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Feasibility of Isokinetic Training to Modify Coupling of Upper Limb Muscle Synergy Activation in Stroke-affected Upper Limb

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Abstract— **Abnormal intermuscular coordination in stroke-affected upper limbs contributes to motor deficits after stroke. In particular, abnormalities in the activation of upper limb muscle synergies after stroke were demonstrated for endpoint force control during isokinetic exercises. This study aimed to investigate the feasibility of isokinetic training to alter these abnormal synergy activations and improve motor control. Muscle synergies and Wolf Motor Function Test Functional Ability Scale (WMFT-FAS) score were compared before and after three weeks of electromyography-based training. The proposed training changed the synergy activation and improved the WMFT-FAS score in a chronic stroke survivor while preserving the muscle weights of the synergies.**

Clinical Relevance— **This study presents the feasibility of neuromuscular training to modify the activation of upper limb muscle synergies against stroke-specific patterns of intermuscular coordination and improve WMFT-FAS score.**

I. Introduction

Stroke impairs the generation and transmission of motor commands in the central nervous system, leading to abnormalities in intermuscular coordination [1]. Abnormal coordination of upper limb muscles after a stroke can degrade motor performance. Since the upper limb motor function affects the quality of life [2], modification of the stroke-affected intermuscular coordination is important for stroke rehabilitation.

Muscle synergy analysis reveals the structure underlying muscle activities with high complexity utilizing various numerical methods to factorize multi-channel electromyographic (EMG) data into a small number of co-activation patterns of muscles (*known as* muscle synergies) [3]. The EMG factorization can be expressed as (1)

$$\boldsymbol{E}_{t\times m} = \boldsymbol{E}^*_{t\times m} + \boldsymbol{R}_{t\times m} = \boldsymbol{C}_{t\times k} \cdot \boldsymbol{W}_{k\times m} + \boldsymbol{R}_{t\times m} \quad (1)$$

where $\boldsymbol{E}$, $\boldsymbol{E^*}$, and $\boldsymbol{R}$ are t(number of sample points) by m(number of the muscles) matrices of original EMG data, EMG reconstructed with the muscle synergies and reconstruction error, respectively. $\boldsymbol{C}$ is a t by k(number of the synergies) matrix of activation profiles of the k synergies, while $\boldsymbol{W}$ is a k by m matrix of muscle weights, representing the synergy structure. The number of muscle synergies implies how many different ways a person combines the muscles to achieve the given motor tasks. The muscle weights of each synergy represent the relative contribution of each muscle, and the activation profile of each synergy describes timing and magnitude of the synergy activation.

In our previous study, we compared muscle synergies in proximal upper limbs (*i.e.,* shoulder and elbow) of chronic stroke survivors and neurologically intact (able-bodied) adults for three-dimensional isokinetic upper limb movements [4]. The result indicated that when the participants were instructed to direct the endpoint force toward the movement direction, the stroke survivors showed larger directional errors compared to the able-bodied people. In terms of muscle synergy, the able-bodied participants utilized five muscle synergies: elbow flexor (EF), elbow extensor (EE), shoulder flexor/abductor (SF/Ab), shoulder extensor/abductor (SE/Ab), and shoulder flexor/adductor (SF/Ad) synergies. The stroke survivors had a similar number and composition of muscle weights, with the exception of the merging of the two shoulder abductor synergies. The increased coupling of the shoulder abductor (deltoid) muscles in the stroke-affected upper limb has been reported in literature [5]–[7]. In addition, several methods of stroke rehabilitation, which targeted the abnormal coupling between muscles, have been proposed [8]–[10].

Our study also identified two patterns of synergy activation coupling in the affected upper limb: 1) the EF synergy with SF/Ab and SE/Ab synergies, and 2) EE synergy with SF/Ad synergy. These patterns were consistent with the coupling in joint torque and kinematics in hemiparetic upper limbs [11], [12]. However, there is a lack of research on altering muscle synergy activation patterns for stroke rehabilitation.

The aim of this study was to test the feasibility of modifying coupled synergy activation in the stroke-affected upper limb. A simple synergy activation training system that aimed to increase the activation of major contributor muscles within a specific synergy was developed for this study. Isokinetic reaching for six different directions was performed while inducing simultaneous activation of 1) the EF synergy with SF/Ad synergy, and 2) EE synergy with SF/Ab and

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SE/Ab synergies, which are in opposition to the stroke-affected coupling of synergy activation.

One chronic stroke participant with moderate motor impairment received a total of 12 training sessions. The change in EMG of the proximal upper limb muscles within a single training session was evaluated to verify if the proposed training was capable of inducing activation of the target muscles. In addition, pre- and post-training muscle synergies and Wolf Motor Function Test Functional Ability Scale (WMFT-FAS) scores were compared to assess the effect of long-term training. We hypothesized that the proposed training can not only alter the synergy activations of stroke survivors but also enhance overall motor performance by combining the elbow- and shoulder-related synergies freely.

II. Methods

A. Participant

One female chronic stroke survivor with moderate motor impairment was recruited (age: 58 years, months after a stroke: 9 months, Fugl-Meyer assessment for upper limb: 43 out of 66). An interview was conducted to ensure that 1) the participant was capable of following instructions and understanding the experimental tasks, 2) had the upper limb mobility to perform the experimental tasks with the affected side, and 3) did not have any other neurologic or orthopedic diseases. This study was approved by the institutional review boards of the Korea Advanced Institute of Science and Technology (KH2020-180). The participant provided written informed consent before the study.

B. Training Setup

The isokinetic training was implemented utilizing our custom training setup, KAIST upper limb synergy investigation system (KULSIS, Fig.1) [13]. A force-sensing handle mobilized by a linear actuator allowed the user to reach straightly in an isokinetic manner. A six-axis force/torque sensor (ATI-Delta, ATI Industrial Automation, NC, USA) was combined with the handle. The linear actuator was rotated to enable reaching in six orthogonal directions: anterior (Ant), posterior (Post), medial (Med), lateral (Lat), superior (Sup), and inferior (Inf).

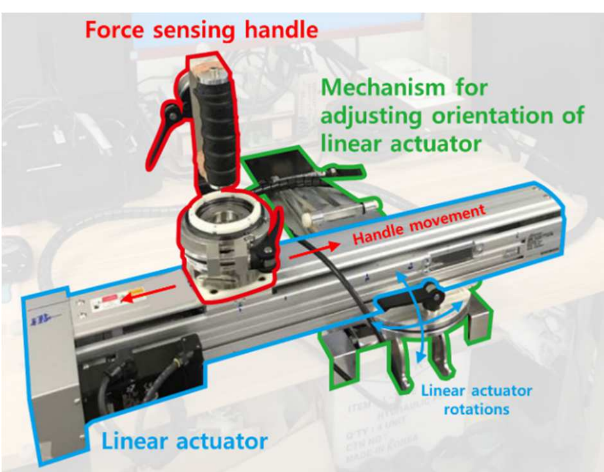

Figure 1. The KULSIS consists of a force sensing handle (red) that moves along a linear actuator (blue) in an isokinetic manner. The base (green) can rotate and lock the linear actuator to allow the handle to move in six orthogonal directions in a three-dimensional space.

The neuromuscular activities of eight muscles were recorded using surface EMG sensors (Delsys Trigno EMG, Delsys, MA, USA). The EMG electrodes were placed on the biceps (Bic), brachioradialis (Brd), triceps long (Tlo) and lateral (Tlat) heads, clavicular head of pectoralis major (PM), anterior, middle, and posterior heads of the deltoid (AD, MD, and PD, respectively). All EMG signals were collected at 2000 Hz and synchronized with the KULSIS.

C. Training Protocol

For the training, the participant performed 200 mm isokinetic reaching at a selected speed in the six orthogonal directions. A total of twelve training sessions were held over three weeks, and the total training time per session was 50 minutes. Each session consisted of six blocks (four ten-minute blocks, and two five-minute blocks) with breaks inbetween. The target muscle synergy that was trained for each movement direction was selected to oppose the commonly found abnormal stroke-specific coupling patterns (Table 1). The training was conducted once in each of the six movements for the first six sessions. For the last six sessions, intensive training was given for three selected movements: anterior, lateral, and superior directions (*i.e.,* two training sessions per movement). The WMFT-FAS was assessed by an experienced physical therapist before and after the training.

Synergy activation training was implemented through EMG based verbal feedback from the experimenter. While the participant was performing the tasks, the experimenter monitored the EMG intensity and gave verbal feedback on which muscles should be activated or inhibited. In addition to the EMG feedback, upper limb tasks that induced the desired muscle activation patterns were described to help the participant quickly adapt to the training. For example, during the posterior reaching, the participant was instructed to slightly pull the handle inwards and keep their elbow tucked towards their trunk to promote PM activity while inhibiting deltoid activity. Verbal feedback was implemented to allow the experimenter to give immediate feedback according to the performance of the participant.

TABLE I. The Basic Muscle Activity and Target Synergies for Each Movement Direction

Direction	Basic Muscle Activity	Target Synergy / Contributor muscles[a]
Anterior	Elbow extension	Shoulder flexor/abductor (SF/Ab)
		MD, AD
Posterior	Elbow flexion	Shoulder flexor/adductor (SF/Ad)
		PM, AD
Medial	Shoulder adduction	Elbow flexor (EF)
		Bic, Brd
Lateral	Shoulder abduction	Elbow extensor (EE)
		Tlo, Tlat
Superior	Elbow flexion	Shoulder flexor/adductor (SF/Ad)
		PM, AD
Inferior	Elbow extension	Shoulder extensor/abductor (SE/Ab)
		MD, PD

a. The major contributor muscles for each target synergy are listed.

D. Data Analysis

First, we verified that the proposed training could induce activation of the target muscles. EMG of the shoulder and elbow muscles for the initial untrained habitual movements and EMG for movements during training were compared for each direction. At the beginning of each training block, the habitual EMG was collected for five trials, and representative trials were selected for comparison.

Second, to assess the muscle synergies pre- and post-training, the participant performed 200 mm isokinetic reaching tasks at a maximum speed of 30mm/s using the training setup. The participant was instructed to exert maximal force at the handle with their upper limbs only along the given direction. No feedback of endpoint force was provided during the experiment. This was repeated in six trials for each of the six directions. EMG signals were filtered to obtain their envelopes and concatenated across the trials, and movements. The processed EMG was factorized into five muscle synergies and activation profiles using non-negative matrix factorization (NNMF) algorithm [14] in accordance with our previous finding [4]. The similarity of muscle weights between the synergies before and after the training was evaluated using the cosine similarity measure, an inner product of two corresponding synergies. For synergy activation, pre- and post-training synergy activation were compared for the selected movements for intensive training.

III. RESULT

A. Immediate Change in Muscle Activity during Training

The participant was able to immediately alter muscle activation according to the EMG feedback and task-based instructions based on the training targets (see Table 1) (Fig. 2). For example, the activities of the MD and AD muscles increased in the training for the anterior movement while the other shoulder muscles were activated with the comparable intensity as the habitual EMG. When the activation of the SE/Ab synergy was trained for the inferior movement, the MD and PD muscles were more highly activated than in the habitual movement. For the medial and lateral movements, activation of the elbow flexor (i.e., the Bic, and Brd), and elbow extensor (i.e., the Tlo, and Tlat) muscles was induced by the training, respectively. During the training of the medial movement, the Tlat muscle, one of the elbow extensors, was also activated in addition to the elbow flexor muscles. When activation of the SF/Ab synergy (i.e., the PM, and AD muscles) was trained for both posterior and superior movements, the training increased activation of the PM muscle.

B. Changes in Synergy Activation after Training

The proposed training did not produce a substantial change in muscle weights (cosine similarity, mean: 0.85, range: 0.65~0.97). Despite the elbow muscles' weights being changed in the shoulder-related synergies, the weights of the major contributor muscles for each synergy were comparable (Fig. 3).

Synergy activation before and after training were compared for the selected movements that received intensive training. The activation of the SF/Ab synergy for the anterior movement was increased. However, the SF/Ad synergy, another synergy for the shoulder flexion, was also increased. The training for the superior movement increased the activation of the SF/Ad synergy and decreased the activation of the other shoulder synergies. Though the activation of the EE synergy was trained during the lateral movement, there was no change in the activation of the synergy after training. Instead, the weight of the Tlat muscle (one of the elbow extensor muscles) was increased in the SF/Ab and SE/Ab synergies, which were used for the lateral movement. The WMFT-FAS score was initially 43 (out of 75) pre-training and improved to 48 after the training.

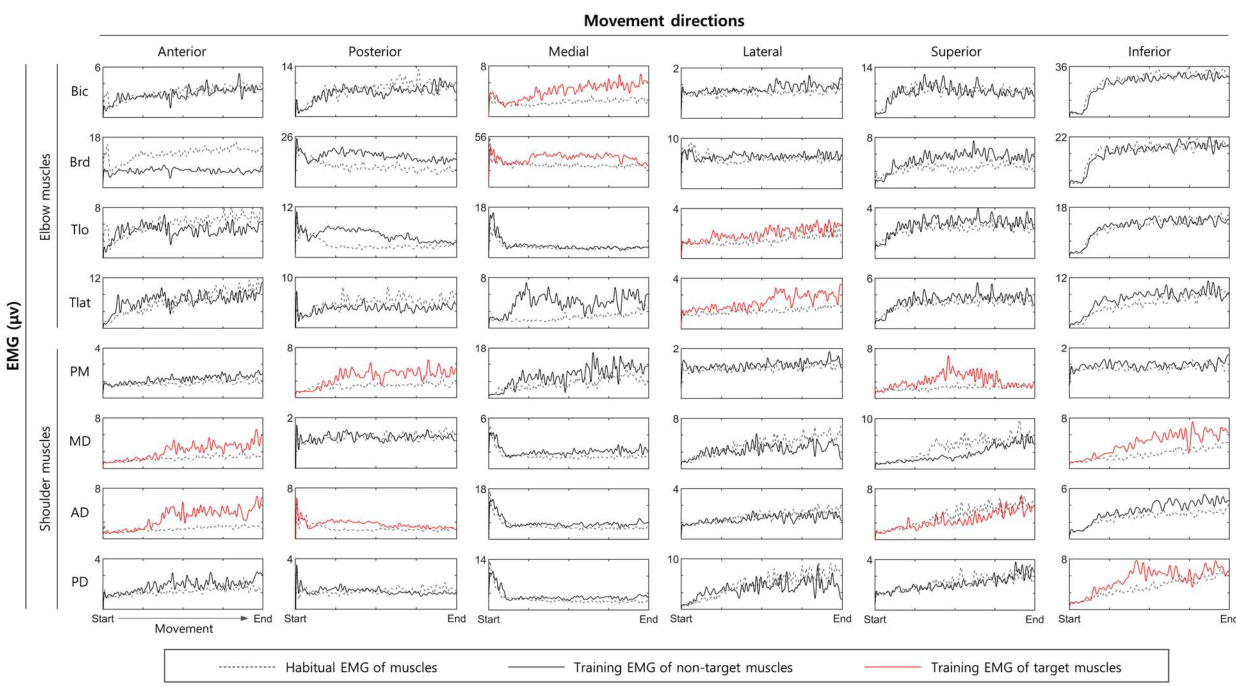

Figure 2. EMG of the upper limb muscles during habitual and training movement for each direction. The habitual EMG is shown as a dotted line and the training EMG of non-target and target muscles are shown as solid black and red lines respectively

IV. Discussion

This study investigated the feasibility of modifying the muscle synergy activation patterns in a chronic stroke survivor. The results showed that with verbal feedback on the muscle activities and task-based instruction, the stroke survivor could increase the activation of the target muscles within a single session. In terms of synergy activation, the intensive training could alter several activation patterns, thereby suggesting that the synergy activation in the stroke-affected upper limb can be trained against the stroke-specific patterns in intermuscular coordination. The training was also shown to be effective in increasing the WMFT-FAS score.

However, it was also noted that for some movements, the proposed training either increased the activation of the non-target muscles or changed the activation of only one of the target muscles. For the lateral movement, the intensive training affected the muscle weights instead of the target synergy activation. This occurred because the training activated one of the two target muscles to a greater extent. Further research with a more elaborate training method, such as providing multiple instructions corresponding to various errors in muscle activation for each movement, is required to achieve precise changes in muscle activity. Although verbal feedback was utilized to allow immediate personalized feedback, a visual feedback interface may enable more intuitive training.

This study was limited in the number of participants recruited, and the findings may not be generalizable. Further research with a large scope of participants with varying degrees of impairment is necessary to validate the results. Additionally, it is important to assess the impact of changing the muscle synergy activation pattern on functionality, which can be done by comparing the muscle synergies with the endpoint force control and clinical evaluation scores.

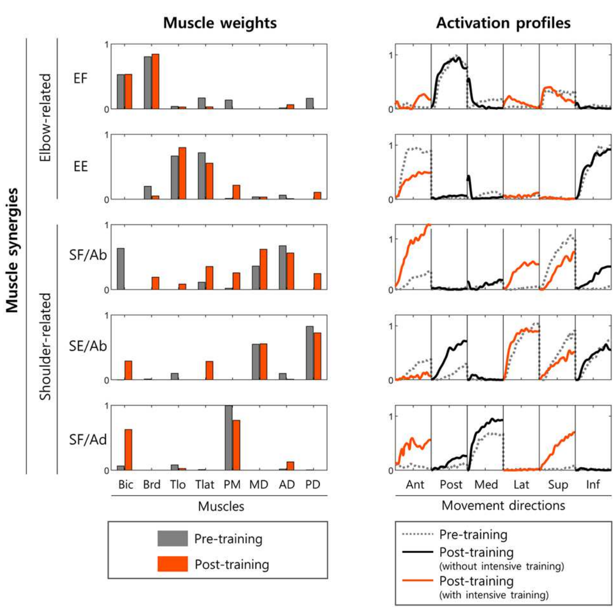

Figure 3. The change in muscle synergy weights and activation profiles pre and post training. The pre-training weights and post-training weights are grey and orange respectively. The pre-training activation profiles are dotted grey lines while the post-training activation profiles without and with intensive training are solid black and orange lines respectively.

V. Conclusion

We found that a chronic stroke survivor with moderate impairment could learn new synergy activation patterns that oppose the coupling between elbow and shoulder muscles found in affected limbs. The proposed training had the potential to modify the stroke-affected coordination of proximal upper limb muscles and consequently improve various motor deficits after stroke. Further research involving a larger sample of stroke survivors is necessary to determine the impact of this training on various measures of motor performance such as endpoint force and clinical evaluations.

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