Reducing Abnormal Synergies of Forearm, Elbow, and Shoulder Joints in Stroke Patients with Neuro-rehabilitation Robot Treatment and Assessment

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Abstract

Chronic stroke patients are often unable to control their joint movements independently due to abnormal synergies. In our previous work, three robot-assisted therapy indices (two biomechanical indices and one electromyography assessment) were applied to quantify the abnormal synergies of upper limbs with the aid of a neuro-rehabilitation robot. In this study, these quantitative indices are employed to investigate the time course of abnormal synergies in the affected upper limbs of chronic stroke patients treated with the robot. Eight chronic stroke patients are recruited to perform rectilinear tracking movements in four directions (back-forth, two oblique movements at 45 degrees, and right-left) during robot-assisted treatments for 4 months and 4 months of follow-up. The robot-assisted therapy indices (variation of forearm pronation/supination torque, and co-activation of elbow and shoulder muscles) reveal a significant decrease of abnormal synergies after 4 months of robot-assisted treatment and a slight regression in the following 4 months. Significant recovery is found in motor outcomes evaluated using Brunnstrom stage and Fugl-Meyer assessments. Both the robot-assisted therapy indices and clinical scales indicate modifications in abnormal synergies. The rectilinear tracking movements along the contra-proximal to ipsi-distal directions are suitable for robot-assisted movement treatment for reducing abnormal synergies.

Keywords: Stroke, Abnormal synergies, Treatment, Upper limb, Rehabilitation robot

1. Introduction

During stroke recovery, flaccidity is usually of short duration and is followed by a stage of motor behavior in which the function that can be initiated is completely tied within abnormal synergies [1]. Brunnstrom has shown that abnormal synergies are caused by the abnormal co-activation of muscles, and are almost stereotypical [2]. In the upper limbs, the abnormal synergies include flexor synergy (characterized by simultaneous shoulder abduction, elbow flexion, and forearm supination) and extensor synergy (characterized by simultaneous shoulder adduction, elbow extension, and forearm pronation). Because of these synergies, the patients cannot exercise independent joint control during movement. Treatment can break down abnormal synergies and facilitate voluntary normal movements. Some studies [3-6] have found abnormal co-activation of the elbow flexors with the shoulder abductors, extensors, and retractor muscles under static conditions in the affected limbs of stroke patients. One such study [5] has demonstrated that, after 8 weeks of isometric training, the abnormal co-activation was reduced and the patients were able to generate joint torque patterns away from the abnormal synergies. In the dynamic condition, some studies have also shown that abnormal shoulder abductor/elbow flexor coupling limits stroke patients from reaching out in the work area [7-9]. A high correlation between shoulder horizontal abduction and elbow flexion was also found during a circle-drawing task. This was also caused by the flexor synergy [10]. After 6 weeks of point-to-point reaching movement therapy, patients were able to execute shoulder and elbow joint movements with more isolated control.

Many robotic systems have been used to promote motor recovery and quantify treatment efficacy [11-13]. The MIT-Manus workstation [14,15] has shown a convincing beneficial effect of robot-assisted upper limb treatment for severely affected stroke patients. The MIME system [16,17] has improved muscle activation patterns in chronic patients, and it can allow the affected limb to perform a mirror movement of
that defined by the intact limb. Many positive outcomes [18-23] have been reported in robot-assisted rehabilitation. However, an objective assessment of motor functions, in particular abnormal synergies, is required for designing and improving the training protocol in robot-assisted therapy and for evaluating the progress of patients.

In clinical practice, the Brunnstrom stage (BrS) [2], the Fugl-Meyer assessment (FM) [1], and the Modified Ashworth Scale (MAS) [24] are used to assess motor deficits, functional capability, and spasticity in stroke patients. Although these subjective clinical scales reflect abnormal synergies, they depend on the judgment of raters. In recent studies, some quantitative assessment indices of abnormal synergies have been developed based on either kinematics [8-10,25], kinetics [3,5,7], or electromyography (EMG) [4,6,26] during voluntary movements of stroke patients by robotic systems. In our previous work, quantitative indices derived from both kinematics, kinetics, and EMG in the dynamic condition that covered the shoulder, elbow, and forearm joints have been used to evaluate abnormal synergies with the aid of a neuro-rehabilitation robot [27].

In this time-course study, eight stroke patients received 4 months of robot-assisted treatment and 4 months of follow-up. Robot-assisted therapy indices and clinical scales were utilized to objectively quantify their abnormal synergies. Patients were asked to perform rectilinear tracking movements in four directions with their upper limbs while interacting with a neuro-rehabilitation robot. The aims of this study were to investigate whether the robot-assisted therapy indices reflect the modification of abnormal synergies during exercise, which directions of movement are most relevant for reducing abnormal synergies, and which indices are most suitable for assessing recovery from abnormal synergies.

2. Methods

2.1 Subjects

Eight stroke patients and eight healthy subjects were recruited for this study. All the healthy subjects were right-handed (6 males and 2 females, mean age: 50.5 years, standard deviation: 8.1) and recruited for establishing a baseline without rehabilitation. Six stroke patients were right hemiparetic, and the other two were left hemiparetic (8 males, mean age: 48.1 years, standard deviation: 11.6). Inclusion criteria of the stroke patients were: a stable medical condition, an interval of at least 5 months since stroke onset, intact cognition, and having a BrS number greater or equal to 3. The study protocol was approved by the institutional review board of National Cheng Kung University Hospital. Before the experiment, the purpose, potential hazards, and procedure were explained to the subjects and a written consent form was signed.

2.2 Clinical evaluations

Motor functions of the upper limbs of the stroke patients were evaluated by a given physical therapist with the upper extremity part of the BrS and FM (0 to 66). Because the treatment protocol (described in Section 2.4) involved mainly the shoulder, elbow, and forearm joints, FM$_{prox}$ (0 to 42), the subscore (sum of items 1-18 and 31-33) of the FM score, was utilized [1,19]. Spasticity of the elbow was evaluated with the MAS. The basic information and scores of clinical evaluation were recorded before the experiments (Table 1).

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BrS: proximal upper extremity score of the Brunnstrom stage; MAS: elbow flexors score of the Modified Ashworth Scale; FM: upper extremity score of the Fugl-Meyer assessment; FM$_{prox}$: proximal joints of the shoulder, elbow, and forearm of the Fugl-Meyer assessment

* S used for stroke patients and N for healthy subjects

Table 1. Basic data of the participants

2.3 Neuro-rehabilitation robot and forearm measurement system

A robot for neuro-rehabilitation of the shoulder and elbow joints was adopted [28] (Fig. 1(a)), and a special measurement system [27,29] was installed on it to measure the forearm pronation/supination torque during the shoulder and elbow movements. The robot was designed to perform two-dimensional motion on the horizontal plane. A fuzzy logic controller was employed to perform hybrid position/force control such that the robot could apply either resistant or assistant force along the movement direction while the movement was confined on a predefined trajectory. Subjects were seated in front of the robot with the trunk fastened to the back of the chair by a strap and the hand fastened to the part of the robot that measured the forearm rotation torque. The upper limb gravity loading was supported by a two-link passive mechanism. The robot could be stopped at any time by cutting off the power supply with an emergency button, which could be pushed by either the subject or the physical therapist.

2.4 Treatment protocol

Four directions of rectilinear tracking movements were designed for the robot-assisted treatment, namely D1 (backward), D2 (oblique movement at 45°), D3 (oblique movement at 45°), and D4 (right-left) (Fig. 1(b)). At the beginning of the robot-assisted treatment, the subject’s wrist was positioned at the start point of the target rectilinear trajectory (dashed line in Fig. 1(a)). The start and end points (solid and hollow points) of
Reducing Abnormal Synergies with Robot Treatment

the target trajectory were identical (Fig. 1(b)). The subject faced a screen that provided visual feedback with two icons. One represented the target position (octopus icon), and the other represented the actual position of the subject’s wrist (hand icon). Subjects were asked to actively guide the robot’s movements along the target trajectory and to keep the position error between the two icons as small as possible. In addition, there were two boundary lines (solid lines) 5 cm away from the target trajectory on both sides. The two lines were used to guide the subject’s wrist position, which should not extend beyond them. In addition to this visual constraint, the robot provided a soft constraint in the orthogonal direction of the trajectory via a hybrid position/force controller [28]. The length of the rectilinear track was 20 cm for the healthy subjects. For the patients, it was reduced to approximately 80%~90% of their maximum range of motion based on the ranges of movement of their shoulder and elbow joints for safety. By trial and error, the velocity of the target was chosen to be 4 cm/s, which allowed all the subjects to accurately follow the target trajectory. Each movement was repeated 5 times. Before the robot-assisted treatment, the end-effector of robot was moved to the center of all rectilinear trajectories (Fig. 1(b)) and fixed there. Then, the subjects were asked to apply maximum force on the end-effector by performing elbow flexion along the D1 direction. The maximum isometric contraction was measured by using the load cell of the robot. During the tracking movements, the robot applied a resistant force, 30% of the maximum force, along the direction tangent to the movement. The subjects did not experience any pain or discomfort when receiving this resistant force. An electrical goniometer was fastened across the elbow joint to measure its flexion-extension angle, \( \theta \) (Fig. 1(b)). The stroke patients received the robot-assisted treatment for one hour per day and two days a week for a consecutive four months. They also practiced conventional therapy for one hour per day and two days a week when they received the robot-assisted treatment. The conventional therapy was then continued for four more months.

Conventional therapy comprised a thirty-minute session of physiotherapy and a thirty-minute session of occupational therapy. The physiotherapy guided the stroke patients to relearn simple motor activities such as walking, sitting, standing, and the process of switching from one type of movement to another. The occupational therapy involved exercise and training to help the stroke patients to relearn daily activities such as eating, dressing, writing, and toileting.

All patients received the robot-assisted treatment for four months and practiced conventional therapy for a total of eight months. The robotic assessments (described in Section 2.5) and clinical evaluations were performed at the end of each month. Additionally, for comparison, the healthy subjects’ bilateral limbs and stroke patients’ intact limbs were evaluated once. This protocol was designed to investigate how abnormal synergies changed during the four months of robot-assisted treatment and the following four months by using robot-assisted therapy indices and clinical scales (BrS, MAS, FM, and FM\(_{proa}\)).

Figure 1. (a) Four directions of rectilinear tracking movement on the transverse plane and photograph of the robot-aided rehabilitation system with a stroke patient (A: shoulder-elbow rehabilitation robot; B: forearm torque measurement device; C: visual feedback; D: surface EMG electrode; E: electrical goniometer; F: two-link support mechanism). Visual feedback shows the target rectilinear trajectory (dashed line), target position (octopus icon), subject’s wrist position (hand icon), and boundary lines (solid lines) of the track. (b) Kinematic relationship between subject’s trunk and upper limb segments, elbow angle (\( \theta \)), and pronation/supination torque (\( r \)).

2.5 Robotic assessments

In our previous study [27], it was found stroke patients could not execute independent control of the elbow and forearm joints to achieve the designed tracking movements due to abnormal synergies. For example, Fig. 2(a) shows typical trajectories of elbow angle (\( \theta \)) and forearm torque (\( r \)) of a healthy subject, N2, and a stroke patient, S1, during a cycle of D2 direction rectilinear tracking movement. From the curves of the stroke patient, when the elbow was flexed, supination of the forearm fits the flexor synergy. Conversely, when the elbow was extended, pronation of the forearm fits the extensor synergy. Two biomechanical indices, \( r_2 \) and \( r_8 \), were developed
to calculate the Pearson’s correlation coefficient between the trajectories of the elbow angle and forearm torque. The equations are:

\[
\rho_y = \frac{\text{cov}(\theta(s_i, s_j), \tau(s_i, s_j))}{\sigma_{\theta(s_i, s_j)} \sigma_{\tau(s_i, s_j)}}
\]

\[
\rho_x = \frac{\text{cov}(\theta(s_i, s_j), \tau(s_i, s_j))}{\sigma_{\theta(s_i, s_j)} \sigma_{\tau(s_i, s_j)}}
\]

where \(\text{cov}\) represents covariance and \(\sigma\) represents standard deviation. The trajectories of the elbow angle and forearm torque were expressed as functions of the displacement along the rectilinear trajectory instead of time. The intervals \((s_1, s_2)\) and \((s_2, s_3)\) are the backward and forward displacements (s) required to perform the elbow flexion and extension, respectively, and \(s_1, s_2,\) and \(s_3\) are the end points of the rectilinear trajectory (Fig. 2(b)). \(\rho_y\) represents the Pearson’s correlation coefficient between the trajectories of the elbow angle and forearm torque when the elbow was flexed, and \(\rho_x\) represents elbow extension. These two indices were utilized to quantify the flexor and extensor synergies between the elbow and forearm joints, respectively. The \(\rho_y\) and \(\rho_x\) values show a negative correlation in the affected limbs of stroke patients, implying that the patients had to invoke involuntary abnormal synergies during tracking movements [27]. In addition, another biomechanical index, \(I_s\), was developed to quantify the total variation of forearm pronation/supination torque.

\[
I_s = \int \left( \tau_x - \bar{\tau}_x \right) ds + \int \left( \tau_y - \bar{\tau}_y \right) ds
\]

where \(\bar{\tau}_x\) and \(\bar{\tau}_y\) are the average torque over the distance between \(s_1\) and \(s_2\), and \(s_2\) and \(s_3\), respectively. A larger \(I_s\) represents a greater forearm pronation/supination torque variation. The previous work also demonstrated that the \(I_s\) values of the stroke patients’ affected limbs were higher than those of healthy subjects’ bilateral limbs and the stroke patients’ intact limbs during tracking movements [27].

To describe the correlations among the activations of muscles, an EMG index, the co-activation ratio (\(C_i\)), was developed to decompose the EMG signals based on principal component analysis (PCA) [30-32] in our previous work [27]. Eight channels of surface EMG signals were used (DE-2.3, Delsys Inc., Boston, MA, USA) from the following muscles: pectoralis major (PM), middle deltoid (MD), biceps brachii (BB), triceps brachii (TB), pronator teres (PT), supinator (SU), flexor digitorum superficialis (FD), and extensor digitorum (ED). The muscles PM, MD, BB, and TB dominated movements in the shoulder and elbow joints, and the muscles PT, SU, FD, and ED dominated the forearm and wrist joints. The signal processing details are described elsewhere [27]. The development of this index is briefly described below. Figure 3 shows typical patterns of the correlation coefficient between the first principal component (PC1) and EMG of each muscle of a healthy subject, N2, and a stroke patient, S1, during the D2 direction rectilinear tracking movement. The muscles PM and BB of all limbs were positively correlated with PC1, whereas the muscles MD and TB of bilateral limbs of healthy subject and intact limb of the stroke patient were negatively correlated with PC1. These patterns indicate that in the affected limbs of the stroke patients, almost all the muscles were co-activated to complete the tasks. Two muscles groups, namely PM-BB and MD-TB, merged together in the affected limbs of stroke patients, suggesting the existence of abnormal co-contraction of antagonistic muscles in the shoulder and elbow joints [27]. The co-activation ratio is used as an indicator of abnormal synergy. The \(C\) value corresponding to the first component is calculated as:

\[
C_{i,j} = \frac{r_{ij}}{r_{ii} + r_{jj}} \cdot 100\%
\]

where \(r_{ij}\) is the correlation coefficient between the PC1 and the EMG of PM, and \(i (= 1 \text{ to } 4)\) is an index of the directions of the rectilinear movement. \(r_{ii}\) and \(r_{jj}\) are similarly defined for BB, MD, and TB, respectively. From the PCA, the
greatest variance of EMGs from the eight muscles during the movement was on PC1, the second greatest variance was on PC2, and so on. The correlation coefficient between the PC1 and EMG of each muscle was calculated. A larger coefficient means a greater contribution during the movement from the muscle as compared with those of other muscles. Positive co-activation ratios indicate abnormal synergies between muscles.

The indices $r_F$, $r_E$, $I$, and $C_I$ showed significant differences between the affected limbs of stroke patients and their intact limbs and also the healthy subjects’ bilateral limbs in our previous work [27]. The indices showed no significant difference between the intact limbs of stroke patients and the healthy subjects’ bilateral limbs. Therefore, the patients’ intact limbs and healthy subjects’ bilateral limbs were clustered into the healthy group in this study. For the four directions of tracking movement, the previous work also showed that the muscle coordination in the healthy group between the shoulder and elbow joints was direction-dependent. Thus, the index $C_I$ was divided into the D1 and D3 group and the D2 and D4 group, respectively. The mean value of $C_I$ in the D1 and D3 group ($C_{I(D1,D3)}$) and that in the D2 and D4 group ($C_{I(D2,D4)}$) were calculated for each subject.

![Figure 3. Typical patterns of correlation coefficient between the first principal component (CP1) and EMG of PM, MD, BB, TB, PT, SU, FD, and ED during D2 direction rectilinear tracking movement. PM: pectoralis major; MD: middle deltoid; BB: biceps brachii; TB: triceps brachii; PT: pronator teres; SU: supinator; FD: flexor digitorum superficialis; ED: extensor digitorum.](image)

2.6 Statistical analyses

In order to investigate the changes from the initial status to the end of the four month robot-assisted treatment and the end of the four month of follow-up, the effects of treatment with the robot on the robot-assisted therapy indices were tested using one-way analysis of variance (ANOVA) with the Bonferroni post hoc test. Since the clinical scales BrS, MAS, FM, and FM$_{post}$ are ordinal scores, their medians and interquartile ranges are presented. The nonparametric Kruskal-Wallis test and the Bonferroni post hoc test were utilized for statistical analyses. The confidence level ($\alpha$) was set at 0.05. The FM scale of stroke patients showed more inter-subject difference (Table 1), which might lead to high variation in the stroke group. Therefore, the changes between the initial status and 4th month were calculated and utilized in all statistical analyses. The other changes between the initial status and 8th month were also analyses by the same way.

3. Results

During the course of robot-assisted treatment and the follow-up, robot-assisted assessment was performed and the values of $r_F$, $r_E$, $I$, and $C_I$ were calculated. The monthly variations of $r_F$, $r_E$, and $I$ are shown in Fig. 4 for comparison with the healthy group (dashed lines). The mean values of $r_F$, $r_E$, and $I$ of the healthy group in the four directions of tracking movement are 0.07, 0.03, and 45.94, respectively. After the first month, the $r_E$ and $r_F$ values of the stroke group showed a slight drop (Figs. 4(a) and (b)). After the second month, these two indices gradually approached the values of the healthy group. The mean value of $r_E$ remained approximately at -0.06 after 2, 3, 4, 5, 7, and 8 months, although it dropped slightly in the 6th month. In addition, the maximum mean value of $r_F$, which was close to that of the healthy group, was obtained after the 3rd month. From the 5th month to the end of the follow-up, $r_E$ showed a gradual regression. The index $I$, of the stroke group also approached the values of the healthy group in the process of treatment and regressed gradually in the follow-up (Fig. 4(c)). The mean value of $I$ remained smaller than that of the initial status at the end of the 8th month.

The time courses of $C_I$ for the stroke group in the D1 and D3 directions (Fig. 5(a)) and the D2 and D4 directions (Fig. 5(b)) were compared with the corresponding mean values of the healthy group (-8.25 and -239.41). After 3 months of robot-assisted treatment, the $C_I$ values of the D1 and D3 directions decreased. In addition, the $C_I$ values of the D2 and D4 directions showed a large decline after two months of robot-assisted treatment and gradually approached the mean value of the healthy group in the process of treatment. At the end of the 4 months of follow-up, the $C_I$ values of the D1 and D3 directions returned to the initial status at the 5th month, whereas the $C_I$ values of the D2 and D4 directions showed only a slight regression.

For the clinical scales, BrS, FM, and FM$_{post}$ showed increases after 4 months of robot-assisted treatment but the MAS showed a slight decrease (Fig. 6). At the end of the 4 months of follow-up, these scales also revealed a gradual regression of patients’ motor recovery. The time course variations of these clinical scales were similar to those of the robot-assisted therapy indices.

The average changes of robot-assisted therapy indices and clinical scales from the initial status to the 4th and the 8th months for all stroke patients are summarized in Table 2. In the robot-assisted therapy indices, one-way ANOVA of $I$ and $C_I$ of the D2 and D4 directions shows significant changes ($p < 0.001$ for both) from the initial status to the ends of robot-assisted treatment and the follow-up. Index $I$, decreased significantly at the ends of robot-assisted treatment and the follow-up (post hoc tests, $p < 0.05$ for both); the average changes were -24.36 and -8.8, respectively. Index $C_I$ in the D2 and D4 directions also decreased significantly at the end of robot-assisted treatment; the average change was -164.31 (post hoc tests, $p < 0.05$). However, $r_F$, $r_E$, and $C_I$ of the D1 and D3 directions showed no significant change from the initial status to either the end of
Figure 4. Time courses of means and standard errors of robot-assisted therapy indices for (a) flexor synergy ($r_F$), (b) extensor synergy ($r_E$), and (c) integration of absolute deviation of torque ($I_{\tau}$) along the four tracking directions in stroke group. The dashed lines are the mean values (0.07, 0.03, and 45.94) of the healthy group.

Figure 5. Time courses of means and standard errors of $C_i$ in (a) D1 and D3, and (b) D2 and D4 tracking directions in the stroke group. The dashed lines are the mean values (-8.25 for D1 and D3, and -239.41 for D2 and D4) of the healthy group.

Figure 6. Time courses of medians of clinical scales. (a) BrS and MAS, and (b) FM and $FM_{prox}$ for stroke patients. BrS: proximal upper extremity score of the Brunnstrom stage; MAS: elbow flexors score of the Modified Ashworth Scale; FM: upper extremity score of the Fugl-Meyer assessment; $FM_{prox}$: proximal joints of the shoulder, elbow, and forearm of the Fugl-Meyer assessment.

robot-assisted treatment or the follow-up. For the clinical scales, the Kruskal-Wallis test of BrS, FM, and $FM_{prox}$ showed significant changes ($p < 0.01$, $p < 0.001$, $p < 0.001$) from the initial status to the ends of robot-assisted treatment and the follow-up. FM increased significantly at the ends of robot-assisted treatment and the follow-up (post hoc tests, $p < 0.05$ for both); the median changes were 11.5 and 6, respectively. BrS and $FM_{prox}$ also increased significantly at the end of robot-assisted treatment (post hoc tests, $p < 0.05$ for both); the median changes were 1 and 4.5, respectively. However, MAS showed no significant change from the initial status to either the end of robot-assisted treatment or the follow-up.

4. Discussion

The indices $I_i$ and $C_i$ of the D2 and D4 directions reflected the modifications of abnormal synergies. They showed significant improvement after the robot-assisted treatment and a gradual regression in the follow-up period. The clinical scales of BrS, FM, and $FM_{prox}$ also showed significant improvement at the end of robot-assisted treatment and a gradual regression at the end of follow-up.

In the designed rectilinear tracking movements, the stroke patients were not asked to perform pronation or supination during the movements. To complete the tracking movements, patients had to invoke involuntary forearm pronation/ supination torque based on abnormal synergies that could be detected by index $I_i$. After robot-assisted treatment, the significant decrease of $I_i$ reflected that the abnormal variation of forearm pronation/supination torque had been reduced significantly. This result indicates that the abnormal contractions of forearm
muscles (such as the pronator and the supinator) during the movements were reduced.

The results of the $C_i$ index also show that the co-contraction of antagonistic muscle pairs between the shoulder and elbow joints decreased after robot-assisted treatment, especially in the D2 and D4 directions of tracking movements. The movement in the D2 direction was dominated by the elbow flexion/extension and the movement in the D4 direction was dominated by the shoulder horizontal flexion/extension [27]. Before the robot-assisted treatment, $C_i$ values of the two direction groups (D1-D3 and D2-D4) were both positive and similar. This indicates that the patients might have only one motor strategy for performing tracking movements in the four directions with their affected limbs. After 4 months of robot-assisted treatment, $C_i$ values of the D1 and D3 directions were different from those of the D2 and D4 directions; the signs of $C_i$ values in the D2 and D4 directions became negative. These results suggest that the patients might have developed two motor strategies, one for the D1 and D3 directions and one for the D2 and D4 directions. In other words, $C_i$ in the D2 and D4 directions showed greater improvement than in the D1 and D3 directions. The movements in the D2 and D4 directions required more independent movements of the shoulder or elbow joints [27]. Therefore, improvement of $C_i$ in the D2 and D4 directions could indicate more independent joint movements and less synergy.

The time course of indices $I_i$ and $C_i$ in the D2 and D4 directions and clinical scales FM and FM$_{max}$ showed the most significant improvement (Table 2). The correlation between the mean value of $I_i$ and the median values of FM and FM$_{max}$ were -0.94 and -0.9, respectively, and the correlation between the mean values of $C_i$ in the D2 and D4 directions and the median values of FM and FM$_{max}$ were -0.86 and -0.91, respectively. The physiological basis for these high correlations was abnormal synergies. When the abnormal synergies gradually disappeared and the patients could complete some isolated movements, the joint coordination approached normalcy. The FM score increased, indicating that the patients had an increased ability of isolated control of each joint. These results indicate that indices $I_i$ and $C_i$ in the D2 and D4 directions were more sensitive and more relevant to motor recovery, especially in abnormal synergies. Furthermore, $C_i$ in the D2 and D4 directions reflects the shoulder and elbow joints and $I_i$ reflects the forearm joint. Together, these two indices give therapists insight into the recovery of abnormal synergies in the shoulder, elbow, and forearm joints.

The indices $r_f$ and $r_e$ showed that the flexor and extensor synergies between the elbow and forearm joints slightly decreased in the stroke patients’ affected limbs. Although the statistical analyses showed no significant improvement after 4 months of robot-assisted treatment, the mean values at the initial status and the end of robot-assisted treatment were different. $r_e$ indicated a relatively higher improvement than did $r_f$, reflecting a greater reduction of the extensor synergy than the flexor synergy in patients. However, the present study was limited by the small sample size of the stroke patients and thus relatively low statistical significance.

Table 2. Changes of robot-assisted therapy indices (mean (standard error)) and clinical scales (median (interquartile range)) from initial status to the ends of robot-assisted treatment and follow-up for the stroke group (n = 8).

<table>
<thead>
<tr>
<th>Robot-assisted therapy indices and clinical scales</th>
<th>End of robot-assisted treatment at 4th month</th>
<th>End of follow-up at 8th month</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_f$</td>
<td>0.09 (0.07)</td>
<td>0.09 (0.07)</td>
</tr>
<tr>
<td>$r_e$</td>
<td>0.16 (0.07)</td>
<td>0.13 (0.08)</td>
</tr>
<tr>
<td>$I_i$</td>
<td>-24.36 (2.29)</td>
<td>-8.8 (3.36)</td>
</tr>
<tr>
<td>$C_{1D1} + C_{1D3}$</td>
<td>-47.66 (36.63)</td>
<td>4.77 (23.03)</td>
</tr>
<tr>
<td>$C_{2D2} + C_{2D4}$</td>
<td>-164.31 (28.43)</td>
<td>87.21 (33.07)</td>
</tr>
<tr>
<td>BrS</td>
<td>1 (0.75-1)</td>
<td>0.5 (0.4-0.875)</td>
</tr>
<tr>
<td>MAS</td>
<td>-1 (-1-0)</td>
<td>-0.5 (-1-0.75)</td>
</tr>
<tr>
<td>FM</td>
<td>11.5 (6.25-15)</td>
<td>6 (5-7.75)</td>
</tr>
<tr>
<td>FM$_{max}$</td>
<td>4.5 (3.75-8.5)</td>
<td>2.5 (0.75-4.75)</td>
</tr>
</tbody>
</table>

BrS: proximal upper extremity score of the Brunnstrom stage; MAS: elbow flexors score of the Modified Ashworth Scale; FM: upper extremity score of the Fugl-Meyer assessment; FM$_{max}$: proximal joints of the shoulder, elbow, and forearm of the Fugl-Meyer assessment

*p < 0.01, **p < 0.001: one-way analysis of variance test used for robot-assisted therapy indices, Kruskal-Wallis test used for clinical scales

The time courses of the assessment indices conform to the recovery progress proposed by the Brunnstrom stages [2]. Abnormal synergies accompany voluntary movements in stage 3. When the recovery progresses, some movement combinations that do not follow the paths of abnormal synergies are mastered in stage 4. When recovery continues, abnormal synergies eventually disappear completely in stage 5 and isolated joint movements become possible and coordination approaches normalcy in stage 6. Most of our subjects (6/8) were initially in stage 3 of BrS, i.e., moving with abnormal synergies. After 4 months of robot-assisted treatment, the assessment indices showed improvement and the mean stage of BrS increased from 3 to 4. The patients were asked whether the motor control or functional ability of the affected limbs had improved after the robot-assisted treatment. Most patients thought that the muscle strength of the elbow and shoulder joints had increased. Some of them found an improved ability to control a spoon with the affected limb during meals. Others used the affected limb to assist body weight translation while getting out of the bed. Others reported that they could operate a remote control, although slowly. These changes indicate that the patients had some motor and/or functional recovery of the affected limb in daily activities. More quantitative evaluation of improvement in daily activities is required.

This study lacked a control group [33] that received only conventional therapy for the treatment period. Therefore, it is difficult to differentiate the contribution of the increased treatment time from that of the robot assistance to the motor improvement. However, the results suggest that adding robot-assisted therapy could improve motor recovery and reduce abnormal synergy. In addition, conventional therapy relies on an experienced therapist and requires substantial man power. If robots can be used to substitute part of the treatment under the supervision of therapists, treatment cost can be reduced without sacrificing benefits. During the follow-up, the patients continued to receive conventional therapy. The results of robot-assisted therapy indices and clinical scales show that the performance, though regressed slightly, did not return to the initial status before starting the robotic-assisted treatment. The effects of the
robot-assisted therapy lasted more than 4 months.

5. Conclusion

The proposed robot-assisted therapy indices and clinical scales showed a significant decrease of abnormal synergies after 4 months of treatment with the aid of a neuro-rehabilitation robot and a slight regression during the following 4 months. The robot-assisted therapy indices reflect the modification of abnormal synergies. Two tracking directions were especially useful for movement practice to reduce abnormal synergies. The robot-assisted treatment had beneficial effects for the patients, as revealed by these indices.

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References


