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Robot-Assisted Wrist Training for Chronic Stroke: A Comparison between Electromyography (EMG) Driven Robot and Passive Motion

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***Abstract*— The motor recovery procedure during robot-assisted wrist rehabilitation for persons after stroke has not been well studied previously. In this work, we carried out a comparative study on the training effects on 10 hemiplegic persons with chronic stroke between a wrist treatment assisted by an electromyography (EMG)-driven robotic system (interactive treatment, n=5, EMG group) and a wrist treatment assisted by a clinical robot system with continuous passive motion (n=5, passive group). Significant decreases (P<0.05) in muscle spasticity were observed at the wrist joint in both the EMG and passive groups; and reduced muscle spasticity at the elbow joint were also obtained in the EMG group (P<0.05). These spasticity decreases were associated with the reduction of EMG activation levels during the training. The EMG-driven robot-assisted training also improved the muscle coordination capability of the persons after stroke.**

I. 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 [1, 2].

Physical training for stroke rehabilitation is an arduous process, because post-stroke 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 [3]. 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 [4-7]. Due to the effectiveness in motor improvement by active-assisted robotic treatment, the recent developments involving rehabilitation robots has been worked towards the active-assisted control strategies for interactive rehabilitation treatment, which allows the robotic system to react to patient's voluntary intention. In the rehabilitation of the upper limb, many stroke survivors experienced reasonable motor recovery of their proximal upper limb (shoulder and elbow) but limited wrist recovery at the distal [8, 9]. In our previous work, an electromyography (EMG)-driven rehabilitation robot has been developed for interactive physical training on the respective elbow and wrist joints of stroke subjects [10-12]. Significant motor improvements were found in the trained upper limbs after the robot-assisted training.

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 post-stroke rehabilitation training is that the robot could be a platform for quantitative monitoring on the motor recovery process during the 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- evaluations by clinical scales (e.g. Fugl-Meyer Assessment (FMA)[13], the FIM instrument, the Modified Ashworth Scale (MAS)[14], etc.) were conducted to assess the training effects, even in most of studies related to robot-assisted rehabilitation [3-5].To explore the effects of a post-stroke treatment and the related recovery process in patients and compare with other treatments are important for the design and improvement of a rehabilitation program. Although the motor improvement in stroke rehabilitation by the interactive robot-assisted treatments has been reported to be better than the continuous passive motion [4], the quantitative comparison in the motor recovery process by these two different training strategies has not been well studied. To understand the difference between the two different post-stroke training strategies is important for later rehabilitation program design. In this work, we made a comparative study on the variation of motor abilities during EMG-driven robot-assisted wrist training (interactive treatment) and during robot-assisted wrist training with continuous passive motion for chronic stroke patients.

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II. METHODOLOGY

After obtaining approval from the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University, we recruited 10 hemiplegic subjects after stroke for the study. All of the subjects were in the chronic stage (at least 1 year postonset of stroke; 7 men, 3 women; age, 50.2±10.2y). Before the wrist training, all of the subjects had intermediate motor impairment in the upper limb assessed by FMA (for elbow and shoulder) and joint spasticity at the wrist and elbow assessed by the MAS score. Then, the recruited subjects were randomly assigned into two groups for the wrist training, i.e., the group received the interactive treatment assisted by the EMG-driven robot (EMG group), and the group received the robot-assisted wrist training with continuous passive motion (passive group). Both of the two groups received a wrist training program consisting of 18 sessions, with at least 3 sessions a week and at most 5 sessions a week, and finished in 7 consecutive weeks.

For the EMG group, in each training session, each subject was seated with the paretic arm mounted on the robotic system developed in our previous work as specified in Fig 1 [10-12]. EMG signals were recorded from the muscles of the triceps brachii (TRI, lateral head), biceps brachii (BIC), flexor carpi radialis (FCR), and extensor carpi radialis (ECR). The sampling frequency for EMG signals was 1000 Hz (NI 6036E, USA). In each session, maximum isometric voluntary contraction of wrist flexion (IMVF) and extension (IMVE) at 0^o of the wrist angle were conducted with a repetition of 3 times for each before the training; and each maximum isometric contraction lasted for 5 seconds. Then, the subject was required to conduct the voluntary wrist flexion and extension in the wrist range from -45^o to 60^o (Negative sign represented the extended position, and the positive sign represented the flexed position.) by tracking a target cursor moving with angular velocity of 10^o/sec for both flexion and extension on the screen. During the tracking, assistive torques were provided by the motor, which were proportional to the EMG amplitudes of FCR and ECR muscles [11, 15]. The reason for choosing FCR and ECR muscles as the driving muscles to the motor system was that the two muscles are the main antagonist muscle pair for the wrist extension and flexion. The assistive torque generated by the motor system during the tracking was defined as:

$$T_a = \begin{cases} G \cdot T_{IMVF} \cdot M_{Flexion}, & \text{During the flexion tracking phase} \\ G \cdot T_{IMVE} \cdot M_{Extension}, & \text{During the extension tracking phase} \end{cases}, \quad (1)$$

where, T_a represents the motor generated assistive torque in the flexion or extension phase during the tracking, G is a constant gain used to adjust the magnitude of the assistive torque; and T_{IMVE} and T_{IMVF} are the maximal values of the torque during isometric extension and flexion respectively, at the wrist angle of 0^o. $M_{Flexion/Extension}$ in Eq 1 is defined as

$$M_{Flexion/Extension} \equiv \frac{EMG_{m,Flexion/Extension} - EMG_{mREST}}{EMG_{mIMV} - EMG_{mREST}}, \quad (2)$$

where $EMG_{m,Flexion/Extension}$ is the EMG of the agonist muscle, *m*, in its contraction phase during the tracking (e.g. the EMG of FCR during the wrist flexion phase, or the EMG of ECR during the wrist extension phase); EMG_{mREST} is the averaged EMG of the muscle, *m*, during its resting state; and EMG_{mIMV} is the maximal EMG value of the muscle, *m*, during its isometric voluntary contractions.

In a training session, there were 14 trials, and each trial had 5 cycles of elbow extension-flexion. Resistances with 10% and 20% of the torques during the maximum voluntary contractions were generated by the motor and alternatively added to the trials in a session [11, 15]. For the passive group, the testing and rehabilitation system (CYBEX and NORM, Computer Sports Medicine, Inc, USA) was used for the training. In each training session, the standard setup for wrist extension and flexion of the CYBEX and NORM system was adopted for the passive mode training [16]. The range of motion for the wrist joint was set from -45^o to 60^o, and the palm was fixed on a handle moving passively with an angular velocity of 10^o/sec for both the wrist extension and flexion. In a passive mode training session, there were 14 trials, and each trial contained 5 cycles of extension and flexion. EMG signals were also recorded from the FCR, ECR, BIC, and TRI muscles in the tested arm. Before the passive mode training in each session, IMVF and IMVE at the wrist angle of 0^o were also conducted with a repetition of 3 times for each as those for the EMG group.

EMG activities from the muscles of interest were recorded during the IMVE/IMVF and during the training trials for both groups. Forth-order, zero-phase forward and reverse Butterworth digital filters were adopted for the offline filtering processes. The raw EMG signal trials were first band-pass filtered from 10 Hz to 500 Hz. Then, the linear envelope of the recorded EMG signals (during the IMVE/IMVF and the training) was obtained by 1) full-wave rectification, 2) lowpass filtering for obtaining the EMG envelope (10 Hz cut-off frequency), 3) subtraction of the baseline EMG activity during the resting state, and 4) normalized to the maximum value of EMG activation during IMVF/IMVE of each session. Fig 2 shows the representative EMG envelope trials during the training for the two groups. The EMG signal length for the EMG group usually is longer than the passive group. It was because the wrist extension and flexion in the EMG group were completed by the voluntary movement from the paretic limb of the subjects (usually associated with some delays); while in the passive group the wrist movements just passively followed the programmed angular velocity for the wrist joint (i.e. 10^o/sec) within the range of motion. The coactivation among muscle pairs during the IMVF/IMVE of each session were studied by the cocontraction index (CI) as used in the previous works [17], that is,

$$CI = \frac{1}{T}\int_T A_{ij}(t)dt, \quad (3)$$

where, Aij(t) is the overlapping activity of EMG linear envelopes for muscle i and j, T is the length of the signal trial. The value of a CI for a muscle pair varied from 0 (non-overlapping at all in the trial) to 1 (totally overlapping of the two muscles with both EMG levels kept at 1 during the trial). EMG activation level of a muscle in a training trial was also calculated by averaging the EMG envelope of the trail. The CIs for different muscle pairs, and the EMG activation levels of each muscle were calculated for each trial of all sessions. The averaged values of the CI and EMG activation level in the same session for a subject were used as the experimental readings for statistical analyses, since it was understood that the subsequent trials in one session were not independent. The analyses of variance with repeated measures [18] (ANOVA, 2-way with respect to the factors of group and training sessions, 1-way with respect to training sessions and with Bonferroni post hoc test) were carried out for the understanding on the effects from the group difference and training sessions. Pre- and post- training assessments by the traditional clinical scores (FMA and MAS) were also conducted by a physical therapist who was blinded to the training protocol. Paired t-test [18] was used to evaluate the variation of the clinical scores after the training. The statistical significant level was chosen at 0.05 in this work as done in many other studies [6, 19, 20].

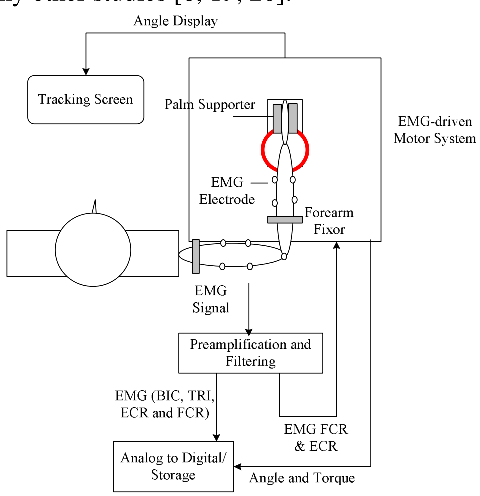

Fig 1. The training setup for the subjects who received the EMG-driven robot-assisted interactive wrist treatment.

III. Results

Fig 3 shows the clinical scores of MAS and FMA before and after the wrist training for the EMG and passive groups. For the EMG group, it was found that the MAS scores of the wrist and elbow joints decreased significantly after the training ($P<0.05$). However, significant decrease was only observed in wrist MAS scores for the passive group ($P<0.05$). The improvement in FMA (elbow/shoulder) was found in the EMG group after the training ($P<0.05$). The mean value of the FMA scores for the wrist/hand part was increased after the training for the EMG group; however, this increase was not significant. There was no statistical significant change in FMA scores for the passive group. Fig 4 illustrates the variation of EMG activation levels of the BIC, TRI, FCR, and ECR muscles across the training sessions for the EMG and passive groups. Significant decreases in the FCR and BIC muscles across the training sessions were found in the EMG group ($P<0.05$, 1-way-ANOVA with post hoc tests). Significant decreasing trends in the ECR and FCR muscles were observed starting from session 5 and 6 respectively in the passive group ($P<0.05$, 1-way-ANOVA with post hoc tests). There were significant differences in the EMG activation levels between the EMG group and passive group for all muscles ($P<0.05$, 2-way-ANOVA on group factor). Most of the mean values of the EMG activation levels of the muscles in the EMG group were higher than those in the passive group. Fig 5 shows the variation of cocontraction indexes of the different muscle pairs across the training sessions for the EMG group and the passive group. Significant decreasing trends were observed in CIs of the muscle pairs of FCR&BIC and BIC&TRI for the EMG group ($P<0.05$, 1-way-ANOVA with post hoc tests). The variations of CI values across the training sessions for all muscle pairs in the passive group were found to be significant ($P<0.05$, 1-way-ANOVA with post hoc tests). However, these variations did not demonstrate a consisting trend in the training process, such as the increasing or decreasing. Significant group differences in the CI values were found for the muscle pairs of ECR&TRI, FCR&BIC, FCR&TRI, and BIC&TRI ($P<0.05$, 2-way-ANOVA on the factor of group).

IV. Discussion

After the robot-assisted wrist training, improvements have been found in both the EMG and passive groups assessed by the MAS score (Fig 3). The reduced MAS scores suggested a release in the muscle hypertonia of the related joints. It has been found that the reduction of the MAS score was not only for the wrist joint but also for the elbow joint in the EMG group, whereas, reduction of MAS score was only observed for the wrist joint in the passive group. The subjects in the EMG group also obtained more motor functional improvements than the passive group in FMA scores (Fig 3). It seems that the EMG-driven robot-assisted wrist training not only benefited the wrist joint, but also improved the motor function of the elbow joint.

The comparison results of the MAS and FMA scores between the EMG group and passive group before and after the wrist training could be illustrated by the EMG activity levels (Fig 4) and cocontraction indexes (Fig 5) during the training course. Significant decreases of the EMG activation level in the ECR and FCR muscles for the passive group during the training were related to the release of the muscle spasticity of the wrist joint. Muscle spasticity is a common symptom in the paretic limbs of persons with chronic stroke, reflected as uncontrollable excessive muscle activities (represented by high EMG activation level) and increased muscle stiffness [8, 9]. In this study, the continuous passive motion could release the muscle spasticity at the trained joint. This release started from session 5 and 6 till the end of training, and there was no steady state reached by the decrease of the EMG activation levels. It suggested that more training sessions might lead to further release of the muscle spasticity. The EMG activation levels in the EMG group were higher than those in the passive group. It was because that voluntary muscle activity was involved in the training trials during the EMG-driven robot-assisted tracking tasks in the training sessions. Significant decreases in the EMG activation levels in the muscles of FCR and BIC suggested a reduction in the excessive muscle activities in these two muscles, which were also related to the reduction in the MAS scores for the wrist and elbow joints of the EMG group. These decreases in the EMG activation level did not reached to a steady state till the end of the training. Therefore, it might be expected to obtained more reductions, if more training sessions were provided. Cocontraction indexes mainly demonstrate the muscle coactivation patterns, or the capability of coordinating a group of muscles, in a design voluntary motor task [10, 11, 17]. Reduced muscle synergy patterns and tight muscle cocontractions (i.e. co-shortening of a pair of muscles) were widely found in the limb movement of persons after stroke [19, 20]. In this study, the muscle cocontraction between the FCR and BIC muscles, and between the BIC and TRI muscles were significantly decreased during the training course for the EMG group, which suggested a better coordination among these muscles. These decreases were also associated with the improvement in the FMA scores observed after the training. However, the robot-assisted wrist training with continuous passive motion did not contribute to the improvement of muscle coordination capability. The standard deviations in Fig 4 and 5 were large mainly due to subject variations; however, variation tendencies associated with statistical significance still could be observed in this work. The standard deviations could be reduced by including more subjects for the training in our future work.

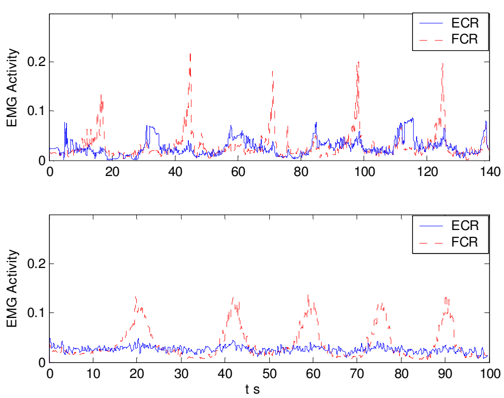

Fig 2.The representative EMG envelope trials from the muscles of ECR and FCR during the wrist training for the EMG group (upper panel) and the passive group (lower panel).

The results in this study provided more information on the difference between the EMG-driven robot-assisted wrist training and the robot-assisted wrist training with continuous passive motion. The continuous passive training only released the muscle spasticity at the trained joint. However, the interactive wrist treatment assisted with the robot driven by EMG not only reduced the spasticity at the wrist joint but also release the muscle spasticity at the elbow joint. The EMG-driven robot-assisted wrist training improved the muscle coordination capability at both the wrist and elbow joints.

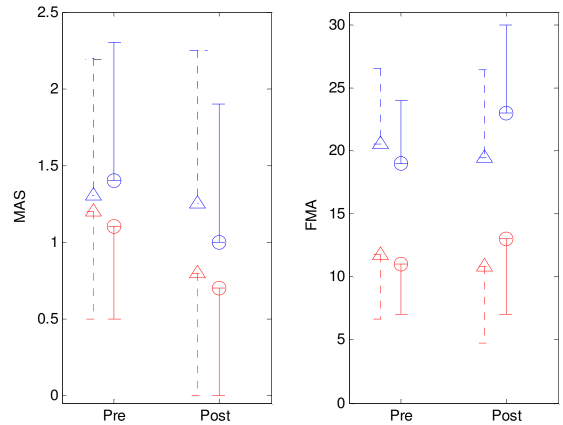

Fig 3. The clinical scores of MAS and FMA for the EMG group (circles) and the passive group (triangles) before and after the wrist training. The clinical score values were represented by mean and standard deviation (the value of a standard deviation was shown as an upper error bar). For the MAS, the mean values with upper error bar are for the elbow joint, and those with lower error bar are for the wrist joint. For the FMA, the mean values with upper error bar are for the elbow/shoulder part, and those with lower error bar are for the wrist/hand.

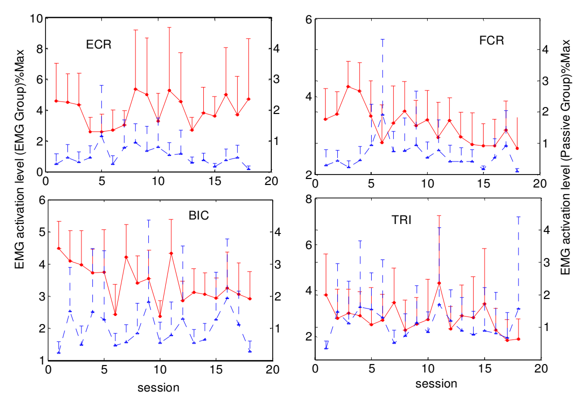

Fig 4. The variation of EMG activation levels of the BIC, TRI, FCR, and ECR muscles across the sessions for the EMG group (solid line) and the passive group (dotted line). The EMG activation levels in each session were represented by mean and standard deviation (the upper error bar).

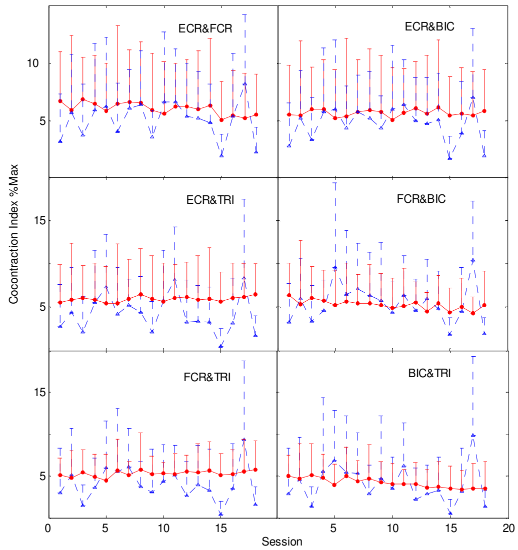

Fig 5. The variation of cocontraction indexes of the different muscle pairs across the training sessions for the EMG group (solid line) and the passive group (dotted line). A cocontraction index in each session was represented by mean and standard deviation (the upper error bar).

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