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A Comparison between Electromyography (EMG)-Driven Robot and Passive Motion Device on Wrist Rehabilitation for Chronic Stroke

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Abstract

Background: *The effect of using robots to improve motor recovery has received increased attention, while the most effective protocol remains a topic of study.* ***Objective:*** *Our objective was to compare the training effects by treatments on the wrist joint of subjects with chronic stroke with an interactive rehabilitation robot and a robot with continuous passive motion.* ***Methods:*** *This was a single-blinded randomized controlled trial with a 3-month follow-up. Twenty-seven hemiplegic subjects with chronic stroke were randomly assigned to receive 20-session wrist training with a continuous electromyography(EMG)-driven robot(interactive group,n=15), and a passive motion device(passive group,n=12), finished within 7 consecutive weeks. Training effects were evaluated with clinical scores by pre- and post-training tests(Fugl-Meyer Assessment(FMA), Modified Ashworth Score(MAS)) and with session-by-session EMG parameters(EMG activation level, co-contraction index).* ***Results:*** *Significant improvement in the FMA(shoulder/elbow and wrist/hand) were found in the interactive group ($P<0.05$). Significant decreases in the MAS were observed in the wrist and elbow joints for the interactive group, and in the wrist joint for the passive group($P<0.05$). These MAS changes were associated with the decrease in EMG activation level of the flexor carpi radialis and the biceps brachii for the interactive group($P<0.05$). The muscle coordination on wrist and elbow joints were improved in the interactive groups in the EMG co-contraction indexes across the training sessions($P<0.05$).* ***Conclusions:*** *The interactive treatment improved muscle coordination and reduced spasticity after the training for both the wrist and elbow joints, which persisted for 3 months. The passive mode training mainly reduced the spasticity in the wrist flexor.*

Keywords: Electromyography, stroke, robot, wrist

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I. Introduction

Physical training for stroke rehabilitation is an arduous process, since 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. The most commonly reported treatment approaches provided by developed rehabilitation robots are: 1) continuous passive movement (CPM), 2) active-assisted movement, and 3) active-resisted movement by applying resistance against movement direction [1-4]. In the training using CPM, no voluntary effort is required from a patient and limb movements are passively controlled by the motor of a robot. CPM treatments could improve the mobility of joint, muscle, and tendon by mainly reducing muscle tone [5, 6], and result in an activation of the corresponding sensorimotor cortical area similar to a voluntary movement [7]. The robots providing active-assisted treatments usually will follow a user's intention to complete a desired task. In the robot-assisted physical trainings with active-assisted movements, voluntary efforts from a patient are involved, and it could result in more significant motor improvements in stroke rehabilitation than a CPM treatment [4]. Therefore, the recent development in rehabilitation robots has been worked towards the active-assisted control strategies for interactive rehabilitation treatment [8]. In our previous work, an electromyography (EMG)-driven rehabilitation robot was developed for interactive physical training on the elbow and wrist joints of persons with chronic stroke [1, 9, 10]. In this robotic system, EMG signals were used as representation of the voluntary motor intention from subjects to continuously drive the robot performing programmed tracking tasks [1]. Improvements in muscle coordination revealed by muscle co-activating patterns and in general motor outcomes measured by Fugl-Meyer Assessment (FMA) [11] were found after the EMG-driven robot-assisted training on both elbow and wrist joints [9, 10].

A rehabilitation robot could not only share a large portion of the repeated labor work in a long-term physical training program, but could also be a platform for continuous and quantitative monitoring of the performance during training which may provide further understanding on the recovery mechanism due to the standardized experimental setup and the high repeatability of motion tasks. However, in many works on rehabilitation training only pre- and post- evaluations by clinical scales (FMA), the FIM instrument [12], the Modified Ashworth Scale (MAS) [13], etc.) were adopted to assess the training effects [4, 14]. Application of robots in rehabilitation attracted wide interest in stroke research, whereas the effectiveness of robot-assisted treatments is still under debate in some randomized controlled trials (RCTs). Positive effects on motor recovery have been reported in many studies on robot-assisted post-stroke trainings, in comparison with conventional treatments [3, 6]. For example, robot-assisted gait training and robot-assisted gait treatment augmented with functional electrical stimulation on subacute stroke subjects had better improvement on walking speed and more independent walking ability than subjects received conventional gait therapy [3]. However, intensive sensorimotor arm training mediated by robot for chronic stroke was found to be no advantage when compared with the intensive arm training conducted by therapist [15]. In a study of gait training on subacute stroke, the improvement in aspects of overground walking speed and distance achieved by robot-assisted treatment even was less than that by conventional gait training [16]. Reasons for these diverse results of robot-assisted treatments could be the difference in the intensity in each session and the duration of the intervention. Rehabilitation robots could have different control strategies with varied mechanical design, which may affect the training effects; however, the underlining mechanisms have not been well understood yet. In comparing the effectiveness of robot-assisted training with active-assisted mode and CPM mode, it is reported that the motor improvement by the active-assisted robot treatments were better than those with CPM by pre- and post-training evaluations [4]; however, the quantitative comparative description on the recovery process (e.g., session by session across the training course) by these two different training strategies has not been reported yet. A description of the recovery process in a treatment and quantitative comparison with different treatment approaches with matched training variables are important for a better understanding on the mechanism related to the recovery and also for a better design of rehabilitation programs. The purpose of the work was to make a quantitative comparison on the recovery process in aspect of muscle coordination, as well as training effectiveness, during EMG-driven robot-assisted wrist training (interactive treatment) and during CPM robot-assisted wrist training for chronic stroke patients.

II. Methodology

Participants

After obtaining approval from the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University, we screened voluntarily enrolled persons after stroke coming from local districts. Subjects recruited in this study satisfied the inclusion criteria as follows: 1) had unilateral ischemic brain injury or intracerebral hemorrhage at least 6 months after the onset of single stroke; 2) had moderate level of motor impairment in the affected upper limb, assessed by FMA (9<shoulder/elbow<27, 6<wrist/hand<18); 3) Subjects had to be able to follow the training procedures. The study design was a single-blinded randomized controlled trial with a 3-month follow-up for comparing the motor functions when the subjects received interactive treatment on the wrist joint with the EMG-driven robot (interactive group) and a treatment with a robotic device providing CPM (passive group). Randomization was done by computer-generated random numbers for different groups, assigned according to the order of the recruitment. The study utilized a multiple baseline design, assessed by the clinical scores of the FMA (shoulder/elbow and wrist/hand), MAS (elbow and wrist), the action research arm test (ARAT) [17], and the FIM instrument. Each outcome was measured 3 times in two weeks before the training. In this study, the clinical assessments were carried out by a blinded assessor, who neither knew the group of a subject, nor knew the training protocol.

Interventions

The subjects received a wrist treatment consisting of 20 sessions, with a training intensity of at least 3 sessions and at most 5 sessions a week. All training sessions were finished in 7 consecutive weeks. For the interactive group in a training session, each subject was seated with the paretic arm mounted on the robotic system as illustrated in Fig 1 [10]. Maximum isometric voluntary contraction of wrist flexion (IMVF) and extension (IMVE) at 0^{o} of the wrist angle were conducted and repeated 3 times before the training; and each maximum isometric contraction lasted for 5 seconds. Between two consecutive maximum isometric contractions, there was a break of 5 minutes for rest to avoid muscle fatigue. Then, the subject was required to conduct voluntary wrist flexion and extension in the range from -45^{o} to 60^{o} (a negative sign represented extended positions, and a positive sign represented flexed positions.) by tracking a target cursor moving with angular velocity of 10^{o}/sec for both flexion and extension on a computer screen. The selection of 10^{o}/sec was according to our previous training experiences [10]. The subjects were told to minimize the distance between the target and actual wrist angles. In each session, there were 14 trials, and each trial contained 5 cycles of wrist extension and flexion. Between two consecutive trials, there was a break of 2 minutes for rest. During the tracking, interactive assistive torques were provided by the robotic system in both flexion and extension phases. The magnitudes of the assistive torque were proportional to the voluntary EMG amplitudes of the flexor carpi radialis (FCR), and extensor carpi radialis (ECR) muscles during their contracting phases (i.e., using the FCR EMG in the flexion phase, and the ECR EMG in the extension phase). In order to obtain the assistance during tracking, the subjects needed to continuously generate voluntary muscular effort for the robot to provide assistive torque; otherwise, if no EMG activity from the target muscle, the robot would not generate any assistance. Besides the interactive assistive torque, interactive resistive torques were also applied in the tracking trials in a session, which were proportional to the maximum wrist torques of IMVE/IMVF of the session (i.e., in the flexion phase, the resistive torque was proportional to the IMVF torque; and in the extension phase, it was proportional to the IMVE torque.). In this study, 10% and 20% of the maximum wrist torques of IMVE/IMVE were selected for the generation of the interactive resistive torques, which were administrated to all trials alternatively in each session, together with the interactive assistive torques, throughout the training course. The control algorithm for the generation of the interactive assistive and resistive torques during tracking tasks has been described in detail in our previous works [1, 9, 10].

For the passive group, the rehabilitation robotic system (CYBEX and NORM, Computer Sports Medicine, Inc, USA) was used for the training. The standard setup for wrist extension and flexion of the CYBEX and NORM system was adopted for the CPM training [18]. In each session, wrist IMVF and IMVE at the joint angle of 0^{o} were first conducted and repeated 3 times. Then, there were 14 training trials, and each trial contained 5 cycles of passive wrist extension and flexion. The range of motion for the wrist joint was set from -45^{o} to 60^{o}, and the palm was moving passively with an angular velocity of 10^{o}/sec in the range.

Evaluation on the Training Effects

i) Clinical scores

The clinical scores in each pre-training measurement were used for comparison with those immediately after the training and in the 3-month follow-up.

ii) Robotic parameters

a) Torque values: Pre- and post-training evaluations and the 3-month follow-up test were conducted on the torques during wrist IMVE and IMVF for the interactive and passive groups by using the same experimental setup as shown in Fig 1. The maximum values for the IMVE and IMVF in a session were selected for later statistical analyses.

b) EMG parameters: For both groups, EMG signals were recorded from the muscles of the triceps brachii (TRI, lateral head), biceps brachii (BIC), FCR and ECR muscles during IMVE/IMVF tasks and during training trials. The co-activation among muscle pairs during the IMVF/IMVE of each session were studied by the co-contraction index (CI) as introduced in Frost 's work [19], that is,

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

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. CI value reflects the co-activation pattern between a muscle pair, which could vary from 0 (non-overlapping in their contracting phases) to 1 (totally overlapping of their contracting phases with both EMG levels kept at the maximum). EMG activation level of a muscle in a training trial was also calculated by averaging the EMG envelope of the trial. The CIs for different muscle pairs and the EMG activation level of each muscle were calculated for each trial of all sessions.

c) Tracking parameter: The root mean squared error (RMSE) between the target and the actual wrist angles during tracking for the interactive group was recorded to evaluate the task performance. The averaged values of RMSE, CI, EMG activation level in the same session for a subject were used as the experimental readings for statistical analyses.

iii) Statistical analyses

The analyses of variance (ANOVA, 2-way and 1-way with Bonferroni post hoc test), as well as t-tests, were used to investigate the effects from the group difference (i.e. the interactive group and the passive group) and training sessions (or each evaluation before the training, e.g., each measure in baseline detection, after the training, and in the 3-month follow-up test) on the clinical scores, torque values, EMG activation levels, and CI of different muscle pairs. The variation of the tracking performance in the interactive group was also measured by the RMSE values of the tracking trajectories across the training sessions by 1-way-ANOVA. The statistical significant level was 0.05 in this work. The primary outcomes of the study were FMA and CI values, reflecting general task-specified voluntary motor functions and muscle coordination capability respectively; and in our previous study these two parameters were sensitive to the EMG-driven robot-assisted training [10]. The other parameters were used as references to provide a more comprehensive view on the performance of the subjects.

III. Results

A total of 86 hemiplegic subjects were screened for the training. Twenty-seven of them met the selection criteria and were recruited for this study. The demographic data on the subjects after the randomization is shown in Table 1.

Scores of clinical assessments

Fig 2 shows the clinical scores of the FMA, MAS, ARAT, and FIM in pre-training baseline tests, in the post-training test, and in the 3-month follow-up test for the two groups. Inter- and intra-group differences associated with statistical significance were marked by respective symbols. Table 2 lists the mean and standard values for each clinical outcome in Fig 2, together with the ANOVA results on the inter- and intra-group differences for each outcome. There was no difference found in the FMA shoulder/elbow baselines before the training of the interactive and passive groups, nor significant variation in the baselines of the two groups. The FMA shoulder/elbow score of the interactive group increased in the post-training test and this was maintained in the 3-month follow-up ($P<0.05$). No significant change was observed in the FMA shoulder/elbow score in the passive group after the training. There was no group difference in the FMA wrist/hand score at enrollment; however, the FMA wrist/hand score of the interactive group was higher than that of the passive group in the post-training test ($P<0.05$).

For the MAS scores (elbow and wrist) in Fig 2, both of the scores for the interactive group decreased significantly after the training, and the reduced elbow and wrist muscle spasticity was maintained in the 3-month follow-up test. There was no change in the MAS elbow score for the passive group. The MAS wrist score for the passive group also decreased significantly in the post-training test; however, the wrist muscle spasticity increased again in the 3-month follow-up test ($P<0.05$). There were no group differences found in the ARAT and FIM tests. The variations in these two clinical scores for the interactive and passive groups were not significant across the tests.

Scores of Robotic parameters

Fig 3 illustrates the variations of the EMG activation levels of the FCR, ECR, BIC, and TRI muscles across the 20 training sessions for the two groups. Group differences were found in the EMG activation levels for all the muscles by 2-way-ANOVAs ($P<0.05$). The EMG activation levels of all the muscles for the interactive group were higher than those for the passive group. The FCR EMG activation level for the interactive group decreased across the large part of the training sessions ($P<0.05$). The normalized mean RMSE values for the interactive group decreased from session 1 to session 7, and remained almost stable in the later sessions ($P<0.05$). The FCR EMG activation level for the passive group also decreased from session 6 to session 20 ($P<0.001$). The BIC EMG activation level of the interactive group demonstrated an almost monotonic decreasing trend across the whole training course ($P<0.001$). The RMSE of the tracking tasks for the interactive group decreased from session 1 to session 7, and there was no further significant variation from session 8 to session 20 ($P<0.05$). There was no EMG activation levels recorded for the 3-month follow-up, since the EMG activation level was a parameter captured only in training tasks.

Fig 4 summarizes the co-contraction indexes of different muscle pairs during repeated IMVE/IMVF in the training sessions and in the 3-month follow-up test. Group differences were found in all muscle pairs by 2-way-ANOVAs ($P<0.05$). The maximum mean values of CI for most of the muscle pairs appeared in the early training sessions (before session 6). The CI of ECR&FCR for the interactive group decreased across the training sessions ($P<0.05$); The value in the 3-month follow-up test was lower than the maximum point at session 2, but had no difference with that in session 20 ($P<0.05$). The CI of ECR&FCR for the passive group also decreased across the training sessions ($P<0.05$); however, the CI mean value in the 3-month follow-up test was found to be significantly higher than that in session 20 ($P<0.05$). The CI of BIC&TRI for the interactive group decreased across the training course ($P<0.05$); and the mean of the CI value in the 3-month follow-up was lower than that in session 1 (the maximum) and had no difference with that in session 20 ($P<0.05$). For the interactive group, the CIs of the muscle pairs of ECR&BIC, ECR&TRI, FCR&TRI, and FCR&BIC varied non-significantly across the training sessions. For the passive group, the CIs of all muscle pairs varied significantly across the training sessions ($P<0.05$); however, no clear trend during the training course (e.g. increase or decrease) could be concluded, except for the CI of ECR&FCR. Most of the variations in the EMG activation levels and CI values across the training sessions in Fig 4 and Fig 5 were not monotonic. The increasing or decreasing tends described above were based on the varying patterns of the parameters across large portion of the training sessions.

Fig 5 shows the variation of the IMVF and IMVE torque values measured in pre-, post-training, and in the 3-month follow-up test. There was no group difference or difference across the test sessions found in the IMVF torque values. However, group difference (P=0.015) and test session difference (P=0.040) were found in the IMVE torque values. The IMVE torque values of the interactive group increased from the pre-test to the post-test and persisted until the 3-month follow-up test (P=0.007). There was no significant variation in the IMVE torque values in the passive group across the test sessions. The IMVE torque values of the interactive group were higher than those for the passive group in the post-training test (P=0.005).

IV Discussion

Training effects evaluated by clinical scores

The increased FMA scores (i.e., shoulder/elbow and wrist/hand) after the training for the interactive group suggested that the interactive wrist training resulted in voluntary motor improvements: not only at the trained joint, i.e., the wrist, but also at the elbow joint. These observations were consistent with previous findings that poststroke training on the distal joints could increase the motor capacity related to the intralimb proximal joint [20, 21]. In this study, we found 9 points of a total change in FMA (max/66) for the interactive group after the training with an admission mean at 29. In comparison with a similar study on robot-assisted wrist training by Krebs et al., motor improvement observed in the total change in FMA (max/66) after a six-week training was 4.17 with an admission mean at 17.35 [21]. Future study could be conducted on the training effectiveness by the interactive treatment on subjects with different admission levels. The results in this study also suggested that the continuous passive mode could not benefit the voluntary motor capability in the upper limb: neither in the wrist, nor in the elbow. This observation is consistent with the findings in the literature that CPM did not contribute a lot to the improvement in voluntary motor outcome [4]. The ARAT assessment mainly evaluates the motor functions of the hand and the whole arm [17]. Although previous studies have reported that the ARAT scores could have a high correlation with the score of FMA for upper extremity assessments [22], the motor improvements in the subjects of this study were not significant after the training when assessed by the ARAT test. The possible reason could be that the ARAT test is more related to the hand functions, i.e., 16 out of totally 19 items are related to the hand movements in the assessment. It also suggested that the robot-assisted wrist training in this study did not benefit the recovery of the hand function that much. As pointed out by Volpe et al., disability from upper limb impairment depends primarily on the loss of hand function and finger dexterity [15]. To improve the functional use of the upper limb related to hand motions, training on hand functions and finger joints could be considered in future training program and in rehabilitation robot design. The reduced MAS scores after the training suggested a decrease in the muscle spasticity of the related joint. For the interactive group, a decrease of the spasticity was observed in both elbow and wrist joints after the training; whereas, the wrist training with CPM only released the spasticity at the wrist joint, and this decrease could not be maintained for 3 months.

Training effects evaluated by robotic parameters

EMG activation level mainly reflected the contraction level of a muscle [23]. In the interactive group, voluntary muscular efforts were needed when doing the tracking tasks. However, in the passive group, there was no voluntary motor output required during the CPM treatment. Therefore, the EMG activation levels in the interactive group were usually higher than those in the passive group (Fig 3). EMG activities in the passive group during the training were mainly related to the involuntary muscle spasticity. The reduction in the FCR EMG activation level for the passive group suggested a decrease of muscle spasticity of this wrist flexor, which was consistent with the MAS wrist score decrease after the training. The decreases in the EMG activation levels of FCR and BIC in the interactive group were associated with two factors, i.e., the reduced involuntary muscle spasticity, and the decreased muscle activities during a learning process for a skillful task [23]. A steady state [24] reached by the RMSE after a decreasing phase (session 1 to 7 in Fig 3) suggested that after session 7 the wrist tracking skill could be regarded as stably learned by most of the subjects. It also implied that the decreases in FCR and BIC EMG levels after session 7 could be mainly related to the decrease of muscle spasticity.

The decreases in the co-contraction index of ECR&FCR (Fig 4) for both the interactive and passive groups suggested a better muscle coordination pattern for the antagonist muscle pair, i.e., alternative relaxing and contracting pattern, when conducting IMVF and IMVE, during the training. Dewald et al. suggested that the primary source of motor dysfunction or global disability in many hemiparetic patients after stroke was abnormal movement coordination [25]. The continuous decrease of the CI of BIC&TRI for the interactive group suggested that the interactive wrist training also improved the muscle coordination related to the elbow joint. Both of the CI values and FMA scores revealed an improvement in the voluntary motor outcome for the interactive group after the training. However, the voluntary motor improvement captured by the ECR&FCR CI values for the passive group was not associated with an improvement in the FMA wrist/hand score in the post-training test. One of the reasons could be that the CI values mainly indicated the muscle co-ordination during the maximum voluntary isometric contractions, while FMA scores reflected the multi-task motor outcomes. It also implied that the two parameters were not totally equivalent in evaluation of the motor outcome. Therefore, the robotic parameter, e.g., CI value, could still be an additional objective measure to follow the motor functional change in aspect of muscle co-ordination in a training program. The improved muscle coordination measured by CI of ECR&FCR in the passive group was not maintained 3 months after the training, while the motor improvement in the interactive group obtained through the training was maintained until the 3-month follow-up test. It suggested that the interactive wrist training had a better long-term effect than the passive training.

The increased IMVE wrist torque in the interactive group (Fig 5) suggested that the training associated with resistance in the tracking tasks could improve the muscle power of the wrist extensor (e.g., the ECR muscle). The non-significant changes in the IMVE and IMVF torques for the passive group implied that the CPM treatment contributed little to the muscle power improvement.

Limitations and Future Work

There was a limitation in the current work of using two robotic systems with different mechanical designs. The EMG-driven robot will be further developed to provide passive motions for future study, in order to minimize setup differences between systems. For understanding on the motor recovery in robot assisted training, investigations by RCT also will be conducted on dose-response for different training intensities, and on comparison of the EMG-driven robot with other interactive rehabilitation robots to find the difference in motor recovery related to variations in robotic control strategies.

V. Conclusions

In this work, the recovery processes during EMG-driven robot-assisted interactive wrist training and during robot-assisted CPM wrist training were quantitatively compared session by session for subjects with chronic stroke. Muscle co-ordination at the wrist joint improved during the training for both treatments. Muscle co-ordination at the elbow joint improved only during the interactive training, but not in the CPM treatment. The interactive training had a better long term effect than the CPM treatment.

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Figure Captions

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

Fig 2. The variations of the clinical scores, represented by mean and standard deviation, used for pre- and post-training evaluations and for the 3-month follow-up test. The solid lines with circles are for the interactive group, and the dotted lines with deltas are for the passive group. The significant inter-group difference is indicated by "*" (t-tests, P<0.05), and "#" is used to indicate the significant intra-group difference (1-way-ANOVA with post hoc tests, P<0.05).

Fig 3. The variation of the EMG activation levels of the FCR, ECR, BIC, and TRI muscles for the interactive group (solid lines) and the passive group (dotted lines), and the RMSE of the tracking for the interactive group. The data are represented by mean and standard deviation.

Fig 4. The variation in co-contraction indexes, represented by mean and standard deviation, of the muscle pairs, ECR&FCR, ECR&BIC, ECR&TRI, FCR&BIC, FCR&TRI, and BIC&TRI when doing the IMVF and IMVE in each training session and in the 3-month follow-up test (labeled with FU on the horizontal axes). The values for the interactive group are represented by the solid lines (the mean values for the 3-month follow-up are labeled with circles), and the values for the passive group are represented by the dotted lines (the mean values for the 3-month follow-up are labeled with deltas).

Fig 5. The variation of IMVF and IMVE torque values, represented by mean and standard deviation, for the interactive group (solid lines with circles) and the passive group (dotted lines with deltas) in pre-, post-training tests, and in the 3-month follow-up test. The significant inter-group difference is indicated by "*" (t-tests, P<0.05), and "#" is used to indicate the significant intra-group difference (1-way-ANOVA with post hoc tests, P<0.05).

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Fig 1

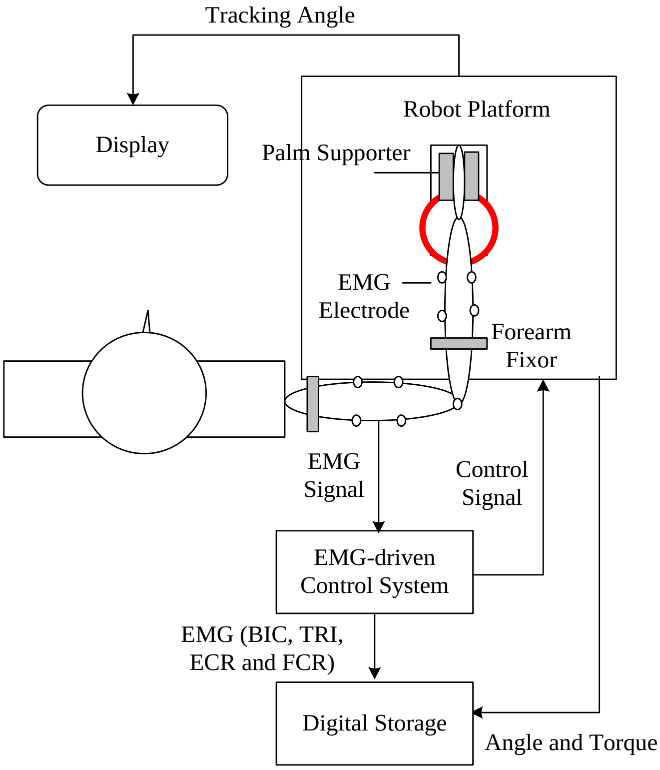

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Fig 2

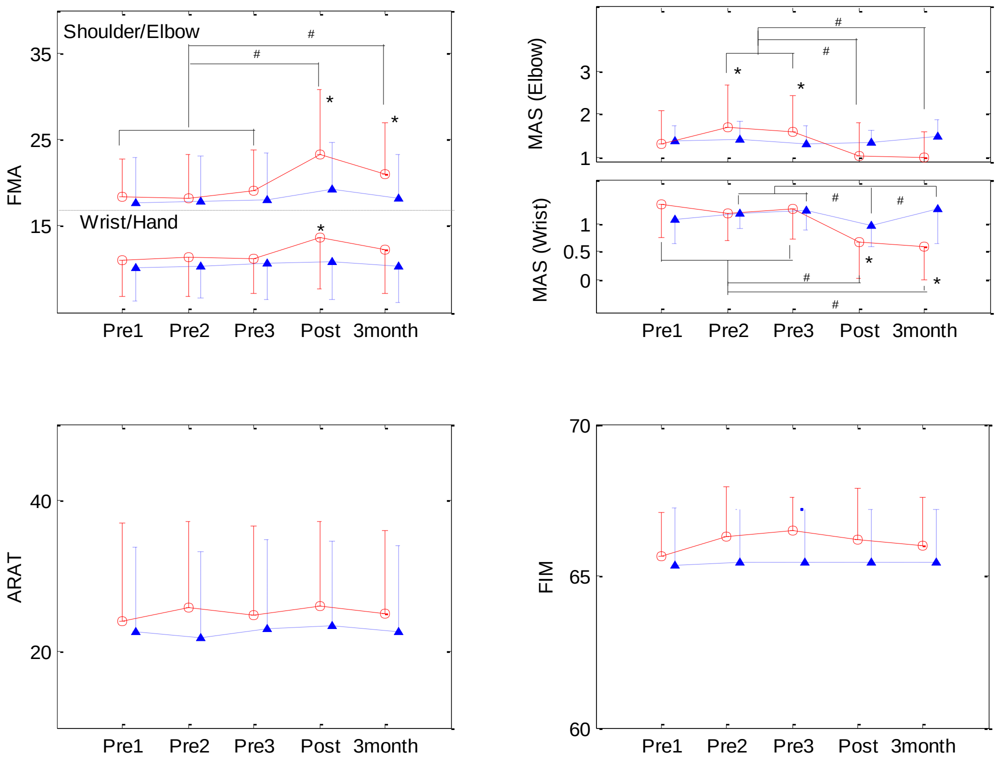

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Fig 3

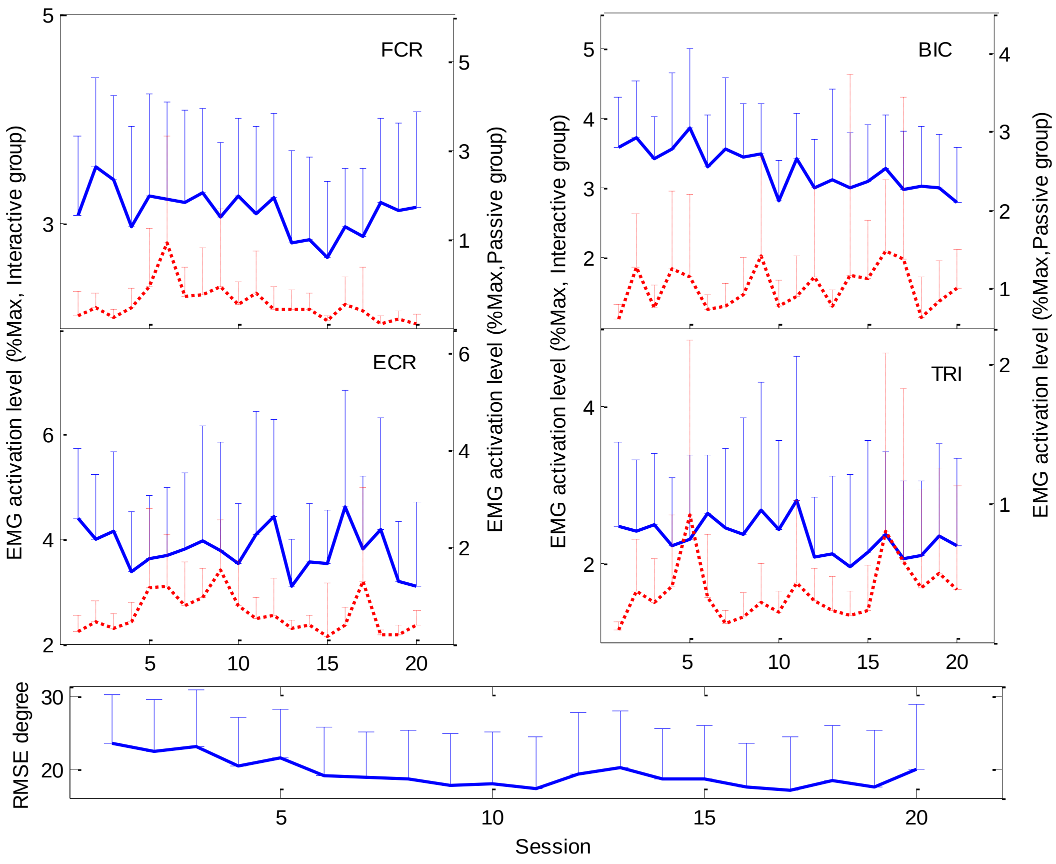

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Fig 4

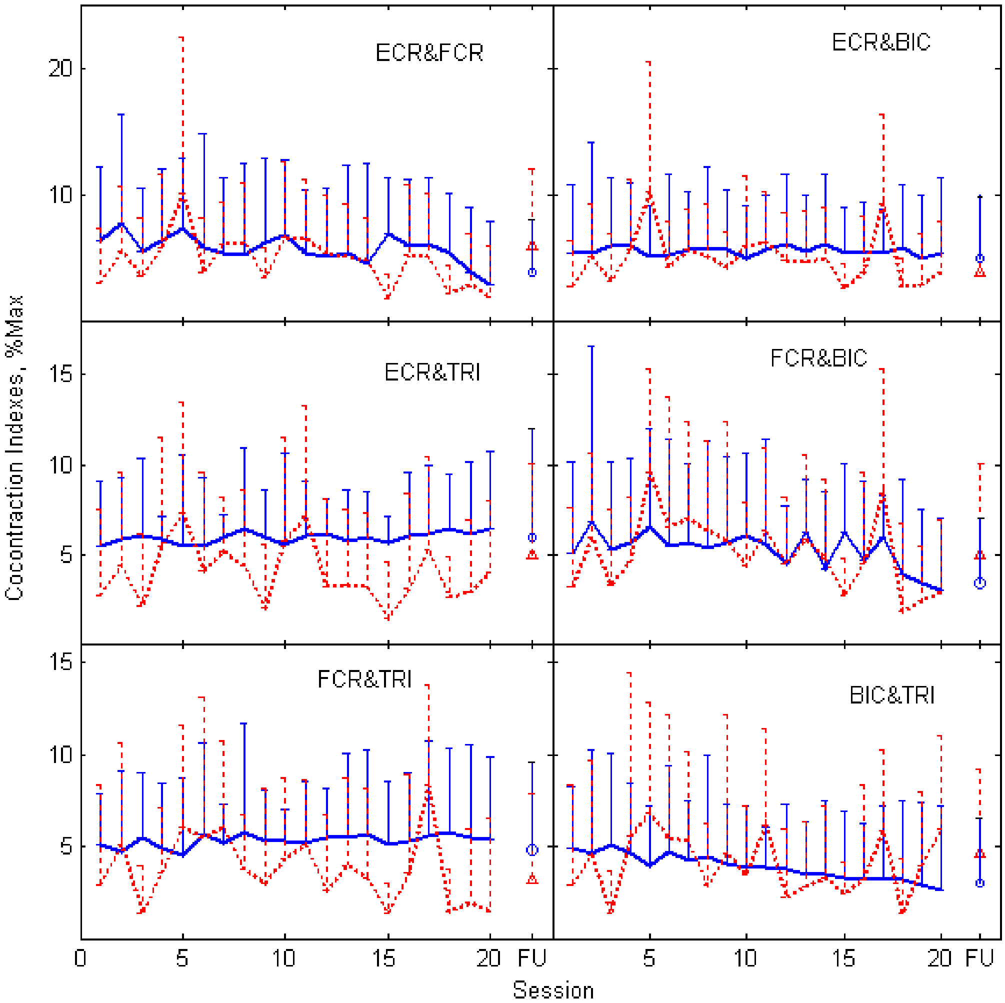

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Fig 5