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Electromyogram-controlled assistive exercise for the motor recovery of shoulder in chronic hemiplegia: A pilot study

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Abstract. Correct-active-repetitive exercise is important for the motor recovery in hemiplegics. The present study hypothesizes that the electromyogram (EMG)-controlled assistance of motion would be an effective implementation of the concept for the rehabilitation of the hemiplegic shoulder, even in chronic patients. This study aims to investigate the feasibility of the suggested method. The motor intention is derived from the EMG of the shoulder muscles and the shoulder movement (flexion and abduction) is assisted by an electro-mechanical system only when the motor intention (EMG amplitude) exceeded the threshold. Twelve patients in the chronic stage of stroke participated in this pilot study. The EMG-controlled assistive exercise lasts for two weeks, 20 min per day and 5 days a week. The active range of motion in both abduction and flexion increases significantly after the intervention ($p < 0.01$). The maximum torque increases in both directions, and the increase is significant in the abduction ($p < 0.01$). The Fugl–Myer motor assessment score is improved greatly in the shoulder-related items ($p < 0.01$), but neither in the shoulder-unrelated items of the upper extremity ($p = 0.13$) nor in the lower extremity items ($p = 0.19$). This pilot study demonstrates that EMG-controlled assistive exercise can improve shoulder motor functions related to selected muscles and the suggested method is promising for the motor recovery of the shoulder in chronic hemiplegia.

Keywords: EMG-control, assistive exercise, hemiplegia, shoulder, motor recovery

1. Introduction

Hemiplegia is a major cause of serious disability among older adults [1]. The motor impairment of the upper extremity is a common and devastating consequence of hemiplegia, significantly contributing to functional disability [2-4]. The shoulder muscles play important roles in the upper limb function, because the common daily tasks of the upper limb, e.g., reaching hands to an object and moving the object by hand, require intact shoulder function. Therefore, the recovery of the shoulder motor function is very important to the hemiplegic patients. It has shown that many people

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with hemiplegia recover their proximal movement earlier and more than the distal hand and finger movements [5]. The reasons for this phenomenon may be: 1) proximal muscles of the upper limb (e.g., shoulder muscles) are innervated by various pathways, i.e., bilateral pathways of the reticulospinal, tectospinal, and vestibulospinal tracts, and the uncrossed pathway of the ventral corticospinal tract [6-8]; 2) the crossed pathway of the lateral corticospinal tract exerts less influence on the proximal upper limb muscles compared with the distal upper limb muscles [9-11]. This study focuses on the recovery of the shoulder muscles, due to their importance in the recovery of upper limb function in the hemiplegic patients.

The functional recovery following the hemiplegia has been shown several important substrates. An earlier intervention is desirable, because most recovery of the motor function occurs in the first three months after the hemiplegia onset [4, 12-14]. The experimental and clinical studies have shown that the post-stroke motor recovery is task-relevant and enhanced by active and repetitive use of the affected limb [15-21]. The correction of the abnormal movement pattern is also important in the development or refinement of motor programs [22, 23]. In summary, the functional recovery is enhanced by the correct-active-repetitive exercise (CARE) or the correct-active-repetitive tasks (CART).

Different therapeutic methods for CARE or CART have been developed to improve the upper limb motor function resulted from the hemiplegia [24]. One recent technique for this criterion is the robot-assisted training. Recent robotic devices for the rehabilitation have been designed to interact with the signals coming from the voluntary motor intention and correct misdirected movement of the upper limb during repetitive exercises [25-27]. Therefore, the interactive robotic training system provides correct, active, repetitive, and task-specific movement of the paretic upper limb, which is proven to promote the motor recovery of the upper limbs in the stroke survivors [28, 29]. To acquire the motor intention from patients, kinetic and kinematic quantities such as force, position, and velocity have been commonly used [30, 31]. However, these signals are produced from the activations of multiple muscles, hence a specific muscle cannot be targeted as the source of the motor intention. Moreover, muscle force is produced after a delay (30–60 ms) from the muscle activation [32, 33] and the kinematic variables are even more delayed from the force, hindering spontaneous reaction of the robot in response to the motor intention. Because EMG can be derived from a specific target muscle and represents muscle activation with little delay, the EMG-driven robotic devices are developed to facilitate the interactive physical training of the elbow, wrist, and hand, which was shown to be effective [34-39].

However, the EMG-driven robotic device has not been applied to the recovery of the shoulder motor function, to the best of our knowledge. The motor function of a specific shoulder muscle is expected to be improved more effectively by this method in chronic patients who have been considered to be in the saturation stage of the motor recovery. Therefore, a robotic equipment controlled by voluntary EMG from a target muscle is motivated for the shoulder exercise in this study. The shoulder movement is assisted by an electro-mechanical system only when the subject generates EMG to a sufficient level, exceeding a preset threshold. The feasibility of the therapeutic effect of active-assistive exercise is investigated using this shoulder equipment on the recovery of the shoulder motor function in the patients stabilized with upper extremity hemiparesis in the chronic stage of hemiplegia.

2. Materials and methods

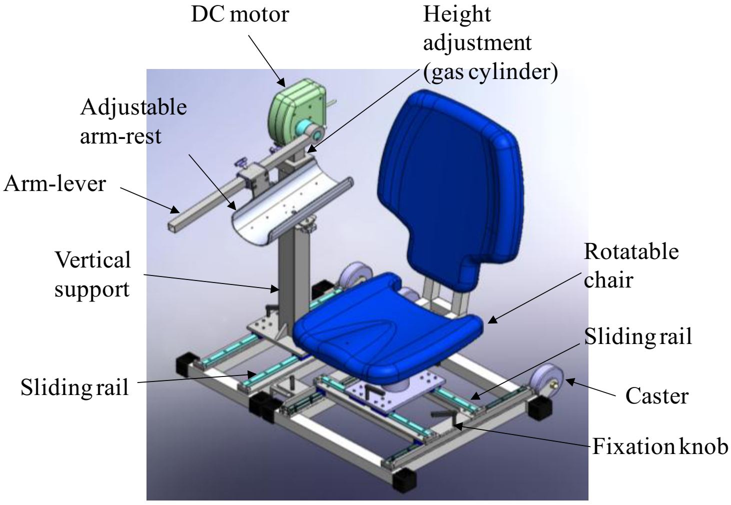


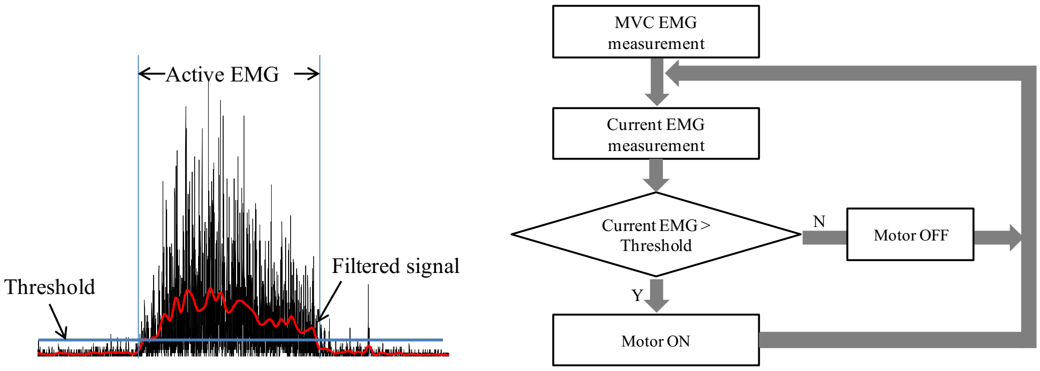
Fig. 1. Motorized equipment for the assisted shoulder movement.

2.1. EMG-controlled assistive exercise system

Figure 1 shows the motorized equipment for the shoulder abduction and flexion, consisting of a DC motor, an arm-lever, an arm-rest, a vertical support, a rotatable chair, base frames, and adjustment mechanisms. The adjustment mechanisms include the height adjustment of the motor axis and the sliding adjustment of the positions of the chair, vertical support, and armrest. The equipment is designed to assist flexion and abduction exercises of both sides shoulders. For example, the configuration in Figure 1 is for the flexion exercise of the right shoulder. For the abduction exercise of the ipsilateral shoulder, the chair is rotated 90° counter-clockwise, whereas the horizontal position of the chair and vertical support are adjusted. For the flexion exercise of the left shoulder, the arm-lever is inverted to the opposite side with the armrest overturned, and the chair is rotated 180° from the configuration of Figure 1. Similarly, the left shoulder abduction exercise requires a 90° clockwise rotation of the chair from the configuration of the left shoulder flexion.

EMG was measured using a surface EMG system (LXM3204, LAXTHA, Seoul, Korea) and derived from the lateral deltoid and anterior deltoid muscles to obtain the motor intentions of the shoulder abduction and flexion, respectively. The EMG signal was transported to a personal computer (PC) via a data acquisition board (PCI-6221, NI, Austin, TX, USA) where the analog signal was digitized at a sampling frequency of 1 KHz. The PC program (developed using LabVIEW) designated the exercise settings (the initial and final angles and movement velocity) and controlled the motor driver via serial communication. The initial and final angles were set as 20° and 70°, respectively, for both the flexion and abduction. This shoulder motion range was applied to all patients and there was no patient who reported pain.

The velocity of the shoulder flexion or abduction by the motor assistance was set to a moderate speed of 6.25°/s. The PC program requested the motor driver to assist the movement with the preset speed, only when the voluntary movement intention was detected (i.e., when EMG exceeds the threshold). The PC program also monitored the current angular position and velocity of the arm lever. No feedback of the current muscle activation was provided to the patient, because the patient could recognize if his/her motor intention was enough from the immediate movement of robot arm.



(a) Detection of motor intention (b) Assistive control algorithm

Fig. 2. EMG-controlled assistive exercise method.

Figure 2 shows the details of the assistive exercise method. The EMG processing and the detection of motor intention are shown in Figure 2(a). To obtain a smooth envelope of the muscle activity, the EMG was full-wave rectified and low-pass filtered by a digital Butterworth filter (cutoff frequency = 0.5 Hz, 4th order). The assistive control algorithm is depicted in Figure 2(b). The EMG was normalized using the maximum voluntary contraction (MVC) value measured before the exercise so that the EMG amplitude was described as %MVC. When the EMG exceeded the threshold (20–30% MVC), it was recognized as a movement intention and the “Motor ON” command was delivered to the motor driver so that the movement was assisted by the motor at the preset speed. If not, the motor would be turned off. When the flexion or abduction was completed (shoulder angle was at final 70°), PC sent the “return” command to the motor driver so that the shoulder angle went back to its original position (initial 20°).

2.2. Subjects and experiments

Twelve patients with chronic hemiplegia and stabilized with the upper extremity hemiparesis participated in this study. The stabilization was defined as hemiplegia longer than four months without documented change in the motor function and muscle tone in the one month before the study enrollment. The subjects were six males and six females; mean age, 64.4 ± 12.4 years; mean period after hemiplegia onset, 32.2 ± 33.0 months (four months to eight years). All the participants were right-handed, and the paretic side was right for 10 subjects and left for two subjects. The cause of hemiplegia was hemorrhagic in seven subjects and ischemic in five. No control subject is included in this study, because 1) this study is a pilot study to investigate the feasibility of the suggested method; 2) the motor recovery in chronic hemiplegia is negligible with the conventional therapy; 3) hemiplegia is stabilized in all the subjects, hence any noticeable enhancement in the motor function would show the efficacy of the suggested active-assistive exercise. This study was approved by the Institutional Review Board, and all the subjects gave informed consents for the participation in the study.

Before the intervention, baseline performance was investigated through multiple tests, including 1) active range-of-motion (ROM) of the shoulder abduction and flexion measured by a goniometer, 2) the Fugl–Meyer Motor Assessment (FMA), 3) maximum isometric torques of the shoulder abduction and flexion.

Active ROM was assessed in the neutral position (0° of shoulder flexion and abduction) with the patient seated. The FMA aims to measure post-stroke motor impairment of the upper and lower limbs and consider evolving synergy patterns, isolated strength, coordination, and hypertonia. The reliability and validity of the FMA have been well established [40, 41]. Scores of the items in the FMA were summed for the upper (maximum score of 66) and lower limbs (maximum score of 34) in this study. Shoulder-related items were newly categorized by selections from the upper extremity FMA, including shoulder retraction, shoulder elevation, shoulder abduction, shoulder external rotation, shoulder adduction with internal rotation, positioning the hand on the lumbar spine, shoulder flexion to 90° (with elbow extended and forearm neutral), shoulder abduction to 90° (with elbow extended and forearm pronated), shoulder flexion from 90° to 180°. The maximum score for the shoulder-related items was 18 (9 items × 2). The shoulder-unrelated items (e.g. wrist circumduction) of the upper extremity were made by subtracting the shoulder-related items from all items of the upper extremity FMA, resulting in 24 items and a maximum score of 48.

The isometric torque values of the abduction and flexion were measured at 30° in each direction. An identical equipment as shown in Figure 1 was used while the arm attachment with a torque sensor (model TORQUE, MS Cell Corp., Seoul, Korea) integrated at the shoulder rotation axis. The maximum torque was defined as the peak value in the torque profile.

The EMG-controlled assistive exercise lasted for two weeks, 20 min per day and 5 days a week. One intervention in a day was consisted of 10 min of flexion and 10 min of abduction exercise. The conventional rehabilitation program was also performed for all patients according to the ethics committee suggestions. The performance tests were repeated after the 2-week intervention. Performance was compared before and after the intervention using Wilcoxon's signed-rank test, considering a moderate number of subjects ($n = 12$).

3. Results

Figure 3 shows the performances before and after the intervention and their statistical comparisons. Active ROM increased significantly after the intervention both in the abduction (mean, 1.50 times) and flexion (mean, 1.34 times) ($p < 0.01$). The maximum torque increased in both the directions. However, the increase was significant only for the abduction (mean, 1.55 times, $p < 0.01$).

The score of the shoulder-related items of the upper extremity FMA significantly increased from 5.5 to 8.2 ($p < 0.01$), whereas the score of the shoulder-unrelated items did not improve ($p = 0.29$). Therefore, the significant improvement in the upper extremity FMA score (from 19.1 to 22.6, $p < 0.01$) may have been caused by the change in the shoulder function. As expected, the lower extremity FMA score did not improve ($p = 0.19$).

4. Discussion

The principal finding of this pilot study is that the EMG-controlled assistive exercise is feasible for the motor recovery of the target joint after the hemiplegia. Most recovery occurs in the first three months after the hemiplegia with the conventional therapy [4, 12, 13], and all patients in this study were in chronic (32.2 ± 33.0 months) and stabilized hemiplegia.

Therefore, significant improvements in the shoulder active ROM, torque, and motor function (Figure 3) may result from the suggested exercises rather than the natural recovery or the conventional therapy. In fact, this kind of study design (focusing on chronic patients with stabilized

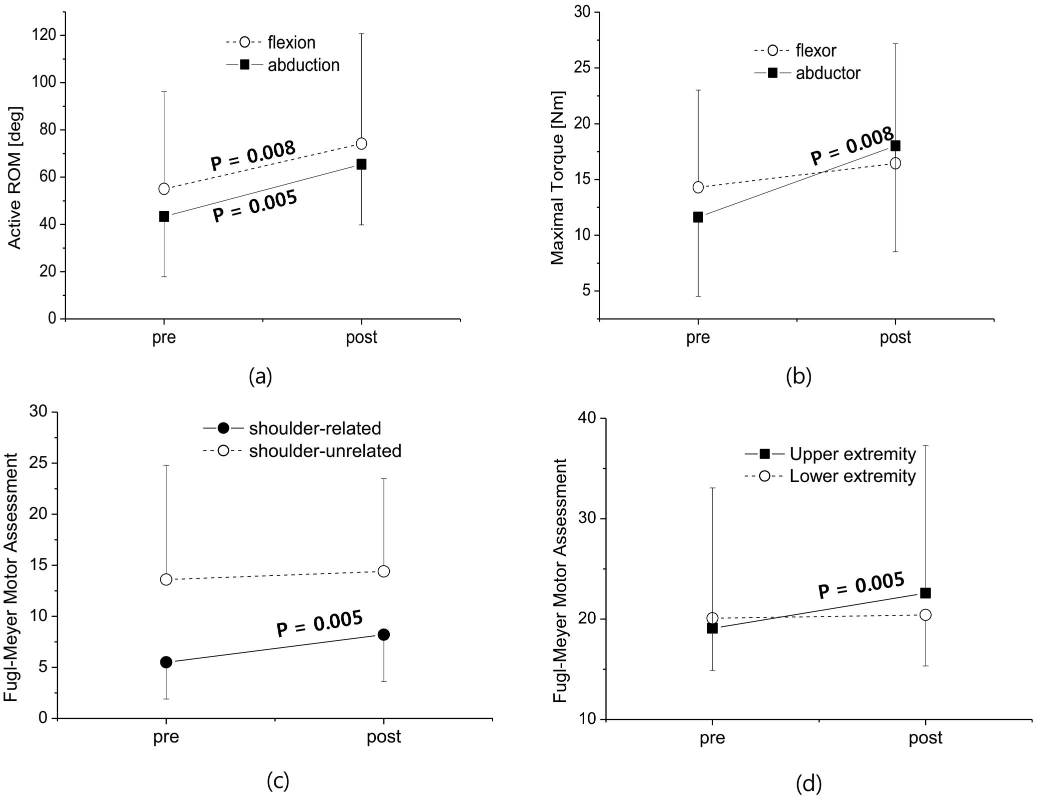


Fig. 3. Change in motor performances after the EMG controlled shoulder exercise.

hemiplegia and without control subjects) is often taken in the pilot studies where the effect of new rehabilitation therapy for the hemiplegia was investigated, e.g., to evaluate the effects of electrical stimulation on the upper limb function and pain [42-45] and the effects of robotic therapy on the upper extremity functions [46, 47].

Negligible effects of the natural recovery or the conventional therapy on the improvement of the shoulder motor function is also supported by the fact that the functional (FMA score) improvement is exclusively demonstrated for the shoulder-related items (Figure 3). That is, if the improvement in the shoulder function was affected by the natural recovery or the conventional therapy, the shoulder-unrelated functions of the upper limb and lower limb functions should have been improved. This is also supported by the findings that the patterns of the natural motor recovery are similar for the upper and lower extremities [48].

As for the mechanism of the recovery in this study, the requirement of a certain level of motor intention (EMG) may have elicited activity of the target muscle in the patients. The timely assistance controlled by the promptly detected motor intention may have resulted in timely feedback to the central nervous system. The repetitive exercise in correct trajectory is provided by the assistive exercise protocol. Therefore, the correct-active-repetitive exercise (termed as CARE in this study) may have resulted in the motor recovery, probably through the brain reorganization. However, the conclusions regarding the efficacy of the suggested method cannot be made from the present results, because the study is insufficient in its size and the control group. Further studies addressing these issues are needed for the suggested method to be put into clinical applications.

The active ROM increased both in the flexion and abduction. However, the increase in the maximum torque was significant only for the abduction, not for the flexion (Figure 3). This might be related to the difference in the associated muscles of the shoulder in each direction. The muscles of the abduction are relatively simple. The abduction was generated by the supraspinatus muscle for the first 15–30° and by the lateral deltoid muscle above the range [49-51]. In this study, the lateral deltoid muscle was taken as the main muscle of the abduction, because the exercise range is designed from 20 to 70°. The isometric torque values of the abduction were measured at 30° abduction. Therefore, any recovery of the lateral deltoid would have enhanced the abduction torque and the active abduction ROM.

In contrast, the shoulder flexion is known to be generated by numerous muscles, i.e., anterior deltoid, biceps brachii long head, pectoralis major, and coracobrachialis. Therefore, the recovery of only the anterior deltoid muscle (from which the flexion intention was derived) may have been insufficient to significantly improve the flexion torque. However, a small increase in the flexion torque by the recovery of the anterior deltoid may have been enough to enhance active ROM, because the minimal requirement for the ROM enlargement is the torque resisting the gravity of the arm. These results may support that the exercise controlled by the EMG from a specific muscle can lead to the selective improvement of the identical muscle. In this respect, the derivation of the flexion intention from the EMG of multiple flexors may be effective to achieve a significant increase in the shoulder flexion torque and needs further investigation.

5. Conclusion

We demonstrated the feasibility of the therapeutic effects of the EMG-controlled assistive exercise for a chronic hemiparetic shoulder after spontaneous recovery is considered to be completed in this study. The shoulder-related impairment and movement quality significantly improved following the intervention, as indicated by the changes in motor impairment scores, active ROM, and active torque. It also indicates that the new intervention can be effective in clinical applications.

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