:

$$\left\{ \begin{array}{l} score = 100 - \frac{40\theta_{rms}'}{2d/3} \\ \theta_{rms}' = \sqrt{\frac{\sum_{i=1}^N (\theta_{ref}^i - \theta_s^i)^2}{N}} \end{array} \right. \quad (1)$$

where  $\theta_{ref}$  denotes ideal position;  $\theta_s$  is the position of the slave (right) terminal;  $\theta_{rms}'$  is position RMS;  $N$  is the number of the sampled data in one task.

However, the score can not be used as a statistical result to reflect the training effect. Here, training effect in each mode was assessed by comparing evaluation parameters between the last and first tasks. The evaluation parameters are the mean position error, and RMS values of the position errors and velocity errors between the reference values and actual values ( $\bar{\theta}$ ,  $\theta_{rms}$ , and  $\omega_{rms}$ ):

$$\bar{\theta} = \frac{\sum_{i=1}^N \delta_{\theta}}{N} \quad (2)$$

$$\theta_{rms} = \sqrt{\frac{\sum_{i=1}^N \delta_{\theta}^2}{N}} \quad (3)$$

$$\omega_{rms} = \sqrt{\frac{\sum_{i=1}^N (\omega_{ref} - \omega_s)^2}{N}} \quad (4)$$

$$\delta_{\theta} = \begin{cases} \theta_s - \theta_{Uref}, & \theta_s > \theta_{Uref} \\ \theta_{Lref} - \theta_s, & \theta_s < \theta_{Lref} \\ 0, & \theta_{Lref} \leq \theta_s \leq \theta_{Uref} \end{cases} \quad (5)$$

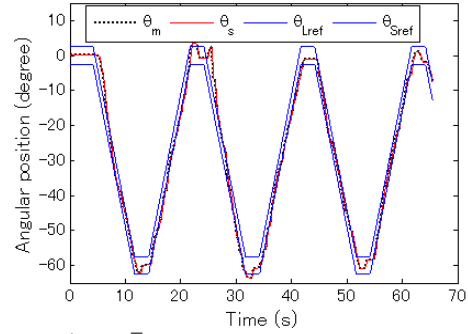
$\omega_{ref}$  and  $\omega_s$  denote the ideal velocity that induced from the dynamic reference movement and the actual velocity in the slave terminal.  $\theta_{Uref}$  and  $\theta_{Lref}$  represent the position values of the upper and lower reference trajectories.

3) *Results*: A representative motion tracking result of S3 (subject 3) in active-resisted mode is given in Fig. 6, where  $\theta_m$  and  $\theta_s$  denote the actual positions of the left and the right terminals, respectively. It can be seen that the mean position error and the RMS values of position errors and velocity errors decreased greatly. As for all the subjects, the same variation trend was obtained in resisted mode. In assisted mode, the mean values and RMS values of position errors were also reduced after training. However, 5 subjects got a slight increase in velocity RMS values (increments: 0.0175, 0.134, 0.0541, 0.3757, and 0.2705). For the 9 subjects, the average values of evaluation parameters' differences between the seventh and the first tasks are listed in Table I. Negative values reflect that the movement performance was improved after exercises. However, the effect on velocity RMS was not obvious in assisted mode. Overall, it can be concluded that the subjects learned how to accomplish the tasks with practice. In addition, the improvement of movement performance in resisted mode was greater than that in assisted mode. This shows that bimanual training in resisted mode may be more favorable for promoting recovery process.

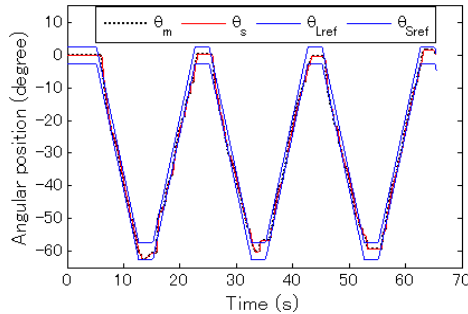
TABLE I.

AVERAGE VALUES OF EVALUATION PARAMETERS' DIFFERENCES BETWEEN THE SEVENTH AND THE FIRST TASKS

Mode	$\Delta\bar{\theta}$	$\Delta\theta_{rms}$	$\Delta\omega_{rms}$
Resisted	-0.2061	-0.3819	-0.2565
Assisted	-0.1355	-0.2566	-0.0046

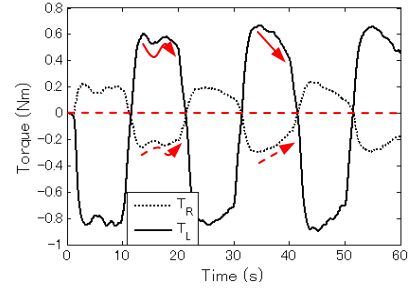


(a) The 1<sup>st</sup> task:  $\bar{\theta} = 0.6753$ ,  $\theta_{rms} = 1.6359$ ,  $\omega_{rms} = 4.3040$

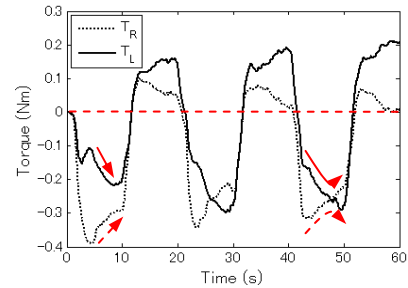


(b) The 7<sup>th</sup> task:  $\bar{\theta} = 0.2183$ ,  $\theta_{rms} = 0.6290$ ,  $\omega_{rms} = 3.9137$

Fig. 6. Motion tracking results in active-resisted mode



(a) Active-resisted mode



(b) Active-assisted mode

Fig. 7. Relationship between the two terminal torques

The representative results of the torques in two terminals for both training modes are given in Fig. 7, where  $T_R$  and  $T_L$  denote the produced torques in the right and left terminals. Comparing the Fig. 7 (a) and (b), it can be concluded that the resistant force increased the burden on the left limb, while the assistant force reduced the force requirement for the left limb. Both the resistant and assistant forces were regulated as the variation of the active force in the contra-lateral side: when the active force was increased, the resistant force was also increased; whereas the assistant force was decreased. Then, the resultant force was kept almost constant. Thus, for both

training modes, the movement was stable without a sharp variation of velocity. In addition, when the resistant torque is considered as load torque, and the active torque is reckoned as a control torque, the active-resisted mode can also be regarded as passive mode. The results confirm that the subject can sense both the resistant and assistant forces and accomplish motion tracking tasks in different modes.

#### IV. CONCLUSION

This paper introduces a bimanual training system including physical and visual interactions. Experimental results verified that the movement performance of the healthy subjects was improved after practice in different training modes. This preliminarily reflects that the system has a great potential for supporting self-assisted rehabilitation exercise.

Self-assisted training is implemented by coordinating the forces of the two limbs. This can motivate subjects' initiative and cognitive processing in exercises. In addition, visual feedback with dynamic reference movements can actuate subjects to pay much attention during the process of training. Furthermore, the displayed score after each task can stimulate subjects' much interest and make them participate in exercises actively. The above characteristics are favored for improving motor function recovery. Besides, force sensing is realized without a force sensor or a force controller, thus a compact system structure and a simple control strategy are achieved.

In the proposed system, the required control force in passive mode, assistant force in active-assisted mode, or resistant force in active-resisted mode is from the healthy limb. Based on visual feedback and force sensation, a subject can regulate the forces of the two limbs and track the predefined reference movement steadily. This bilateral arm training with a coordination of two limbs in force controlling may invoke the cooperation of the right and left hemispheres throughly. It is hypnotized that the proposed training pattern is superior to the robot-assisted bimanual training in MIME, in which the healthy limb provides a reference movement and the robot assists the impaired limb to accomplish the movement. In order to verify this merit, many more training tests will be performed in the future study.

However, the terminal handles in present system have a different mechanism with human limbs. This is unfavourable for enhancing training efficacy and the safety of the system. In future study, the handles will be redesigned to conform to the mechanism of human limbs. Additionally, in order to reduce the vibration that caused by a sudden change in velocity, a motion tracking controller with adjustable control parameters will be considered. Furthermore, we plan to combine brain wave technology and study training effect based on blood activity.

#### REFERENCES

- [1] P.S. Lum, C.G. Burgar, M. Van Der Loos, P.C. Shor, M. Majmundar, R. Yap, "The MIME robotic system for upper-limb neuro-rehabilitation: Results from a clinical trial in subacute stroke," *Proc. 2005 IEEE 9th Int. Conf. on Rehabilitation Robotics, Chicago, Illinois*, 28 June-1 July, pp. 511-514, 2005.
- [2] P.S. Lum, C.G. Burgar, M. Van Der Loos, P.C. Shor, M. Majmundar, R. Yap, "MIME robotic device for upper-limb neurorehabilitation in subacute stroke subjects: A follow-up study," *J. Rehabil Res Develop*, vol. 43, no. 5, pp. 631-642, 2006.
- [3] T. Nef, M. Mihelj, R. Riener, "ARMin: A robot for patient-cooperative arm therapy," *Medical and Biological Engineering and Computing*, vol. 45, no. 9, pp. 887-900, 2007.
- [4] Q. Peng, H.-S. Park, L.-Q. Zhang, "A Low-Cost Portable Tele-Rehabilitation System for the Treatment and Assessment of the Elbow Deformity of Stroke Patients," *Proc. 2005 IEEE 9th Int. Conf. on Rehabilitation Robotics, Chicago, Illinois*, 28 June-1 July, pp.149-151, 2005.
- [5] H.-S. Park, Q. Peng, L.-Q. Zhang, "Causality-Based Portable Control System Design for Tele-Assessment of Elbow Joint Spasticity," *Proc. 2005 IEEE 9th Int. Conf. on Rehabilitation Robotics, Chicago, Illinois*, 28 June-1 July, pp.303-306, 2005.
- [6] H.-S. Park, Q. Peng, L.-Q. Zhang, "A Portable Telerehabilitation System for Remote Evaluations of Impaired Elbows in Neurological Disorders," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 16, no. 3, pp. 245-254, 2008.
- [7] R. Colombo, F. Pisano, S. Micera, A. Mazzone, C. Delconte, M. Chiara Carozza, P. Dario, G. Minuco, "Robotic Techniques for Upper Limb Evaluation and Rehabilitation of Stroke Patients," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 13, no. 3, pp. 311-324, 2005.
- [8] R. Colombo, F. Pisano, A. Mazzone, C. Delconte, S. Micera, M.C. Carozza, P. Dario, G. Minuco, "Design strategies to improve patient motivation during robot-aided rehabilitation," *Journal of NeuroEngineering and Rehabilitation*, vol. 4, no. 3, 2007.
- [9] V.G. Popescu, G.C. Burdea, M. Bouzit, V.R. Hentz, "A Virtual-Reality-Based Telerehabilitation System with Force Feedback," *IEEE Trans. Inf. Technol. Biomed.*, vol. 4, no. 1, pp. 45-51, 2000.
- [10] D.J. Reinkensmeyer, C.T. Pang, J.A. Nessler, C.C. Painter, "Web-based telerehabilitation for the upper extremity after stroke," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 10, no. 2, pp. 102-108, 2002.
- [11] S.V. Adamovich, G.G. Fluet, A.S. Merians, A. Mathai, Q. Qiu, "Incorporating haptic effects into three-dimensional virtual environments to train the hemiparetic upper extremity," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 17, no. 5, pp. 512-520, 2009.
- [12] S. Guo, Z. Song, "VR-based active rehabilitation system for upper limbs," *Proc.IEEE Int. Conf. on Mechatronics and Automation, ICMA*, pp. 230-235, 2008.
- [13] J. Whitall, S.M. Waller, K.H.C. Silver, R.F. Macko, "Repetitive bilateral arm training with rhythmic auditory cueing improves motor function in chronic hemiparetic stroke," *Stroke* vol. 31, no. 10, pp. 2390-2395, 2000.
- [14] A.R. Luft, S. McCombe-Waller, J. Whitall, L.W. Forrester, R. Macko, J.D. Sorkin, J.B. Schulz, D.F. Hanley, et al. "Repetitive Bilateral Arm Training and Motor Cortex Activation in Chronic Stroke: A randomized controlled trial," vol. 292, no. 15, pp. 1853-1861, 2004.
- [15] C. Li, T. Liu, Y. Inoue, K. Shibata, "A master-slave control system with energy recycling and force sensing for upper limb rehabilitation robot," *IEEE/ASME Int. Conf. on Adv. Intell. Mechatronics, AIM*, pp. 36-41, 2009.
- [16] C. Li, Y. Inoue, T. Liu, K. Shibata, K. Oka, "Design and Implementation of a Compact Master-Slave Robotic System with Force Feedback and Energy Recycling," *JSME, Journal of System Design and Dynamics*, vol.4, no.1, pp. 13-25, 2010.
- [17] V.Zatsiorsky, "The Mass and Inertia Characteristics of the Main Segments of the Human Body." *Biomechanics V-IIIB Ma*, Available: <http://www.dh.aist.go.jp/bodyDB/m/k-05.html>. pp. 1152-1153, 1983.