Muscle Synergies in Chronic Stroke during a Robot-Assisted Wrist Training

X. L. Hu, K. Y. Tong, R. Song, X. J. Zheng, I. F. Lo, K. H. Lui

Abstract— **The motor recovery procedure during robot-assisted wrist rehabilitation for persons after stroke has not been well studied previously. In this work, we analyzed the variations in the muscular co-activation patterns related to the wrist and elbow motions in hemiplegic persons with chronic stroke (n=4) during a 20-session's interactive robot-assisted training. Significant decreases in muscle cocontractions (P<0.05) for all muscle pairs were observed, which was mainly due to the reduction in the muscle activation levels. Improvements were also found in motor functions assessed by clinical scales before and after the training. The results suggested an increased selective control on individual muscles for both wrist and elbow joints in a designed task after the robot-assisted training.**

I. Introduction

ALTERED neural functions were commonly observed in the contralesional neuromuscular pathways in stroke survivors with unilateral brain injury, causing the consecutive neuromuscular changes, such as decreased motor unit firing rates, stiffened and shortened muscle fibers, muscle fiber type alterations, etc [1, 2]. Those changes are often companied with clinical neuromuscular symptoms at the paretic side of stroke survivors, for example, weakness, spasticity, contracture and loss of selective control of muscle coactivations [3-6].

Rehabilitation therapies are helpful to reduce motor impairments and to improve the functional use of the affected limb in persons after stroke. One of the factors for the success of a rehabilitation treatment is to understand the variation of the impaired neuromuscular system during the recovery procedure, based on which adaptive treatment can be applied [7, 8]. For spontaneous recovery after stroke, proximal muscles could gain more than distal muscles, due to anatomical and physiological factors [9]. In rehabilitation trainings of the upper limb, many stroke survivors also experienced reasonable motor recovery of their proximal upper limb (shoulder and elbow) but limited wrist recovery at the distal [10, 11]. A possible reason for the relatively less recovery progress achieved in poststroke wrist rehabilitation training was due to the limited understanding on the relationship between the pathological changes and the physical disabilities at the wrist during rehabilitation trainings; and an appropriate clinical measurement was important for exploring this relationship during rehabilitation treatment. In most studies, only pre- and post-assessments with some common clinical scales (e.g. Fugl-Meyer Assessment, FMA and Modified Ashworth Scale, MAS, etc.) on the motor functions were used for the assessment of the recovery due to the treatment [12-14].

Robot-assisted training is a relatively new approach for poststroke rehabilitation [7, 12, 13, 15]. It has been reported that rehabilitation robots, especially with an interactive control strategy (rather than the devices only conducting passive motions), has been proven to effectively bring further recovery of poststroke motor function, even in the chronic stage after stroke [13]. However, seldom works have been done on monitoring and evaluating the recovery procedure during robot-assisted rehabilitation programs. Muscle coactivation patterns, reflecting the nervous control on the synergy of muscle groups, are highly related to the motor functions, such as stability, dexterity, and accuracy. Excessive and abnormal muscular coactivations, associated with symptoms of stiffness, contracture, motion impairments, etc, are often observed in the affected limbs of persons after stroke. A lot of works have been done on analyses of abnormal muscle coactivating patterns in persons after stroke [16-19]. However these works did not study the pattern changes during a post-stroke rehabilitation training. In our previous work, the changes of muscle synergy in persons with chronic stroke during a robot-assisted elbow training were analyzed [4, 20, 21]. It was found that the improvement in muscle synergy related to the elbow and shoulder movements was associated with the observed improvements in pre- and post- clinical scores [4]. In this work, the progressive changes in

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coactivations among wrist and elbow muscles in hemiplegic persons with chronic stroke were studied by surface electromyographic (EMG) signals during a robot-assisted training, with the purpose of providing a better understanding on the motor recovery mechanism.

II. METHODOLOGY

After obtaining approval from the Human Subjects Ethics Subcommittee of the Hong Kong Polytechnic University, we recruited 4 hemiplegic subjects after stroke for the study. All of the subjects were in the chronic stage (at least 6 months after the onset of stroke, 3 males and 1 female, age=51.3±9.3). Before the training, clinical scores, the Motor Status Score (MSS), the FMA, the MAS, and the Action Research arm test (ARAT), were measured for the paretic upper limb of the all subjects by a blinded assessor. The Functional Independence Measure (FIM) of the subjects was also conducted. Then, all subjects received a wrist training program, consisting of 20 sessions (3 to 5 sessions/week) at their affected limbs. After the training, all the clinical scores mentioned above were assessed by the same assessor again in the next day.

During a training session, the subject was comfortably seated, and the affected upper limb was placed horizontally on a motor-sensor system (The motor: Dynaserv, Yokogawa, Japan; and the torque sensor: AKC-205A, accuracy 0.03Nm, China) with the wrist joint positioned at the origin, as shown in Fig 1. The shoulder angle was around 0^o, the elbow angle was placed around 90^o. The forearm of the affected side was fixed on the platform of the motor-sensor system, and the hand was attached to a manipulandum, which could rotate with the motor with the rotation center at the wrist joint. EMG signals (Noraxon electrodes, USA) were amplified (INA126, Texas Instruments, USA), collected, and stored in a computer from the muscles of flexor carpi radialis (FCR), extensor carpi radialis (ECR), biceps brachii (BIC), and triceps brachii (lateral head, TRI). The sampling frequency for EMG signals was 1000 Hz (NI 6036E, USA). Before the training session, the EMG activities during the maximum isometric voluntary contraction of both wrist flexion (IMVF) and extension (IMVE) at 0^o of the wrist angle were recorded. 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, supportive torques were provided by the motor, which were proportional to the EMG amplitudes of the ECR and FCR muscles. The active-assisted torque during either the extension or the flexion were defined as:

$$T_a = G \cdot T_{IMVC} \cdot M_i \text{, (1)}$$

where, G is a constant gain used to adjust the magnitude of the assistive torque; and T_{IMVC} is the maximal value of the torques during IMVF when doing flexion, or IMVE when doing extension. M_i is defined as

$$M_i = \frac{EMG_i - EMG_{irest}}{EMG_{iIMVC} - EMG_{irest}} \text{, (2)}$$

where, EMG_i is the EMG of the agonist muscle i (ECR during the extension, or FCR during the flexion) after the processes of full wave rectification and moving average with 100ms window, EMG_{irest} is the averaged EMG of muscle i during the resting state, and EMG_{iMVC} is the maximal value of muscle i during its maximal isometric contractions at wrist angle of 0^o. Robot-assisted poststroke rehabilitation with proportional EMG control has been applied in our previous study on elbow training [21]. In a training session, there were 14 sections, and each section had 5 cycles of wrist extension-flexion. Resistive torques were also applied to each section with values of a percentage of the torques during the maximum voluntary contractions (extension and flexion), i.e., $T_r = a \cdot T_{MVC}$, where T_r is the resistive torque, a is the percentage (10% or 20%, alternatively applied to the sections in a session), and T_{MVC} including two parts, the maximal T_{IMVF} (applied in the flexion phase only) and T_{IMVE} (applied in the extension phase only). The net torque provided by the robot during the training is $T_n = T_a - T_r$, where T_a is the supportive torque and T_r is the resistive torque. The purposes of applying the resistive torques proportional to the IMVF/IMVE during the training were 1) to improve the muscle force generation of the paretic limb, and 2) to keep the effective muscular effort at a level, which was associated with the possible increase of muscle force during the training. Subjects were allowed to have a rest of 2 minutes between two consecutive sections. A training session was completed in 1.5 hours.

EMG activities from the muscles of interest and angle signals during the training were recorded and stored in a computer during each session of the training for offline processing. The wrist angle signals were low-pass filtered with a cutoff frequency at 20Hz. A forth-order, zero-phase forward and reverse Butterworth digital filter was adopted for the filtering processes. The linear envelope of the recorded EMG signals was obtained by 1) full-wave rectification, 2) lowpass filtering for obtaining the EMG envelope (10 Hz cut-off frequency with fourth-order, zero-phase forward and reverse Butterworth filter), 3) subtraction of the baseline EMG activity during the resting state, and 4) normalized to the maximum value of EMG activation in each muscle during either a training session or the IMVF/IMVE of each session. The coactivations among muscle pairs during the training were studied by the cocontraction index (CI) as introduced in Frost's study [22], ie,

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

where, $A_{ij}(t)$ 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, which represents an extreme case that the muscle pair contract at their maximal at the same time). The contraction levels of the muscles during the wrist tracking of this study were relatively low (the maximal resistive torque applied during the tracking is 20% of the torques during MVC). Thus the recorded CI for the muscle pairs usually varied below 4%. As the representative segments of EMG envelopes from the muscle pairs and the detected angle signals in a tracking trial were shown in Fig 2, EMG activation level of a muscle in a tracking trial was also calculated by averaging the EMG envelope of the trial. The CIs for different muscle pairs, the EMG activation levels of each muscle, and the root mean squared error (RMSE) between the target and the actual wrist angle were calculated for each section of all sessions. The averaged values of the CI, EMG activation level, and RMSE of the sections 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 (ANOVA) on the variation of the CIs, EMG activation levels and the RMSEs across the sessions, summarizing the performance of all subjects were conducted with Bonferroni post hoc test. The statistical significant level was 0.05 in this work.

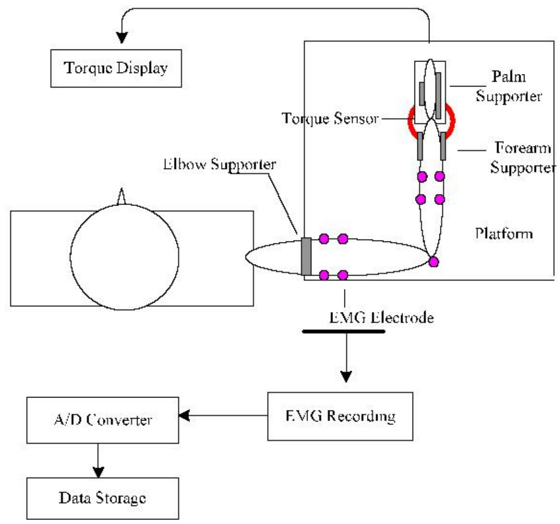

Fig 1. The diagram of the training system.

III. Results

Table 1 shows the comparison on the clinical scores of the hemiplegic subjects before and after the training. Improvements were observed in FMA and MSS (shoulder function) for all subjects after the wrist training. Decrease in the spasticity of the elbow and wrist angle were found in the third subject. All subjects, except the second subject (no change), had improvement in the ARAT score after the training. There was almost no change in the score of FIM assessment before and after the training for all subjects. Fig 3 shows the variation of the RMSE between the target and actual angels during the wrist tracking across the training sessions. A significant decrease (1-way-ANOVA, $P<0.05$, with post hoc tests) in the RMSE values were observed. This decrease occurred mainly from session 3 to session 6. The variation in RMSE from session 7 to 20 was not significant. Fig 4 shows the variations in CI of the muscle pairs studied in this work. The CI values during the tracking task varied significantly across the training sessions in all muscle pairs (1-way-ANOVA, $P<0.05$). A decreasing tendency in the CI values for all the muscle pairs were also observed by the post hoc tests ($P<0.05$). Fig 5 shows the EMG activation levels of the four muscles during the wrist tracking training. The EMG level of the ECR muscle varied significantly across the training sessions. However, no consistent decreasing or increasing tendency was found in the variation of the ECR EMG level. Significant decreases (1-way-ANOVA, $P<0.05$, with Post hoc tests, $P<0.05$) were found in the variation of FCR, BIC, and TRI EMG levels in the training course.

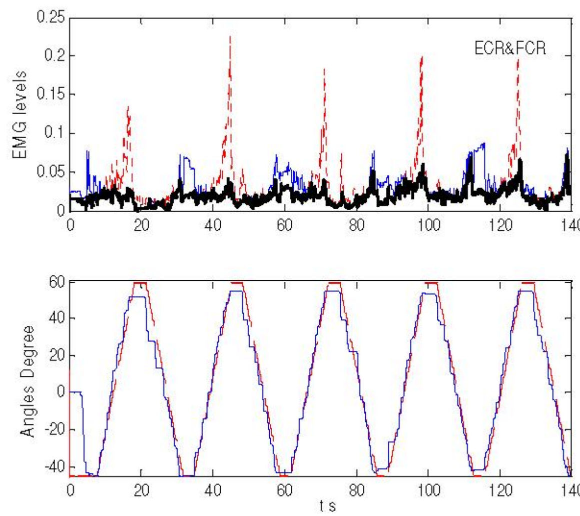

Fig 2. The representative EMG envelopes (upper pane, the thin solid line is for ECR, the dotted line is for FCR, and the thick solid line is for the EMG overlap of the ECR and FCR, CI=2.1%) and wrist angle signals (lower pane, the dashed line is the target angle, the solid line is the actual angle during the tracking.) in a tracking trial.

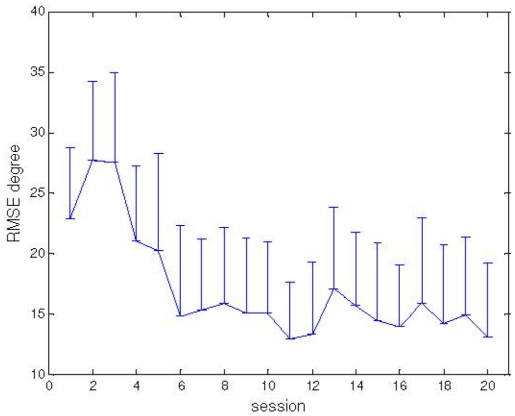

Fig 3. The RMSE summarizing the performance of all subjects during the tracking across the training sessions, represented by the values of mean and standard deviation (error bars).

Subject	MSS		MAS		FMA		ARAT	FIM
	S	EF	E	W	S/E	W/H		
1 (Pre)	21	6.8	0	0	24	18	32	67
1 (Post)	22.8	7	0	0	25	22	38	68
2 (Pre)	15.2	5.6	1+	0	19	7	19	64
2 (Post)	16.2	6.8	1+	0	20	8	19	64
3 (Pre)	17	5.8	1+	1+	22	7	20	67
3 (Post)	18.6	5.8	1	0	24	9	26	67
4 (Pre)	20.4	6.6	1+	1+	17	10	25	67
4 (Post)	22.8	7	1+	1+	22	14	28	67

Table 1. Clinical scores of the subjects before and after the training. In the MSS field, S is for the shoulder, and EF is for the elbow and forearm. In the MAS field, E is for the elbow, and W is for the wrist. In the FMA field, S/E is for the shoulder and elbow, W/H is for the wrist and hand.

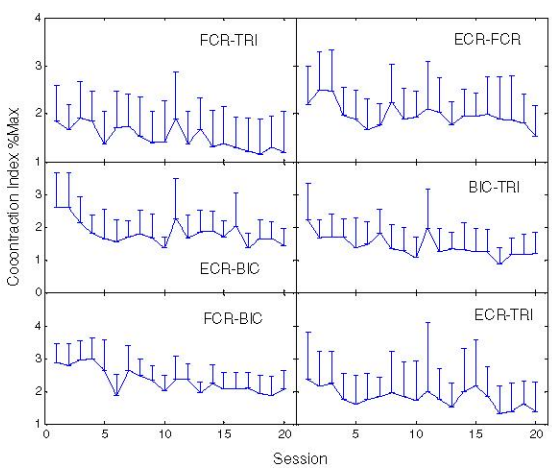

Fig 4. The variations in CI of the muscle pairs, FCR and TRI, ECR and FCR, ECR and BIC, BIC and TRI, FCR and BIC, and ECR and TRI.

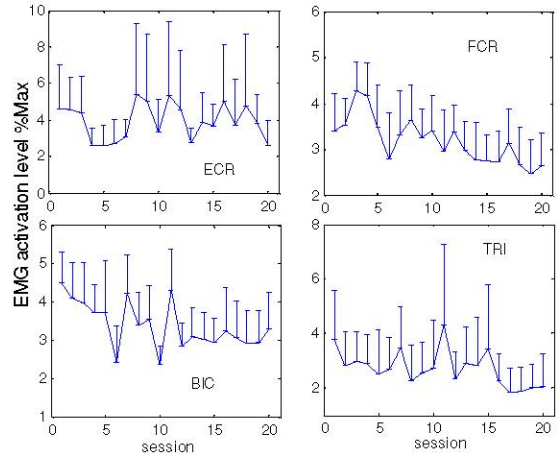

Fig 5. The variations of EMG activation level for the muscles of ECR, FCR, BIC, and TRI.

IV. Discussion

For chronic stroke subjects, it was found that interactive robotic treatment was effective in motor functional improvement [13]. In this work, motor improvements in the wrist, elbow and shoulder were found in almost all hemiplegic subjects after the 20-session's robot-assisted wrist training as assessed by the clinical scales. However, the training effects on reducing the spasticity are not clear at this moment, since only one subject (the third subject) showed the reduction in the MAS. In our previous work on the robot-assisted elbow training [4], almost all subjects (n=4) demonstrated a decrease in elbow spasticity after the training. One of the possible reasons could be that the subjects recruited for this study had minor spasticity. Further analysis is deserved on subjects with more severe spasticity at the wrist and elbow.

The decreased RMSE between the target and the actual wrist angles during the training (Fig 3) suggested the improvement in the tracking performance. After session 6 the tracking skill could be regarded as well established, since no significant variation in RMSE was found. The decreased CIs in all muscle pairs in Fig 4 suggested the improved motor control on individual muscles related to both wrist and elbow joints for the experimental task (the tracking). Decrease in the CI of a muscle pair could be related to the decrease in the EMG levels of the two muscles and the decrease in co-contraction phase of the two muscles during the tracking task. In the subjects recruited in this work, the reduction in the CI of the muscle pairs should be mainly due to the decreased EMG levels in FCR, BIC, and TRI (Fig 5). For many persons after stroke, their wrist movements are always associated with unnecessary elbow motions. The reduction in the EMG levels of BIC and TRI suggested the increased muscle selectivity for the wrist movements, which was less correlated to the elbow activities. This improvement also could be associated with the better motor functions in the elbow and wrist after the training assessed by the clinical scores. Since the decreases in CIs for all muscle pairs (Fig 4) and the reduction in EMG levels for FCR, BIC, and TRI did not reach a steady state, it possibly implied that more training sessions could result in better motor improvement; and EMG co-contraction index, i.e., CI, could be used as a simple measure for monitoring the improvement in muscle synergy during the training.

The results in this work could provide further quantitative understanding on the motor functional recovery of chronic stroke during interactive robot training. In this study, the pre-training motor functions of the subjects after stroke were better than the moderate level, as compared to those in other studies [13]. Further investigation with subjects associated with more severe motor disabilities will be conducted to evaluate the effects of the robot-assisted wrist training with the expectation of more significant motor improvement after the training.

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