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# Service Robotics: Robot-Assisted Training for Stroke Rehabilitation

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## 1. Introduction

Stroke, a cerebrovascular accident, is a leading cause of permanent disability in adults, with clinical symptoms such as weakness, spasticity, contracture, loss of dexterity, and pain at the paretic side. Approximately 70% to 80% of people who sustain a stroke have limb impairment and require continuous long-term medical care to reduce their physical impairment<sup>1,2</sup>.

In the absence of direct repair on the damaged brain tissues after stroke, neurological rehabilitation is an arduous process, because poststroke rehabilitation programs are usually time-consuming and labor-intensive for both the therapist and the patient in one-to-one manual interaction. Recent technologies have made it possible to use robotic devices as assistance by the therapist, providing safe and intensive rehabilitation with repeated motions to persons after stroke<sup>3,4</sup>. The most commonly reported motion types provided by developed rehabilitation robots are: 1) continuous passive motion, 2) active-assisted movement, and 3) active-resisted movement<sup>5</sup>. During treatment with continuous passive motion, the movements of the patient's limb(s) on the paretic side are guided by the robot system while the patient stays in a relaxed condition. This type of intervention was found to be effective in temporarily reducing hypertonia in chronic stroke<sup>6</sup>, and in maintaining joint flexibility and stability for persons after stroke in the early stage (within 3 weeks of onset)<sup>5</sup>. However, passive movement did not significantly benefit motor improvement. In active-assisted robotic treatment (or interactive robotic treatment), the rehabilitation robot would provide external assisting forces when the patient could not complete a desired movement independently. For chronic stroke (>1 year after stroke), it has been found that with voluntary attempts by the patients, the interactive robotic treatments were more effective for motor functional improvement than treatments using continuous passive motions<sup>5,7</sup>. Robotic treatment with active-resisted motion involved voluntarily completing movements against programmed resistance<sup>8</sup>. It has been found that repetitive practice of hand and finger movements against loads resulted in greater improvements in motor performance and functional scales than Bobath-based treatment<sup>9</sup>, transcutaneous electric nerve stimulation, and suprathreshold electric stimulation on hand and wrist muscles<sup>10</sup>. In robotic therapy, repeated practice against opposing force mainly improved the muscle force from

the elbow and shoulder in a reaching task, and also benefited the functional improvements in the wrist and hand for chronic stroke<sup>8</sup>.

In recent years, robotic systems developed for stroke rehabilitation have been widely reported in the literatures. Most of these robotic systems can provide all the three motion types mentioned above for poststroke rehabilitation. For example, MIT-MANUS is one of the robotic systems for poststroke upper limb rehabilitation<sup>11, 12</sup>. The key feature of MIT-MANUS is its impedance control which could keep a compliant trajectory under perturbation. ARM Guide is a robotic system designed both for training and evaluation of upper limb reaching functions in a linear trajectory<sup>13, 14</sup>. Colombo et al. also designed a wrist manipulator with one-degree of freedom and an elbow-shoulder manipulator with two-degrees of freedom for the rehabilitation of upper limb movements<sup>3</sup>. They used admittance control to reduce the inertia and facilitate the movement.

Due to the effectiveness in motor improvement by active-assisted robotic treatment, the recent developments involving rehabilitation robots has been worked towards the interactive control, which allows the robotic system to react to patients' voluntary intention. However, most of the interactive controls used in rehabilitation robot are still preliminary and oversimplified on the voluntary inputs from stroke patients. The easiest and most commonly used algorithm for the interactive control is the "on/off" strategy, i.e., once the voluntary indicator from a subject is captured or disappears, the assistive function of robotic system will be triggered to help the subject finish the programmed motion<sup>15</sup>. Usually the subject only needs to stay passively and have a sensory experience after the assistive function is triggered. The voluntary indicator could be represented by limb torques, limb acceleration, electromyographic (EMG) signal amplitude, etc<sup>5, 11, 16</sup>. According to the sensorimotor integration theory, the voluntary motor efferent and the afferent sensor experiences together are important and helpful to promote the reorganization of the brain<sup>17</sup>. A more advanced design in the interactive control requires continuous voluntary motor inputs from a stroke patient to the robot, and the robotic system gives support, or even encourages the output from the motor system of the stroke patient but not to override, during the training. In this chapter, we introduced an interactive robotic system with continuous voluntary intention control developed in our laboratory for poststroke rehabilitation training, and its associated training effects.

## **2. Continuous EMG(cEMG)-driven robot for poststroke rehabilitation**

EMG is the electricity generated in muscles under the control of the nervous system. When an action potential (AP) transmitted from a motor neuron axon to the muscle fibers it innervates, a motor unit action potential (MUAP) is evoked. EMG signal of a muscle is the summation of MUAPs evoked at the same time. Therefore, EMG activities could be used to reflect the nervous instructions on a muscle. In comparison with the amplitude of APs in nerve fibers stimulating a muscle, the EMG amplitude of the muscle is higher (usually in millivolt), if detected non-invasively by surface electrodes from skin surface. Thus, EMG signals have been used as indicators of subjects' voluntary intention in some orthotic and prosthetic devices for paralyzed people<sup>18-21</sup>, and the trigger signals in some interactive robotic system for stroke rehabilitation training<sup>15</sup>. In our works, we developed an interactive robotic system with continuous EMG control<sup>22</sup> for poststroke rehabilitation

training on elbow joint with the attempt to encourage the participants to involve more voluntary efforts during the training<sup>23, 24</sup>. This developed robotic system was also named as PolyJbot.

#### *i. The Design of the Robot*

The experimental setup for the elbow training with the robotic system is shown in Fig 1. During the training, a subject was seated, and the affected upper limb was mounted horizontally on a cEMG-driven robotic system. The subject would conduct elbow flexion and extension horizontally by tracking a target cursor on a computer screen, moving with an angular velocity at  $10^\circ/\text{sec}$  in both flexion and extension directions from  $0^\circ$  (full extension) to  $90^\circ$  of the elbow angle. During the tracking, continuous interactive torque would be provided by the robot to help the subject finish the task.

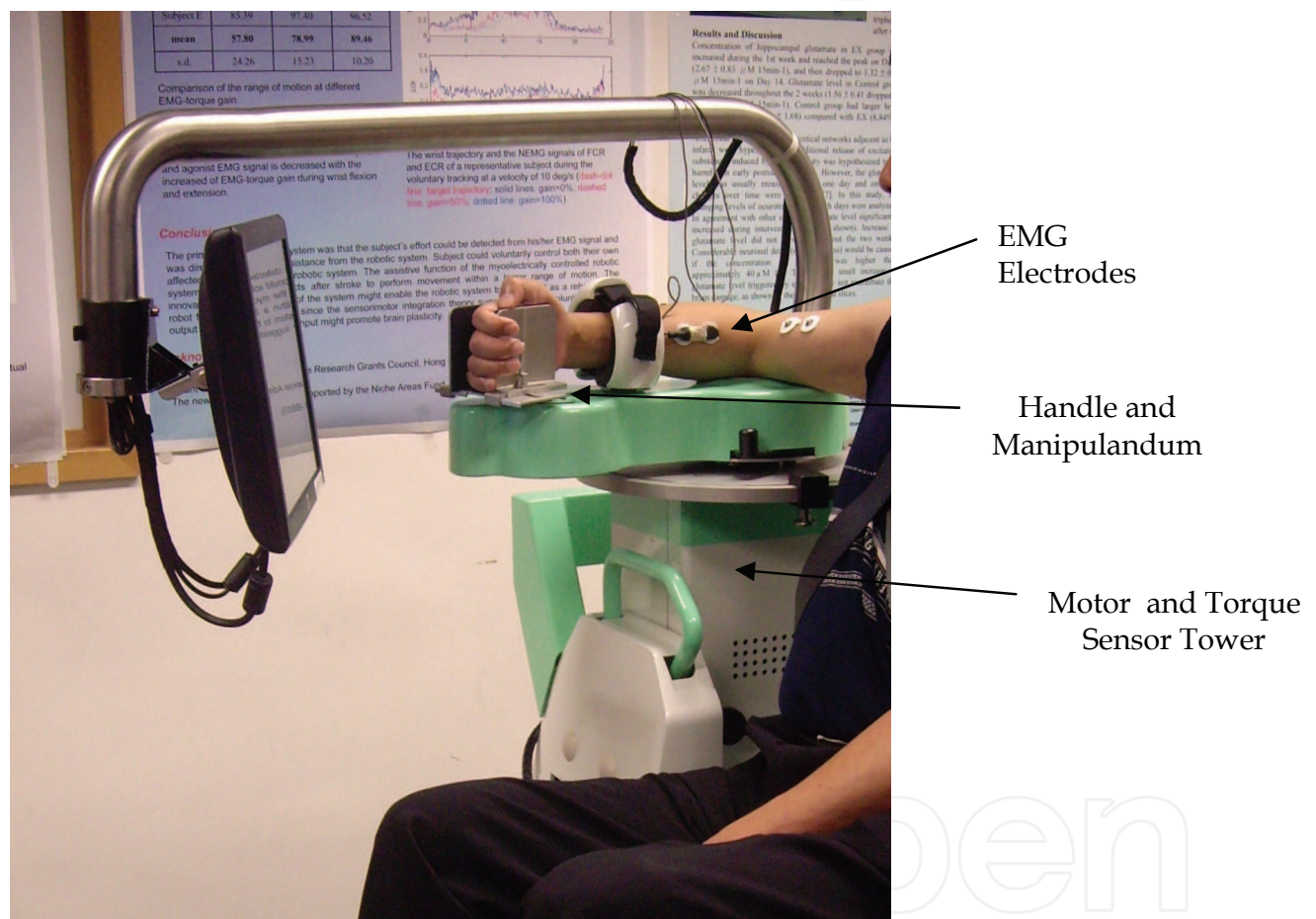


Fig. 1. Diagram of the continuous electromyography driven robotic system.

The detailed structure of the cEMG-controlled robotic system for poststroke elbow training is illustrated in Fig 2, which consists of a personal computer (PC), a PC based data acquisition device, an actuated mechanical part, and an EMG amplifier. The captured EMG signals together with the torque and the angle signals can be inputted through the data acquisition (DAQ) card into the computer. The PC-based program has three functions: 1) to provide a programmed tracking task; 2) to generate a control signal and control the motor to provide interactive torque; and 3) to guide the movement of a subject with visual feedback, which displays both the target and the actual elbow joint angle in a computer screen in front

of the subject. The mechanical part of the robotic platform with one-degree of freedom (DOF), i.e. elbow flexion and extension on the horizontal plane, was designed and fabricated for assisting the movement of elbow flexion and extension. A two-layer of aluminium plates were connected by four aluminium pillars inside of a motor and torque sensor tower. The lower plate was fixed to the base of the tower. The direct drive (DDR) brushless AC servo motor was fixed to the lower plate. The motor was connected to a torque sensor. The other end of the torque sensor was connected to a manipulandum with an orthosis to fix the forearm. During the training, the forearm of the paretic side of a subject was placed into the orthosis on the manipulandum which could rotate with the motor; and the elbow angle signals were measured via readings of the positions of the manipulandum. A belt was used to fasten the shoulder joint in order to keep the joint position still during elbow flexion and extension.

In the design of the interactive control algorithm of the robotic system, EMG signals from the main antagonist muscle pairs related to the elbow flexion and extension was detected, i.e. the biceps brachii (BIC) and the triceps brachii (TRI, lateral head) muscles. Clinically, it is observed that most of persons after stroke have difficulties in elbow extension rather than flexion in the affected side, and the paretic upper limbs are always flexed even in the resting state<sup>25</sup>. One of the major reasons is the muscle spasticity commonly observed in flexors, e.g. the biceps brachii (BIC) muscle, and the weakness in extensors, e.g. the TRI muscle<sup>26, 27</sup>. Reduced nervous control on muscle coordination in achieving a target movement is another factor that affects the elbow movements in persons after stroke; and significant muscle cocontractions, i.e. co-shortening, may be found during elbow extension in the affected limb<sup>28, 29</sup>. Therefore, in our robotic system, the assistive torques provided by the motor was only in the extension phase of a tracking task, and was proportional to the amplitude of TRI EMG signal, described as follows<sup>22, 24</sup>.

1. The raw TRI EMG signals were first amplified with a gain of 1000 and were band-pass filtered in 10-400 Hz band. Then, the signals were sampled at 1000 Hz through the A/D card and captured by the PC-program. The envelope of the EMG signals was obtained by full-wave rectification and filtering with a moving average window (100 ms). The processed TRI EMG at this step was named as,  $EMG_{TRI}$ .
2. TRI EMG,  $EMG_{TRI}$ , was then normalized to the range 0-1, i.e.,

$$M_t = \frac{EMG_{TRI} - EMG_{trest}}{EMG_{tIMVE} - EMG_{trest}} \quad (1)$$

where  $EMG_{trest}$  was the amplitude of processed TRI EMG signal at rest, and  $EMG_{tIMVE}$  was the maximal amplitude of the processed TRI EMG signal during the maximum isometric voluntary extension (MIVE) at 90 deg of the elbow angle, which was detected before the training session.

3. The assistive torque during the extension was formulated as:

$$T_a = G \cdot T_{IMVE} \cdot M_t \quad (2)$$

where,  $T_{IMVE}$  was the maximum value of the extension torque at the elbow angle of 90°, and  $G$  is a constant gain used to adjust the magnitude of the assistive torque for a training program<sup>22, 24</sup>.

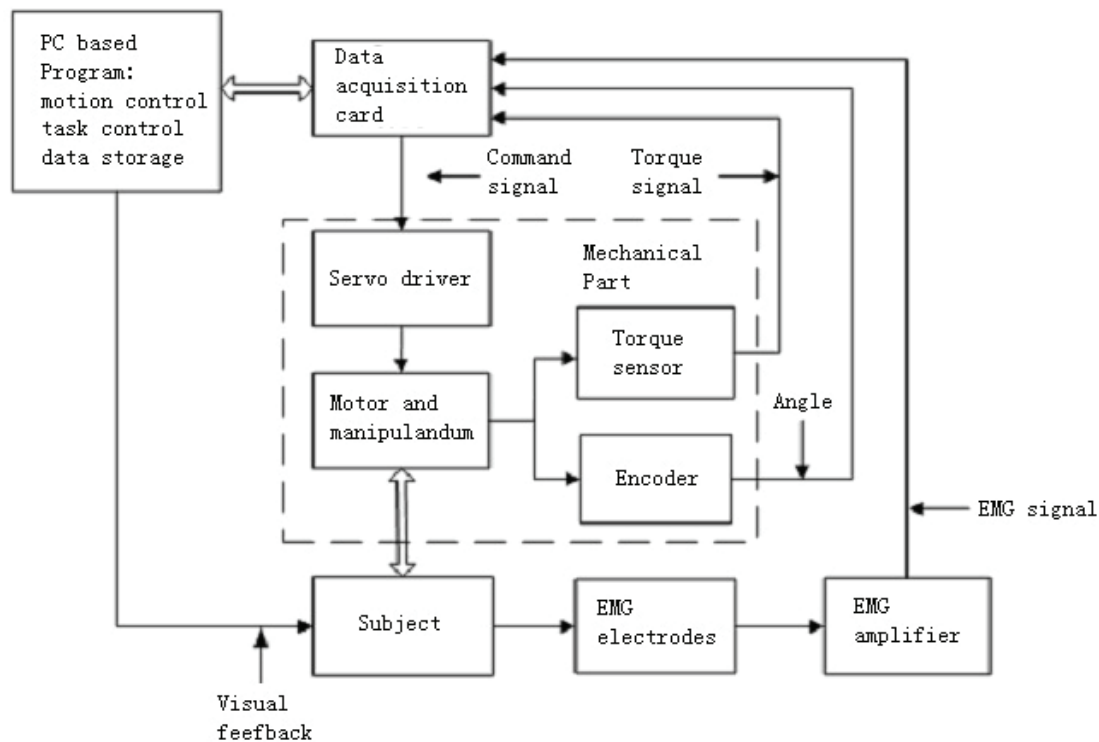


Fig 2. Architecture of the continuous electromyography driven robotic system

The interactive robotic system we developed not only provided the assistive torque to the affected limb during elbow extension, but also could generate resistive torque for muscle strength training in the tracking tasks. The resistive torque could be applied in both flexion and extension directions, that is,

$$T_r = a \cdot T_{MVC}, \quad (3)$$

where  $T_r$  was the resistive torque,  $T_{MVC}$  that included two parts, the torque of isometric maximum voluntary flexion (IMVF, detected before the training),  $T_{IMVF}$ , (applied in the flexion phase only) and the torque of IMVE,  $T_{IMVE}$ , (applied in the extension phase only), and  $a$  was a percentage value used to adjust the range of resistive torques applied for a training. The selection on the values of  $G$  in Eq 2 and  $a$  in Eq 3 is related to specific training program, during which subjects should not feel too difficult or too easy to follow. The net torque provided by the robot during the training should be the combination of the assistive torque and the resistive torque, that is,

$$T_n = T_a - T_r, \quad (4)$$

where  $T_a$  was the assistive torque, and  $T_r$  was the resistive torque. The resistive torques provided by the robotic system were highly related to the torque values of isometric voluntary contractions before a training session. In a multi-session training program, the resistive torques provided by the robot were adaptive to the variation of muscle force generation during the training course, i.e., to keep the effective muscular effort at a level associated with a possible increase in muscle force during the training. Although  $T_a$  and  $T_r$  in Eq 4 would tend to cancel, the two torques were directly related to the personal effort of

the subjects during the training. Therefore, the net torque provided by the robot was interactive to the motor ability of subjects.

*ii. Robot as an Evaluation System*

Rehabilitation robot could share the large portion of the repeated labor work in a long-term physical training program, with the proper administration by a physical therapist. Another advantage of using robot-assisted poststroke rehabilitation training is that the robot could be a platform for quantitative monitoring on the motor recovery process during rehabilitation training, due to the standardized experimental setup and the high repeatability of training motions compared to the modes manually offered. However, in many works on rehabilitation training, only pre- and post- training evaluations were conducted to assess the training effects, even in most of studies related to robot-assisted rehabilitation<sup>5</sup>. The commonly used clinical scores include the Fugl-Meyer Assessment (FMA)<sup>30</sup>, the FIM instrument<sup>31</sup>, the Motor Status Score (MSS) test<sup>32</sup>, and the Modified Ashworth Scale (MAS)<sup>33</sup>.

In our previous work on the poststroke elbow training assisted by the interactive robot, several robotic parameters were used to monitor the motor recovery process during a training program<sup>22,24</sup>. They were:

1. EMG activation levels of muscles: EMG activation level mainly reflects signal amplitude, and is related to the muscle power, or force, generated in a task. Besides the EMG signals of BIC and TRI muscles, another two muscles related to the shoulder joint, i.e. the anterior deltoid (AD) and posterior deltoid (PD) muscles were also studied in the training program. The raw EMG signals of these four muscles during elbow tracking tasks were recorded and stored in a computer. Then, the linear envelope of the recorded EMG signals was obtained by i) full-wave rectification, ii) low-pass filtering (10Hz cutoff frequency with forth-order, zero-phase forward and reverse Butterworth filter), iii) subtraction of the average EMG activity during the resting state, and iv) normalized to the maximum value of EMG activation in each muscle during either a training session or the IMVE and IMVE of each session. The EMG activation level of a muscle in a tracking trial was calculated by averaging the EMG envelope of the trial.
2. Muscle cocontraction indexes (CI) of muscle pairs: After obtaining the EMG envelope of the muscles of interest, we also calculated the coactivations between different muscle pairs during the tracking task, which could be expressed by the cocontraction index as introduced in Frost's study<sup>34</sup>, that is,

$$CI = \frac{1}{T} \int_T A_{ij}(t) dt \quad (5)$$

where  $A_{ij}(t)$  was the overlapping activity of EMG linear envelopes for muscles  $i$  and  $j$ , and  $T$  was the length of the signal. The value of a CI for a muscle pair varied from 0 (no overlapping at all in the signal trial) to 1 (total overlapping of the 2 muscles with both EMG levels kept at 1 during the trial). The representative segments of EMG envelopes obtained in the tracking experiment are shown in Fig 3. The CI value of a muscle pair represents the coordination pattern in a motion task.

3. The root-mean-squared-error (RMSE) of tracking trajectories: The root-mean-squared-error of a trial calculates the difference between the target and the actual elbow angles during the tracking task. This measure represents the performance of a tracking task,

i.e. the smaller the RMSE value, the better the accuracy of performance. An example of the measured actual elbow angle, in comparison with the target angle, is shown in Fig 3.

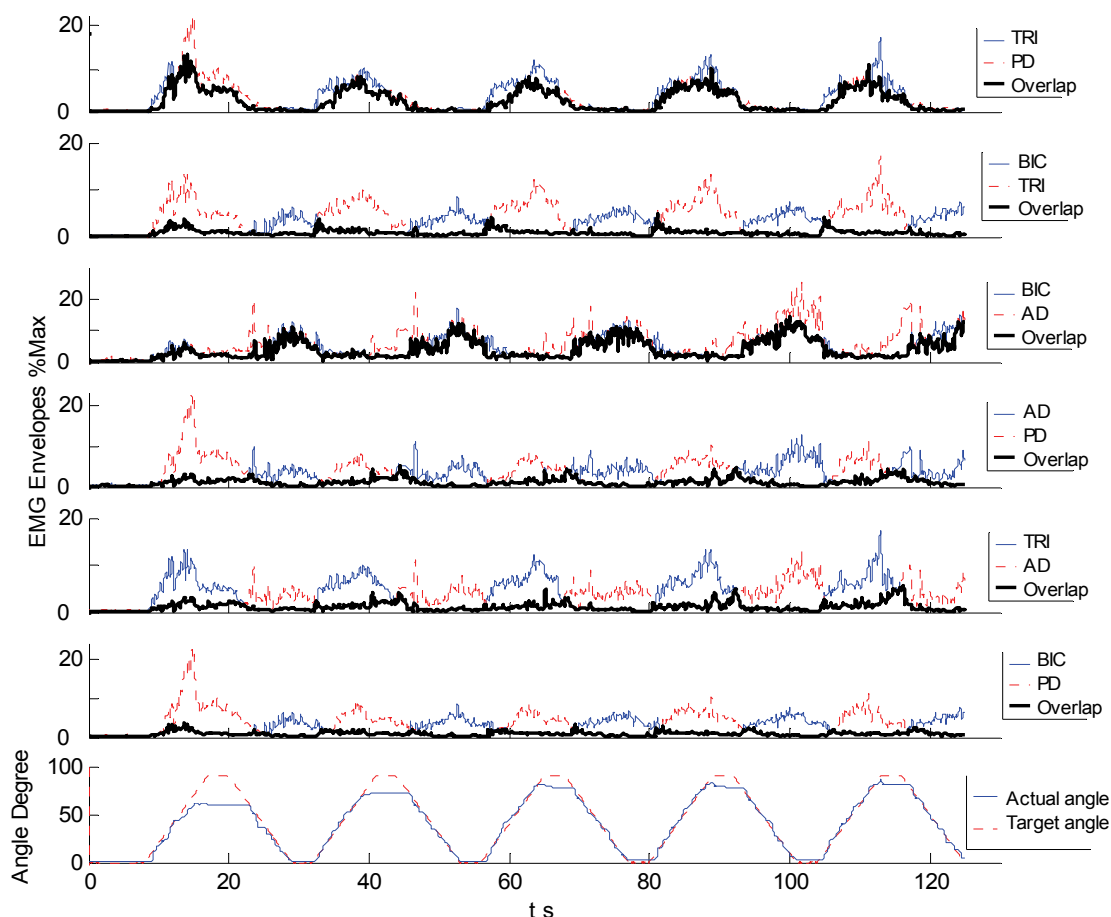


Fig 3. Representative signal envelopes of electromyography captured in a tracking trial, as well as the angle signals during the tracking.

### 3. Elbow training with cEMG-driven robot for chronic stroke

The developed cEMG-driven robot has been used in the elbow training for people with chronic stroke; and the training effects were evaluated by both traditional clinical assessments and robotic parameters during the training with the purpose of quantitatively revealing the recovery process during the training<sup>22,24</sup>.

#### *i. Training Protocol*

After obtaining approval from the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University, we recruited 6 hemiplegic subjects after stroke for the study. All of the subjects were in the chronic stage (at least 1y postonset of stroke; 5 men, 1 woman; age,  $51.1 \pm 9.7$ y) All subjects received a robot-assisted elbow training program consisting of 20 sessions, with at least 3 sessions a week and at most 5 sessions a week, and finished in 7



consecutive weeks. Each training session was completed in 1.5 hours. Before and after the training, we adopted 2 clinical scores to evaluate the voluntary motor function of the paretic upper limb (the elbow and shoulder) of the subjects: the FMA (for elbow and shoulder; maximum score, 42) and MSS (shoulder/elbow; maximum score, 40). Spasticity of the paretic elbow of each subject before and after the training was assessed by the MAS score. The clinical assessments of this study were conducted by a blinded therapist.

During each training session, each subject was seated with the paretic arm mounted on the robotic system as specified in Fig 1. EMG signals were detected from the muscles of TRI, BIC, AD, and PD muscles. Before the tracking tasks in a session, each subject was asked to conduct the IMVF (duration, 5s) and IMVE (duration, 5s) of the elbow at a 90° elbow angle at a repetition of 3 times respective, with a 5-minute rest break after each contraction to avoid muscle fatigue. The EMG signal trials with maximum torque values of IMVE and IMVF were used for control algorithm calculation. In each training session, there were 18 trials of the tracking tasks; and in each trial there were 5 cycles of elbow flexion and extension, following the target cursor moving with 10°/Sec on the computer screen. The assistive torques during the extension phases were provided according to the formula of Eq 2, where  $G$ , the gain, used in this study was equal to 0%, 50%, and 100% alternatively applied to the tracking trials in a session. The resistive torques in the tracking trials in a training session were provided according to Eq 3, where  $a$ , the percentage value, used in this work was 10% and 20% alternatively applied to the tracking trials in a session. The robotic parameters of the EMG activation levels, CI values, and RMSE of the tracking trajectories were also calculated for each trial of all even sessions. The averaged values of the CIs and RMSEs of all trials in a session for subject were used as the experimental readings for statistical analyses. Statistical analyses on the variation of the overall cocontraction indexes, overall EMG activation levels, and the overall RMSEs across the sessions, summarizing the performance of all subjects, were carried out by analyses of variance (ANOVAs) with Bonferroni post hoc test. A paired  $t$  test was used for comparison of the clinical scores before and after the training. The statistical significant level was 0.05 in the study.

#### *ii. Training Effects*

After the 20 sessions of robot training of the elbow extension/flexion, motor improvements could be observed in all subjects, associated with the improved clinical scores of FMA, MSS, and MAS, as shown in Table 1. It was found that the mean values of scores for FMA and MSS had increased significantly ( $P < 0.05$ ) and that of the MAS score also decreased significantly ( $P < 0.05$ ) after the training. For each subjects, the clinical scales indicated improvements in at least 2 items.

Improvements also were observed in the tracking performance evaluated by the RMSE values, shown in Fig 4. The overall RMSE values decreased significantly across the training sessions ( $P < 0.05$ ). The statistically significant decrease occurred at the 10<sup>th</sup> session compared with the values of the 2<sup>nd</sup>, 4<sup>th</sup>, and 6<sup>th</sup> sessions. The decreasing process of RMSE during the training represented a motor re-learning procedure in a physical task<sup>8</sup>, which is characterized by a plateau of little or no change in performance<sup>35</sup>. Therefore, in this work, after the 10<sup>th</sup> session, the tracking skill had been stably developed or learned by the subjects after stroke, because the RMSE reached its steady state after the 10<sup>th</sup> session.

The EMG activation levels of the individual muscles (see Fig 5) and the cocontraction indexes of the muscle pairs (see Fig 6) were used to investigate the muscle coactivation patterns during the task-oriented and robot-assisted training. Before the 10<sup>th</sup> session, the overall RMSE values during tracking were relatively high. This was associated with the higher overall EMG levels of the BIC, TRI, and AD muscles, during which the cocontractions, i.e., the overall cocontraction indexes, between the different muscle pairs were also high. This was mainly due to the over-activation of muscles during the initial period of motor learning for a skillful task, and the spasticity after stroke, which could cause extra muscle activities. Significant decreases were found in EMG levels of BIC and AD muscles in later training sessions ( $P < 0.05$ , after the 10<sup>th</sup> session), which was mainly due to the reduction of muscle spasticity, since the tracking skill of the subjects was stable after session 10.

Subject	Pre-Training			Post-Training		
	MAS	FMA	MSS	MAS	FMA	MSS
1	1	15	15	1	17	19.6
2	2	14	16.4	0	17	18.6
3	2	14	12	1+	15	16
4	2	12	18.6	1	15	18.6
5	2	14	12.6	1	14	14.4
6	2	10	14.4	1+	14	21
Mean±SD	1.8±0.4	13.2±1.8	14.8±2.4	0.96±0.5	15.3±1.3	18.0±2.4

Table 1. The clinical scales measured before and after the training.

The cocontraction between the antagonist muscle pair around a joint in subjects without impairment could contribute to stabilizing the joint in a static motion <sup>36</sup>, and to movement accuracy in a dynamic motion <sup>37</sup>. However, excessive cocontractions are energetically expensive <sup>37</sup>, and abnormal muscle coactivation patterns, mainly cocontractions, in the paretic limb after stroke even degrade the accuracy and efficiency of limb movements <sup>28</sup>. Significant decreases in the cocontraction index values of all muscle pairs (see fig 5) were observed during the training ( $P < 0.05$ ), which suggested overall improvement in the coordination of the individual muscles in the tracking task. There are two major reasons that could explain the decreased cocontraction index of a muscle pair: the reduction in the EMG level of the muscles, and the reduced cocontracting phase of the two muscles. The decrease in the overall CI of TRI and PD was mainly due to the reduction of the EMG level of TRI, since the variation of this CI was consistent with the change in the overall TRI EMG levels. However, for the overall CI between BIC and TRI, further decrease after 10<sup>th</sup> sessions were observed, when the overall EMG levels of the two muscles were almost unchanged. It suggests that this decrease was not related to the reduction in the excessive EMG activation of the antagonist muscle pairs, but the reduced cocontracting phase of the BIC and TRI. It also indicated an improved contracting/relaxing phasic pattern of the BIC and TRI during the elbow extension and flexion in the later sessions of the training. The decrease of the

overall CI for BIC and TRI appeared later with a longer time course than the decreases in EMG levels of the respective BIC and TRI muscles. There was no steady state reached by the decreasing CI for BIC and TRI within the 20 sessions. It implied that further improvement in the coordination between the BIC and TRI possibly could be obtained by providing additional sessions. The decreasing in the overall CIs of BIC & AD, TRI & AD, and BIC & PD in later training sessions indicated the better isolation in movements related to the two adjacent joints, i.e. the shoulder and elbow, during the elbow tracking task. This improvement was related to the reduction in excessive activation of shoulder muscles, e.g. the AD muscle. The decrease in the overall CIs of BIC&AD, AD&PD, and TRI&AD till the 20<sup>th</sup> session also suggests that further reduction in these CIs was possible with more training sessions.

#### 4. Conclusion

Significant motor improvements in the poststroke subjects were obtained after the elbow training assisted by the cEMG-driven robot. Robotic parameters also could be used to quantitatively monitor the process of the motor recovery, which provided more information on the extent of the motor recovery than the clinical scores assessed before and after the training. In the future works, comparison should be carried out between the training effects by the cEMG-driven robot and those by the other rehabilitation robots with control strategies, such as, the EMG-triggered control<sup>15</sup>, impedance control<sup>11</sup>, etc, by large-scale randomized control trials. In the robot design aspect, the cEMG-driven interactive control algorithm can be applied to other joints, such as, the wrist, the knee, and the ankle. The related robot-assisted training effects on the different parts of the body also need to be evaluated in future works. It is possible that the training effects may be elevated by integrating more vigorous visual sensory feedbacks, such as virtual reality programs.

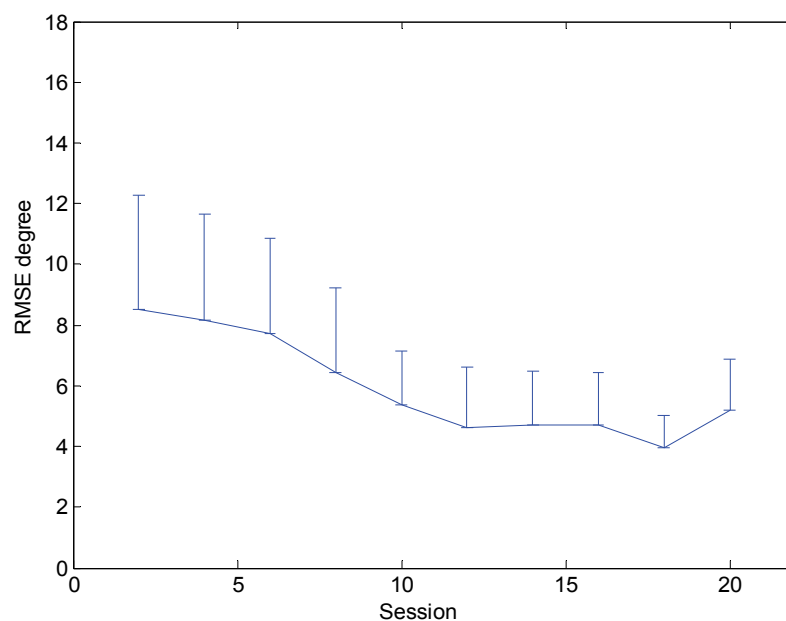


Fig 4. The variation of the overall RMSE values across the training sessions, represented by the values of mean and standard deviation (SD) (error bars).

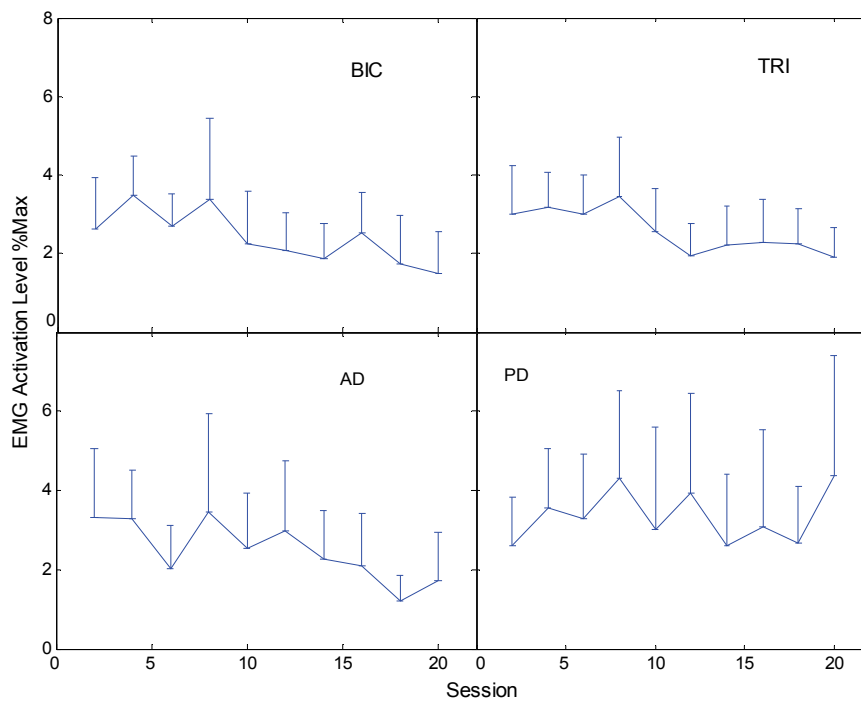


Fig 5. The variations of the overall electromyographic activation level for the biceps brachii, triceps brachii, anterior deltoid, and posterior deltoid muscles, represented by values of mean and SD (error bar).

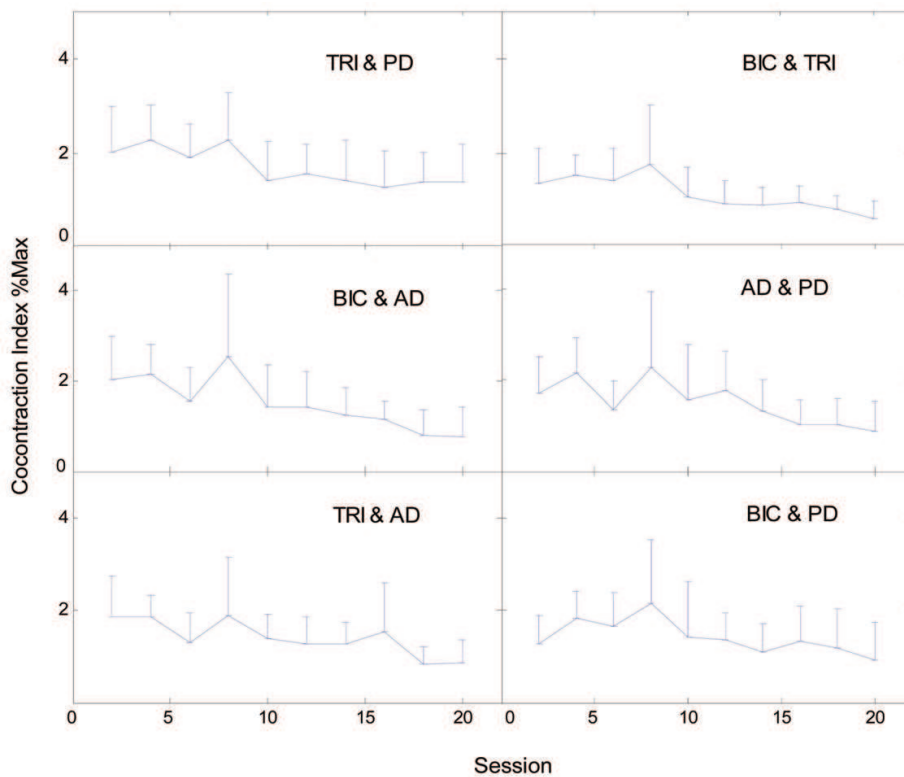


Fig 6. The variations in the overall cocontraction index of the muscle pairs, triceps brachii and posterior deltoid, biceps brachii and triceps brachii, biceps brachii and anterior deltoid, anterior deltoid and posterior deltoid, triceps brachii and anterior deltoid, and biceps brachii and posterior deltoid, represented by the values of mean and SD (error bar).

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The aim of this book is to provide new ideas, original results and practical experiences regarding service robotics. This book provides only a small example of this research activity, but it covers a great deal of what has been done in the field recently. Furthermore, it works as a valuable resource for researchers interested in this field.

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