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Coordinated Upper Limb Training Assisted with an Electromyography (EMG)-driven Hand Robot after Stroke

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***Abstract*— An electromyography (EMG)-driven hand robot had been developed for post-stroke rehabilitation training. The effectiveness of the hand robot assisted whole upper limb training on muscular coordination was investigated on persons with chronic stroke (n=10) in this work. All subjects attended a 20-session training (3-5 times/week) by using the hand robot to practice object grasp/release and arm transportation tasks. Improvements were found in the muscle co-ordination between the antagonist muscle pair (flexor digitorum and extensor digitorum) as measured by muscle co-contractions in EMG signals; and also in the reduction of excessive muscle activities in the biceps brachii. Reduced spasticity in the fingers was also observed as measured by the Modified Ashworth Score.**

I. Introduction

Approximately 70% to 80% of people after stroke have upper-extremity impairments [1, 2]. However, in the rehabilitation of the upper limb, many stroke survivors experienced reasonable motor recovery of their proximal upper limb (e.g., the shoulder and the elbow) but limited recovery at the distal (e.g., the wrist and the fingers) [3, 4]. Disability from upper limb impairment depends primarily on the loss of hand function and finger dexterity [5]. This might be due to the difficulty of managing the movements of the proximal joints and the finger movements at the same time, and the therapist and the patient usually start a training program with the large and proximal joints first. It is possible that incorporating well controlled finger movements during the upper limb training may improve the training effects, especially at the hand.

Rehabilitation robots not only can provide therapy for long time period, in a consistent and precise manner, but also can facilitate some fine control on the limb movements by motors, such as for the fingers. However, most of current rehabilitation robots are designed for large joints, e.g., the elbow and the shoulder [6-9]. Some robots for hand also have been developed for post-stroke training, e.g., the Hand Wrist Assistive Rehabilitation Device (HWARD) system [10], which can provide the hand grasping/opening and wrist extension/flexion movement, and the HapticKnob system for hand grasping and forearm pronation/supination [11]. However, when using these hand/wrist systems, subjects mainly focus on the hand/wrist practices, but not the whole upper limb movements, e.g., the proximal joints (i.e., the shoulder and the elbow), which could be one of the reasons that limits the further improvement of the proximal joint functions as reported [10] [11]. Furthermore, most of the evaluations on training effectiveness by robot-assisted rehabilitation are only conducted by the traditional clinical assessments before and after the training. More detailed and quantitative descriptions on the training progress are needed for further understanding on the treatment-method-related motor recovery.

In this study, we applied a hand robot on the paretic hand of subjects with chronic stroke during the whole upper limb training. The robot hand can perform hand grasp and open according to the subject's voluntary motor intention represented by the electromyographic (EMG) signal from the residual muscles [12, 13]. We investigated the training progress during the robot hand assisted practice by monitoring the variation of EMG properties.

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II. Methodology

A. *The EMG-driven Hand Robot*

Fig 1 shows the experimental setup and the illustration of the mechanical structure of the robot hand in the study. The hand robot had five individual fingers, and each of them was actuated by a linear actuator (Firgelli L12, Firgelli Technologies Inc.) and could provide 2 degrees of freedom for each finger. The proximal section would rotate around the virtual centre located at the metacarpophalangeal (MCP) joint, whereas the distal section would rotate around the virtual centre located at the proximal interphalangeal (PIP) joint for the index, the middle, the ring and the little fingers. The position of the thumb could be adjusted according to the object size. The thumb would rotate around the virtual centre of its MCP joint. From fully extended position to fully flexed position, the finger assembly would provide 55 degrees and 65 degrees range of motion (ROM) for the MCP and PIP joints respectively, and the two joints would rotate together to help the hand perform close and open movements. The total weight was 489 grams [12]. The finger positions and the palm position could be well fixed by belts with velcro on the hand robot.

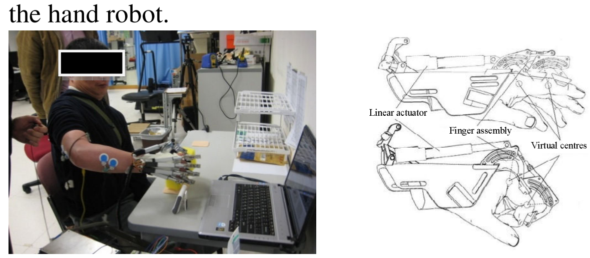


Fig.1 Experimental setup and the illustration on the mechanical structure of the robot hand.

The hand opening motion was controlled by the EMG signal from the extensor digitorum (ED) muscle; and the hand closing movements was controlled by the EMG from the abductor pollicis brevis (APB) muscle. Before the digitization, the EMG signals were first amplified with a gain of 1000, then were filtered with a band-pass filter from 10 to 500 Hz. After the digitization, the EMG signals of the APB and ED were rectified and low-pass filtered (10Hz cutoff frequency with forth-order, zero-phase forward and reverse Butterworth filter) to obtain the envelope of the signal, i.e. the EMG level. The motor movement was initiated by the EMG levels of APB and ED for respective hand closing and opening, once the mean EMG level of a muscle with a length of 100ms exceeded a threshold pre-set before each session; then, the motor of all the fingers would move at a constant angular velocity of 22^{o}/s with the virtual center of the MCP joint and 26^{o}/s with the virtual center of the PIP joint (The thumb only has the MCP joint).

B. Training Protocol

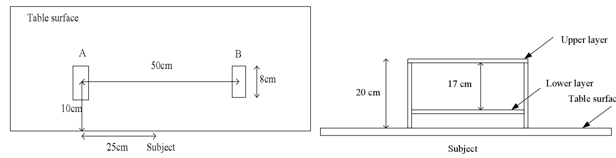
Ten subjects with chronic stroke (i.e., at least 6 months after the onset of a singular and unilateral brain lesion due to stroke, 3 females and 7 males, age=53.2±11.5 yrs) were recruited after obtaining approval from the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University.

Each subject was invited to attend a 20-session hand robot assisted upper limb training with a training intensity of 3 to 5 sessions/week and within 7 consecutive weeks. In each session, a subject first was required to conduct the maximum voluntary contractions (MVCs) at the muscles of APB, ED, flexor digitorum (FD), the biceps brahcii (BIC), and the triceps brachii (TRI) for two times. Each MVC was maintained for 5 seconds, and 2 minutes rest was allowed between two consecutive contractions to avoid fatigue. In each training session, a subject was seated in front of a table with a position that the height from the surface of the table to the shoulder of the subject is from 30cm to 40cm (Fig 1). The subject was first required to conduct two bare hand evaluation tasks by using the paretic upper limb without wearing the robot system:

1) Lateral arm reaching and grasp: For left hemiplegia, grasp a sponge with a thickness of 5 cm and transport 50 cm horizontally from point A on the left of a table and to point B on the right of the table (Fig 2.a). Release the sponge at point B, and then grasp it again and return to A. For right hemiplegia, a subject would start from point B.

2) Vertical arm reaching and grasp: Grasp the sponge from the lower layer of a shelf, lift it 17 cm vertically, and put it on the upper layer, then pick it up and put it back to the lower layer (Fig 2.b).

Each lateral and vertical task was repeated for three times. The subjects were also instructed to use their natural speed to perform the evaluation tasks. In an evaluation trial, the start of the EMG recording was when a subject received the command from the operator, and the end of the recording is when the sponge was released from the testing hand at the target position. All the subjects could grasp the sponge during the bare hand evaluation across the sessions. However some (n=5) could not release the sponge in the early sessions of the training, and they were instructed to try their best to perform the hand open. Therefore, we set a 10-second maximum time limit: If the paretic hand could not release in 10 seconds, then they were allowed to use the unaffected hand to take off the sponge. At the 20^{th} session of the training, two of the five could release the object by the paretic hand without help.



a. Horizontal Task b. Vertical task

Fig 2. Seating configuration during the evaluation and training. a) is for the horizontal task, and b) is for the vertical task.

After the evaluation tasks, the subject was instructed to conduct the lateral and vertical arm reaching and grasp tasks respectively for 10 minutes with the EMG-driven hand robot on the paretic side with the same seating configuration as for the evaluation. A subject could have 20 minutes rest after the first 10 minutes training.

The EMG threshold in each session for individual subjects was a value that a subject could successfully trigger the motor of the robot hand by their voluntary EMG signals. The threshold value would be gradually increased once a driving muscle (i.e., ED for hand open and APB for hand close) could generate stronger EMG signals. The minimum value of the threshold was 3 times of the standard deviation (SD) of the EMG baseline during the resting state of the paretic hand, and the maximum value was 10% of the EMG level during MVC of a driving muscle throughout the training. Fig 3 shows a representative EMG trial of APB muscle during the robot hand assisted hand closing, when the triggering threshold was set at 10% of MVC.

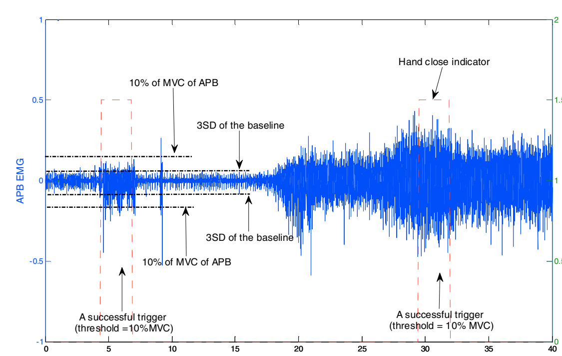


Fig 3. Representative EMG trial of APB during robot hand assisted hand closing from a stroke subject, when the triggering threshould was set at 10% of MVC.

C. Evaluation on the training effects

Before and after the hand robot training, clinical assessment the Modified Ashworth Scores (MAS) on the elbow, wrist and fingers [14] were measured by a blinded assessor. EMG signals from the FD, BIC and TRI were also captured during the bare hand evaluation, together with those from the APB and ED muscles in each session. Two EMG parameters were calculated for the cross-session monitoring, i.e., 1) EMG activation level of each muscle, and 2) co-contraction index (CI) between a muscle pair. The calculation methods for these two parameters had been illustrated in detail in our previous studies [15-17]. Paired t-test was conducted on the MAS scores, by comparing the data pre- and post- training of the same subjects. The one-way analyses of variance (ANOVA) with repeated measures (Bonferroni Post hoc test) were used to evaluate the training effect on the EMG parameters across different sessions during the training. The level of statistical significance was set at 0.05 in this study.

III. Results

Significant reduction of spasticity in fingers was obtained after the training (P<0.05). The MAS (finger) reduced from 1.5±1.17 to 0.78±0.87. However, release of spasticity in the wrist and elbow joints were not significant.

Fig 4 shows the EMG activation levels of the muscles during the bare hand evaluation tasks and across the training sessions. Significant decrease in EMG level was found in the ED and FD for the horizontal evaluation (P<0.05, 1-way-ANOVA with post hoc tests). The EMG level of ED dropped 31.1% and 17.2% for the FD muscle, by comparing the mean values of the first and the last sessions. Significant decrease in BIC EMG level and significant increase in TRI EMG level were observed during the vertical evaluation (P<0.05, 1-way-ANOVA with post hoc tests). The TRI EMG level increased 36.1%, and the EMG level decrease in BIC was 12.1%. Fig 5 shows the co-contraction indexes of the different muscle pairs during the evaluation across the training sessions. The CIs for the muscle pairs of FD&ED, ED&BIC, FD&TRI, FD&BIC, and ED&TRI decreased significantly in the evaluation of horizontal task across the sessions (P<0.05, 1-way-ANOVA with post hoc tests). By comparing the first and the last sessions, the decrease in the CI of FD&ED was 33.4%, ED&BIC was 23.6%, FD&TRI was 27.8%, ED&TRI was 41.8%, and FD&BIC was 28.9%. The co-contraction for the muscle pairs of FD&TRI, BIC&TRI, and APB&TRI increased significantly during the vertical task evaluation (P<0.05, 1-way-ANOVA with post hoc tests). By comparing the mean values in the first and last sessions, the increase of CIs in FD&TRI was 95.8%, in BIC&TRI was 51.5%, and in APB&TRI was 31.6%.

IV. Discussion

The reduction in the MAS_finger indicated a release of the flexor spasticity in the finger joints. It also suggested that by using the hand robot, it was effective to reduce the joint spasticity, which was consistent with other robot assisted trainings on different joints of the upper limb [5, 10, 18]. The spasticity reduction at the elbow and the wrist was not that significant as at the fingers. In this study, there was no robotic support to the elbow and wrist joints to formulate the range of motions of the two joints during the training. It might imply that voluntary physical practice assisted by robot with well defined joint movement could be more effective in releasing spasticity and motor coordination.

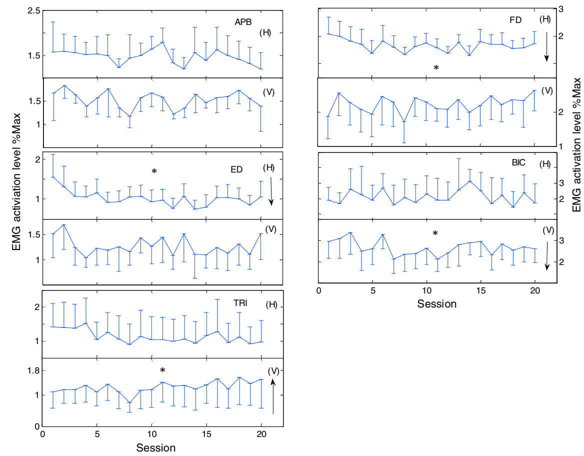


Fig 4. The EMG levels of the muscles of APB, ED, FD, BIC, and TRI during the evaluation. For each muscle, the upper panel is for the horizontal task evaluation (H) and the lower panel is for the vertical task evaluation (V). Variations with statistical significance (P<0.05 with one-way-ANOVA) are marked with '*', and the up and down arrows show the increasing and decreasing trends (with post hoc tests).

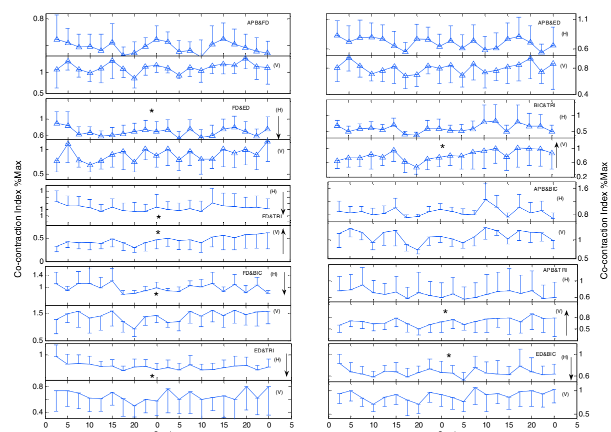


Fig 5. The muscle co-contraction indexes for the muscle pairs of APB&FD, APB&ED, APB&BIC, APB&TRI, FD&TRI, FD&ED, FD&BIC, ED&BIC, ED&TRI, and BIC&TRI during the evaluation. Variations with statistical significance (P<0.05 with one-way-ANOVA) are marked with '*', and the up and down arrows show the increasing and decreasing trends (with post hoc tests).

Individual muscle activation and co-ordination patterns among the firing muscles could be monitored by EMG signals. For the results of the bare hand evaluation, the cross-session significant changes in the EMG levels of ED, FD, BIC, and TRI during the evaluation tasks were mainly caused by two factors: 1) reduction of the spasticity in the flexors, and 2) less muscular effort needed for achieving the task. The muscle coordination in FD&TRI, FD&BIC, ED&TRI, FD&ED, and ED&BIC were improved during the training, as indicated by the decrease in the CI values of these muscle pairs during the cross-session bare hand horizontal evaluation. The decrease of CI value of a muscle pair suggested that the two muscles could contract more independently and might generate more possible co-activation patterns. For example, the subjects who could not release the sponge during the evaluation usually had high CI values in the FD&ED in early sessions, the reduced FD&ED CI was also related to the improved performance, i.e., opening the hand and releasing the sponge without help. The decreases in CI value of the muscle pairs related to the FD and ED muscles also indicated a better motor control on the finger movements during the hand open and close, and more independent hand functions separated from the muscle co-contraction compensated from the proximal joint, e.g., the elbow. The reduction in EMG level of the finger flexor (i.e., FD) also could be related to the reduced MAS_finger score after the training. It was observed that the reduction in FD muscle reached to a plateau around session 8, and that for the ED muscle was around session 12. The reduced FD and ED EMG levels also resulted in a reduction in the co-contraction in FD&ED. That means a better separation of the motion between the two muscles for the hand grasp and open tasks in the horizontal task. However, neither reduction in FD&ED co-contraction nor reduction in EMG levels of the FD and ED muscles was observed in the bare hand evaluation of vertical task. One of the reasons could be that more muscular efforts were needed for the fingers to hold the sponge still and to lift it against the gravity for the up and down movements. Spastic BIC and weak TRI were commonly observed in stroke survivors. During the vertical task, the subjects conducted the forward reaching and arm withdraw, which required more muscle effort for elbow extension and flexion by BIC and TRI muscles than in the horizontal task. The reduced BIC EMG level and increased TRI EMG level in the vertical task suggested the reduction in BIC activities (mainly due to the spasticity and excessive muscle efforts) and increased muscle power in the TRI during the arm reaching movements across the training sessions. It was also found that the increase of the TRI EMG level did not reach a plateau within the 20 training sessions. More training sessions possibly may result in better motor improvement at the elbow joint. The increase of the TRI EMG level also was related to the increased CIs of FD&TRI and BIC&TRI in the vertical evaluation tasks. From the results in the bare hand evaluation, it could be seen that the training would improve the coordination between the FD and ED during hand grasp and open (evaluated in the horizontal tasks), and also could result in a reduced BIC activity and an increase in TRI muscle power (evaluated in the vertical tasks).

V. Conclusion

In this work, we investigated the effects and motor recovery during the EMG-driven robot hand assisted task-oriented upper limb rehabilitation training. The EMG analysis showed that the whole upper limb training incorporated with the EMG-driven robot hand could improve the muscle co-ordination between the antagonist finger muscle pair, i.e., the flexor digitorum and extensor digitorum, and also could reduce the excessive muscle activities in the biceps brachii.

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