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A Bilateral Training System for Upper-limb Rehabilitation: A Follow-up Study

Bo Sheng, Yanxin Zhang, Lihua Tang, Shengquan Xie, Senior Member, IEEE, and Chao Deng*.

Abstract— Previously, we reported a novel bilateral upper-limb rehabilitation system, an adaptive admittance controller and a related bilateral recovery strategy. In this study, we want to get a stronger evidence to verify the robustness of the proposed system, controller and recovery strategy as well as to further investigate the possibility of bilateral trainings for clinical applications. To this end, ten healthy subjects took part in a 60-minute experiment. Trajectories of robots and interaction force were recorded under the proposed bilateral recovery strategy which contained four exercise modes. For mode-1 and mode-2, results showed that the trajectories of master and slave robots can catch the reference trajectory very well, and be changed with active interaction force applied by participants. For mode-3 and mode-4, participants finished tasks very well by drawing the 'square-shaped' trajectories through their own force. In conclusion, the experimental results were good enough to provide a strong and positive evidence for the proposed system and controller. Moreover, according to the feedbacks from participants, the bilateral recovery strategy can be treated as a new and interesting training as compared to the traditional unilateral training, and could be tested in clinical applications further.

Keywords-Bilateral upper-limb rehabilitation system; adaptive admittance controller; bilateral recovery strategy; clinical applications

I. INTRODUCTION

Compared to the traditional manual therapy, the robot involved therapy can alleviate labor-intensive aspects of conventional rehabilitation trainings, and provide precise passive/active repetitive trainings in a sufficiently long timeframe [1, 2]. In terms of upper-limb rehabilitation trainings, some robotic systems have been developed for bilateral exercises, and figured out a problem that performing most activities of daily living tasks with one-hand is awkward, difficult and time-consuming [2].

Up to now, there are some limitations of most existing bilateral systems: first, the reliability of mechanism cannot be guaranteed because of lacking precise real-time data and insufficient tests as compared to industrial robots [3]; second, parameters of controllers in some bilateral systems have to be adjusted manually, which may affect the robustness of a whole system and further cause discomfort or even re-injury for participants [4, 5]; third, a majority of bilateral training protocols are revised from unilateral training protocols, only a few are specially designed for bilateral rehabilitations [6-8]. So to figure out the remaining problems, we proposed a novel bilateral rehabilitation system in previous work. However, only one healthy participant took part in previous experiments based on the proposed system, stronger evidences are needed to validate its safety and stability before clinical applications.

The main goals of this study were to get a stronger evidence to verify the robustness of the proposed bilateral upper-limb rehabilitation system as well as the possibility of the proposed bilateral recovery strategy. To this end, we recruited ten healthy participants to do a series of robot involved bilateral trainings.

II. METHOD

A. Bilateral training system

In previous study we developed a novel bilateral upper-limb rehabilitation system (Fig. 1A). Briefly, this system is aimed to provide a research prototype which can offer greater improvements in motor performance for upper-limb disabled people (especially for stroke patients) as compared to the traditional manual therapy and other rehabilitation devices. The proposed system was comprised of two Universal Robot (UR) robots (UR5 and UR10, Universal Robots A/S, Denmark), two six-axis force sensors (SRI M3713C and SRI M3715C, Sunrise Instruments LLC, China), two handle bars, one PC and one network switch. Each UR robot system contained one UR arm and one UR control box. The UR arm was a six degrees of freedom (DOFs) motor operated mechanical arm, which guaranteed an intrinsic compliance during movements and allowed arms of participants to be positioned within a big range of motion in three-dimensional space. In addition, several safety features were implemented both in software and hardware.

The adaptive admittance controller was proposed for realizing the self-adjustment of a robot's assistance or resistance level in real-time according to a patient' disability level, which can improve the robustness of training processes in both passive or active exercise modes. Moreover, two new training directions were realized under the bilateral recovery

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strategy proposed in a previous work: a participant intervention training and a participant self-training. The so-called participant intervention training is that a participant can revise trajectories by his force rather than strictly follow the reference trajectory, thus the participant's intention and voluntary efforts can be taken into account [9]. While the participant self-training is that trajectories of the robots are all provided by an intact arm of a participant and his impaired arm can mimic or collaborate to finish tasks. These two kinds of trainings can both largely enhance the training enthusiasm.

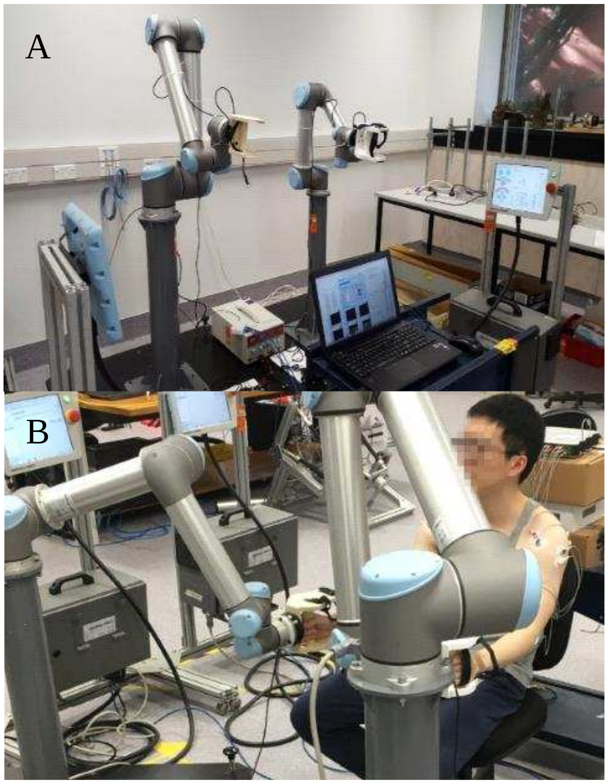

Figure 1. Experimental setup. (A) Prototype of bilateral rehabilitation system; (B) A healthy participant with the system during trainings.

B. Subjects

A total of 10 healthy male participants with no known nervous system diseases took part in this study (mean age: 27.8±1.08 years; height: 178.6±5.37 cm; weight: 73.9±10.6 kg). All experimental procedures were approved by the University of Auckland Human Participants Ethics Committee (reference 015256).

C. Protocol

Each participant was invited to finish a paper test before experiments to acquire his qualification for this experiment. If he passed the test then he was given an explanation of how to control and terminate the bilateral rehabilitation system. A brief demonstration of the rehabilitation system was also given at the same time. Then each participant was asked to sign a participant consent form, and his age, gender, height, weight and other information were collected as well. After the test, explanation and collection, each participant was invited to sit on an adjustable chair in front of the robots and grab onto handle bars of the robots to do experiments (Fig. 1B).

The whole experiment was comprised of four exercise modes, mode-1 and mode-2 contained three parts (part-1, part-2 and part-3) while mode-3 and mode-4 contained one part. For mode-1, the robots moved arms of each participant passively along a predefined trajectory (a vertical motion with a range of [$+60^{o}$ -60^{o}] at a speed of 10o/s [10], Fig. 2A), 5 times for part-1/part-2 and 4 times for part-3. A total of training time for mode-1 was around 6 minutes with a 3-minute break after each part, and a 5-minute break after each mode to avoid muscle fatigue. Main differences between three parts are: the proposed adaptive admittance controller was used in part-2 and part-3 rather than in part-1; a participant followed trajectories of the robots in part-1 and part-2, while in part-3, the participant accelerated or decelerated the robots' movements in 2nd and 3rd loops, and followed in 1st and 4th loops. Furthermore, for mode-2, a basic training protocol was the same as mode-1 except a predefined trajectory was changed to a horizontal motion with a range of [$+60^{o}$, 0^{o}] at the same speed [10], so a total of training time for mode-2 was around 5 minutes with the same break time (Fig. 2B).

For mode-3 and mode-4, each participant was asked to stand in front of the robots to provide bigger force. In mode-3, each participant moved the left robot to draw a 'square' 5 times in 3D space by his left arm, and the right robot followed the left robot's trajectory at the same time. Moreover, the right arm can follow, accelerate or decelerate trajectories by providing corresponding force though the right robot (Fig. 2C). In this mode, we focused on the number of 'square' rather than the training time since it is a task-based training. For mode-4, a basic training protocol was the same as mode-3 except trajectories of the right robot were opposite to those of the left robot (Fig. 2D).

After finishing all exercises, each participant was invited to finish a questionnaire to evaluate the rehabilitation system, the controller and the training protocols. A total of training time for all exercises was round one hour except acclimation phases.

D. Data reduction and analysis

In robot training processes, force was recorded by 6-axis load cells at 2000 HZ and then downsampled at 50 HZ to be the same with moving trajectories recorded by robot systems. It is note that the collected force is not the net joint force but the interaction force exerted by the robots to move participants' limbs (first two modes) and vice versa (last two modes). Angle data of elbow and shoulder were acquired by the NDI Polaris Spectra (Northern Digital Inc., Waterloo, Ontario, Canada) at 60 HZ in both with and without robot trainings. Note that in this study, only passive markers were attached to participants.

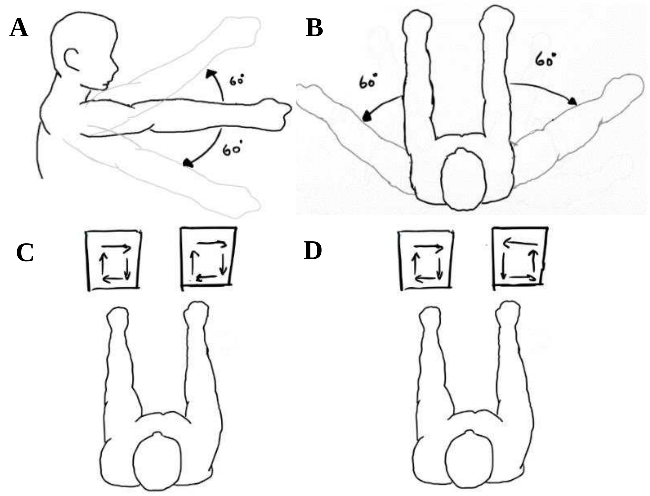

Figure 2. Training protocols. (A) Definition of exercise mode-1; (B) Definition of exercise mode-2; (C) Definition of exercise mode-3 with mimic motion (the same direction of arrows); (D) Definition of exercise mode-4 with cooperate motion (the opposite direction of arrows).

III. RESULTS

A. For mode-1 and mode-2

In general, as shown in Fig. 3A and Fig. 4A, trajectories of the master and slave robots were almost the same as the reference trajectory, and in Fig. 3B and Fig. 4B, the adaptive admittance controller showed an ability to adjust trajectories according to interaction force (active) from participants.

Fig. 3 illustrated the experimental results of part-2 and part-3 under mode-1 (the results of part-1 were the same as the results of part-2, which were not presented). The absolute max errors between reference trajectory (R.T.), master trajectory (M.T.) and slave trajectory (S.T.) can be seen from Table I: for part-2, max errors along the X-axis and Z-axis were 2.34mm and 0.24mm between master and reference trajectories, respectively; 2.51mm and 0.40mm between slave and reference trajectories; respectively, and 2.62mm and 0.43mm between master and salve trajectories, respectively. While for part-3, max errors along the X-axis and Z-axis were 9.38mm and 9.77mm between master and salve trajectories, respectively.

Trajectories and interaction force for mode-2 can be found in Fig. 4, which shown similar results as mode-1. Moreover, Table II represented the absolute max errors between R.T., M.T. and S.T.: for part-2, max errors along the X-axis and Y-axis were 3.84mm and 0.79mm between master and reference trajectories, respectively; 3.86mm and 0.49mm between slave and reference trajectories, respectively; and 3.12mm and 2.27mm between master and salve trajectories, respectively. While for part-3, max errors along the X-axis and Y-axis were 9.58mm and 6.21mm between master and salve trajectories, respectively.

Note that for mode-1 and mode-2, trajectories in Fig. 3A and Fig. 4A were the average results of ten participants, while the results of Fig. 3B and Fig. 4B were not. The reason was that Fig. 3B and Fig.4B showed the results of part-3, in which trajectories were different from each other due to different active force applied by participants and these trajectories cannot be averaged. For this situation, the best trajectory among ten participants was picked up for the presentation for each mode.

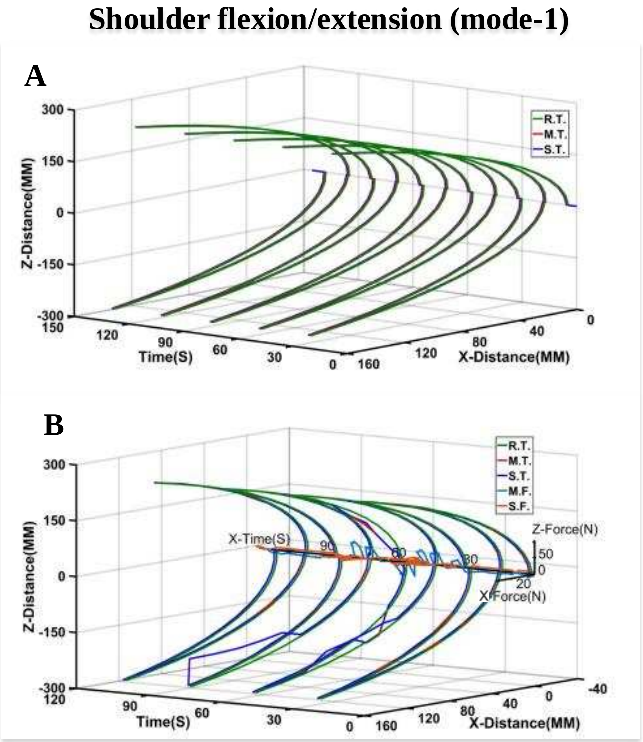

Figure 3. Results of mode-1. (A) Trajectories of Mode-1 with passive force; (B) Trajectories of Mode-1 with active force. (M.F. and S.F. in these graphs mean master force and slave force.)

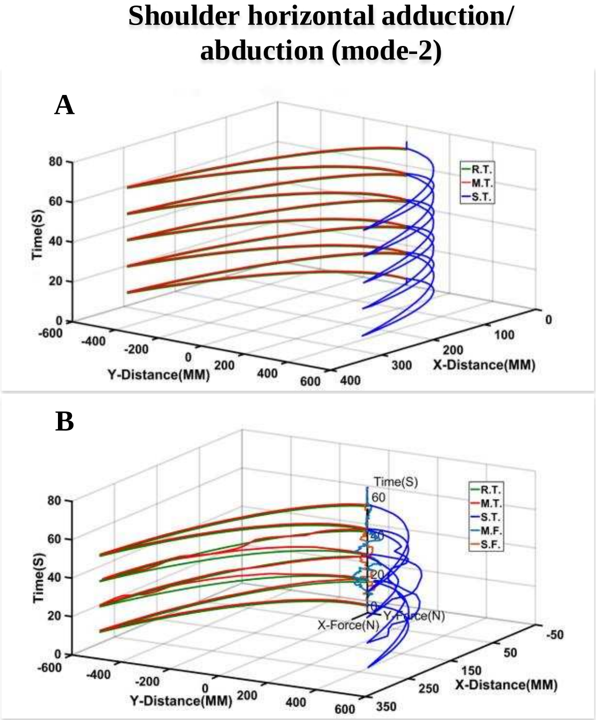

Figure 4. Results of mode-2. (A) Trajectories of Mode-2 with passive force; (B) Trajectories of Mode-2 with active force.

B. For mode-3 and mode-4

For mode-3 and mode-4, trajectories were presented in Figs.5 A, B, respectively. Results showed that a participant can trigger the robots to draw the 'square-shaped' trajectories according his force and its direction. Moreover, Table III represented the absolute max errors: along the Y-axis and Z-axis between master and salve trajectories were 8.9mm and 5.5mm for mode-3, and were 6.2mm and 7.9mm for mode-4, respectively.

Note that trajectories of mode-3 and mode-4 in Fig. 5 were not the average results of ten participants which was the same situation of Fig. 3B and Fig. 4B as described above. Another reason was that in mode-3 and mode-4, the time for each loop was different from each participant, it was impossible to average trajectories. So the best trajectory among ten participants was picked up for the presentation as well.

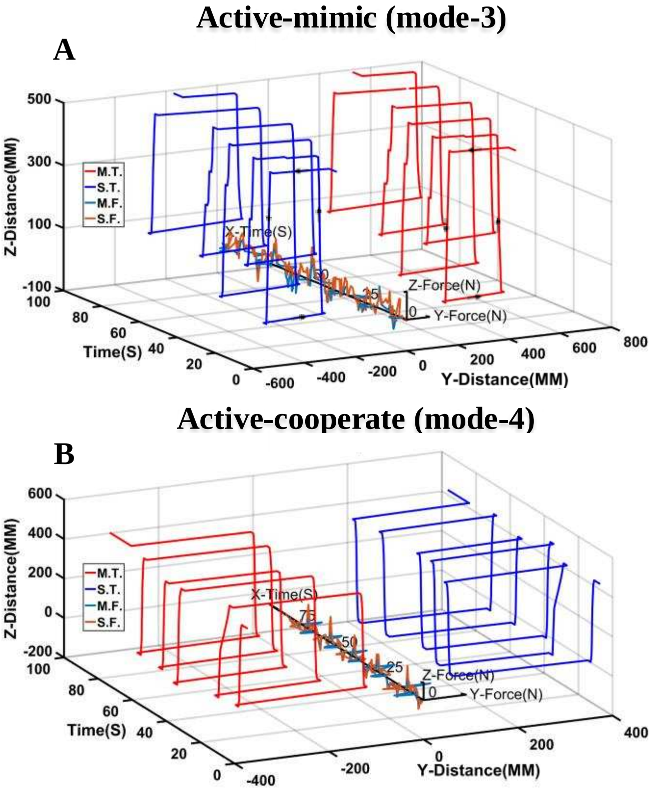

Figure 5. (A) Trajectories of Mode-3 with active force; (B) Trajectories of Mode-4 with active force.

IV. DISCUSSION

A. For mode-1 and mode-2

In general, experimental results of trajectories and the performance of the controller were the same as our expectation, which showed a strong evidence that the proposed bilateral rehabilitation system as well as the adaptive admittance controller were stable and safe, and can be tested in clinical applications further.

Fig. 3A and Fig.4A represented the averaged trajectories of mode-1 and mode-2 with the passive force, respectively. It can be seen from these two graphs, the master and salve robots can catch the R.T. well. According to Table I and Table II, the absolute trajectory errors of mode-1 and mode-2 with passive force were all less than 4mm. It means the slave robot can catch and follow the master robot tightly and thus realize bilateral trainings. At the same time, the controller can keep the stability of the system with passive force as well as reduce internal and external disturbances. By using the controller, the system could keep comfortable and safe for participants with unexpected spasms or other diseases, which is a very important part for rehabilitation trainings especially for stroke patients [11, 12].

In addition, it can be seen from Fig. 3B and Fig. 4B, M.T. and S.T. were different from R.T. in 2nd and 3rd loops according to active force or the same as R.T. in 4th loop as soon as active force descended to the safety threshold (15 N). Moreover, according to Table I and Table II, the absolute trajectory errors of mode-1 and mode-2 with active force were all less than 10mm which were very small as compared to the whole trajectories. It means the controller has an ability to change trajectories quickly and stably, which made a foundation for the active-mimic and active-cooperate training modes. At the same time, the concept of participant intervention training was realized that a participant's intention and voluntary efforts can be taken into account though changed trajectories.

However, some differences of the absolute trajectory errors were found within one mode or between two modes. First, all errors of part-2 were smaller than those of part-3 in both mode-1 and mode-2. The possible reason could be that with active force, the changes of trajectories were bigger than those of trajectories with passive force, which increased errors accordingly. Second, almost all errors in mode-1 were smaller than those in mode-2. This situation can be explained by a fact that during mode-2, participants were easier to offer larger active force as compared to mode-1 due to horizontal movements (shoulder horizontal adduction/abduction) and the short training time (12s for one loop) [13].

B. For mode-3 and mode-4

As for mode-3 and mode-4, the results showed that participants can finish the total active task-based trainings by drawing the 'square-shaped' trajectories through their active force carried out by left and right arms. Figs. 5A, B showed the best trajectories of mode-3 and mode-4 chosen from ten participants, respectively. A definition of 'best' was that a trajectory was smooth and each 'square' was finished at a time, while a 'bad' trajectory was rough and each 'square' was finished at many times. Moreover, it can be seen from Table III, the absolute trajectory errors of mode-3 and mode-4 were all less than 10mm, which was the same results as part-3 of mode-1 and mode-2. These small errors also provided a strong evidence that the system and the robot involved trainings were stable and safe. At the same time, the concept of self-training was realized, which can enhance the enthusiasm of participants as far as possible.

TABLE I. Absolute trajectory errors of Mode-1 in Part-2 and Part-3 (mm).

Exercise Name	**Robot Name**	**Max Error**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**Mean±SD**
Part-2	**master robot**	**Reference X-axis**	1.81	2.16	1.94	2.15	2.21	2.06	1.81	2.11	1.89	2.34	2.05±0.17
		Reference Z-axis	0.23	0.21	0.23	0.14	0.14	0.14	0.14	0.24	0.14	0.24	0.19±0.04
	slave robot	**Reference X-axis**	2.11	2.18	2.48	2.51	2.11	2.18	1.99	2.08	2.38	2.08	2.21±0.17
		Reference Z-axis	0.40	0.24	0.26	0.24	0.24	0.34	0.24	0.24	0.34	0.33	0.29±0.06
	within two robots	**X-axis**	2.22	2.22	2.48	2.62	2.22	2.22	1.98	2.12	2.38	2.32	2.28±0.17
		Z-axis	0.37	0.37	0.37	0.27	0.27	0.37	0.27	0.37	0.43	0.37	0.35±0.05
Part-3	**within two robots**	**X-axis**	9.38	3.48	7.22	4.72	3.68	3.42	8.68	2.78	6.88	2.58	5.28±2.40
		Z-axis	2.57	3.47	6.97	2.47	0.27	4.67	1.23	0.37	9.77	0.33	3.21±2.99

TABLE II. Absolute trajectory errors of Mode-2 in Part-2 and Part-3 (mm).

Exercise Name	**Robot Name**	**Max Error**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**Mean±SD**
Part-2	**master robot**	**Reference X-axis**	1.29	3.16	2.97	1.14	3.01	1.40	2.85	1.89	3.84	1.84	2.34±0.89
		Reference Y-axis	0.26	0.79	0.16	0.26	0.43	0.14	0.16	0.49	0.15	0.28	0.31±0.20
	slave robot	**Reference X-axis**	2.15	3.48	1.75	2.59	3.86	1.82	2.44	2.02	2.79	2.33	2.52±0.66
		Reference Y-axis	0.49	0.26	0.30	0.23	0.25	0.26	0.36	0.27	0.41	0.24	0.31±0.08
	within two robots	**X-axis**	2.42	2.42	2.68	2.89	2.42	2.42	2.98	3.12	2.69	2.75	2.68±0.25
		Y-axis	1.37	1.37	1.37	2.27	1.27	1.37	2.27	1.37	1.43	1.37	1.55±0.36
Part-3	**within two robots**	**X-axis**	8.69	5.69	3.88	1.59	9.58	6.33	7.49	6.38	2.58	3.11	5.53±2.54
		Y-axis	1.58	5.21	6.18	1.44	2.36	6.21	1.47	2.58	3.32	2.23	3.26±1.81

TABLE III. Absolute trajectory errors of Mode-3 and Mode-4 (mm).

Exercise Name	**Robot Name**	**Max Error**	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**Mean±SD**
Mode-3	**within two robots**	**Y-axis**	5.80	1.40	5.58	1.90	2.50	2.20	2.92	2.18	8.90	3.35	3.67±2.24
		Z-axis	4.30	2.90	5.50	3.80	3.80	2.60	2.80	0.40	2.50	1.90	3.05±1.33
Mode-4	**within two robots**	**Y-axis**	5.60	2.20	1.30	4.20	4.00	1.90	2.80	6.20	2.70	1.70	3.26±1.59
		Z-axis	5.50	7.90	2.40	2.60	7.70	6.80	2.40	2.50	2.30	2.60	4.27±2.29

In this study, we want to test how best a trajectory can be since all participants are healthy people and thus to establish a baseline to against results from stroke patients. As we expect, trajectories created by stroke patients would be rough and cannot be finished at a time. But with the improvement of muscle activation of stroke patients, trajectories would be smoother and be finished faster after a series of rehabilitation trainings.

V. CONCLUSION

Overall, the goals for this study are completed by the experimental results that the proposed bilateral rehabilitation system as well as the controller are stable and safe, and the bilateral recovery strategy can be treated as a new and interesting training method. However, the effectiveness of this recovery strategy should be certified by more experiments with more healthy subjects or stroke patients before clinical applications. Future work will be done in two aspects to improve the system performance and to get a deeper understanding of bilateral recovery processes: 1) virtual-reality games will be included in trainings especially in total active modes (mode-3 and mode-4); 2) more healthy subjects or stroke patients would be involved in future experiments.

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