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Feasibility of inducing new intermuscular coordination patterns through an electromyographic signal-guided training in the upper extremity: a pilot study

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Abstract— Abnormal intermuscular coordination has been highlighted in the field of post-stroke upper extremity (UE) rehabilitation. Relatively recent studies have quantified the altered "muscle synergies", distinctive co-activation patterns of a group of muscles, which characterize the stroke-induced abnormal intermuscular coordination. Nonetheless, whether targeting the altered muscle synergy(ies) would ameliorate the stroke-induced motor impairment and improve motor function remains unknown. Our ultimate aim is to design an exercise protocol that modifies abnormal muscle synergies and improves motor function in UE after stroke. In this study, the feasibility of an electromyographic (EMG) signal-guided exercise protocol, which targeted the alteration of an elbow flexor synergy, was tested in healthy subjects. Four neurologically intact adults participated in a six-week isometric exercise to activate two major elbow flexor muscles, biceps and brachioradialis, in isolation. Participants performed an isometric reaching in a virtual three-dimensional (3D) force space to assess any potential changes in muscle synergies during the assessment at week zero, two, four, and six of the training. EMGs of 12 UE muscles and 3D forces were collected simultaneously. A non-negative matrix factorization (NMF) was applied to the EMGs to identify synergies. From the third-to-fourth week of the training, when the participants intended to use the newly learned motor skill, they were able to activate the targeted muscle pair in isolation and induce the formation of newly emerging synergistic muscle groups. As the participants practiced to expand their repertoire of intermuscular coordination patterns, their motor control of the trained UE was improved. These findings suggest that our isometric exercise protocol can potentially modulate impaired muscle coordination in a way that benefits stroke survivor's performance in activities of daily living (ADLs) and, eventually, their quality of life.

I. Introduction

Stroke, damage to the brain from interruption of its blood supply, is a leading cause of long-term disabilities. Around 795,000 people in the USA have stroke every year [1]. About 80% of the survivors undergo motor impairments [2] that include paresis, weakness, and abnormal muscle tone, especially in the upper extremity (UE) [3,4,5]. Along with these motor deficits, impaired intermuscular coordination is also one of the major motor impairments after stroke. Relatively recent studies have characterized the stroke-induced abnormal intermuscular coordination in UE by applying the dimensionality reduction methods, such as non-negative matrix factorization (NMF) [6,7,8] and principal component analysis (PCA) [9], on the recorded electromyographic (EMG) data. The dimensionality reduction method identified a small number of groups of muscles, called muscle synergies, characterizing the coordinated patterns of muscle activity that can combine to produce functional motor behaviors [6,7,8]. According to the findings from the recent studies, stroke-induced UE muscle synergies involve abnormal coupling between elbow and shoulder muscles [10,11,12] as well as the abnormal coactivation of three heads of deltoid muscles as shoulder abductor/extensor [8]. It is, however, still unclear whether targeting or normalizing the altered muscle synergy in a rehabilitation exercise would be feasible, decrease the stroke-induced motor impairment, and improve motor function. Considering that intermuscular coordination patterns can underlie prescriptive neural strategy for motor control [13], it is worthwhile to test a modification of the abnormal UE muscle synergy through a rehabilitation exercise and its potential relationship with an improvement of impaired UE motor function after stroke. As the first step, in this study, an electromyographic signal pattern-guided training protocol, which targets the alteration of a typical elbow flexor synergy observed in healthy subjects, was developed to test its feasibility in developing new synergies or modifying existing synergies which can be applied to stroke survivors as a therapeutic exercise.

II. Methods

A. Participants

Four young healthy subjects (three males, one female; 24.3 $\pm$ 3.8 years of age) with no medical history of neurological disorder and muscular or orthopedic injuries in UE participated in the experiment. All four subjects were right-handed and used their dominant hands for the training and the motor assessment. The study was performed in accordance with the Declaration of Helsinki, with the approval of the

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University of Houston Institutional Review Board. Informed consent was obtained from each subject prior to experiments.

B. Equipment

For the isometric force measurement, a custom-designed device, KAIST Upper Limb Synergy Investigation (KULSIS), was used during the assessment and the training [14]. The device measured three-dimensional forces generated at a gimbal handle mounted on a six-degree-of-freedom load cell. The force signals were collected at a sampling rate of 20Hz. Prior to each experiment, the position of the handle was aligned with the subject's shoulder (dominant hand side) and the distance between the handle and the shoulder was set to 60% of the full length of the arm. Using a harness attached to the KULSIS seat, trunk posture and upper body movement of the subject were constrained.

Through a wireless EMG recording system (Trigno Avanti Platform; Delsys Incorporated, Boston, MA), EMGs were acquired from either eight (one subject) or twelve (three subjects) major UE muscles at 1KHz: brachioradialis (BRD); biceps brachii (BI); triceps brachii, long and lateral heads (TRIlong and TRIlat, respectively); deltoid, anterior, middle, and posterior fibers (AD, MD, and PD, respectively); and pectoralis major (clavicular fibers; PECT); trapezius, upper, middle, and lower fibers (UpTrp, MidTrp, and LowTrp, respectively); and infraspinatus (InfSp). The back muscles (UpTrp, MidTrp, LowTrp, and InfSp) were not included in the eight-muscle set. The force and EMGs were recorded simultaneously and synchronized using an internal clock and the markers.

C. Experimental Design

The subjects received a one-hour-long EMG-guided training under isometric condition (arm remained stationary) three times a week (in total, for six weeks). The task of the training was an target matching in a two-dimensional square by controlling a cursor whose horizontal and vertical displacement was mapped to the activation magnitude of BRD and BI, respectively. BRD and BI in a healthy person are two major elbow flexor muscles typically coupled in the same synergy, which makes it difficult to activate them in isolation from each other. The size of the square space was scaled based on the pre-measured maximum voluntary contraction (MVC) amplitude of the EMG of each muscle (to adjust the difficulty of the task, the width and length of the space were scaled down to the 70% MVC of BRD and BI, respectively). For each trial, the EMG-driven cursor started at the upper left corner of the square space, and a square target randomly appeared either at the upper right corner (BRD target) or bottom left corner (BI target) of the boundary. The size of the target was 30% of the square space. In order to match the target, the subject should utilize independent activation of each muscle to guide the cursor to the target within seven seconds and hold it on the target for one second. If two muscles were simultaneously activated, the cursor would move in a diagonal direction, which would result in unsuccessful target matches. During the training, the subjects were encouraged to explore and build their own strategies to match the target under isometric condition, however, verbal guidance on behaviors that were known to induce the activation of the targeted muscles was provided if needed. Each one-hour training session consisted of three 15 minutes blocks of training and five minutes of break in between. The subjects were instructed to match the targets as much as they could.

At week zero, two, four, and six of the training, the subjects performed an isometric reaching in a three-dimensional force space to assess any potential changes in their intermuscular coordination. During the motor assessment, the subjects were instructed to perform isometric target matches in three-dimensional force space by controlling a virtual cursor in the screen using KULSIS. One of fifty-four targets, uniformly distributed around a sphere, appeared in random order at a time [8]. The target force magnitude was set at 40% of the maximum lateral force, the weakest direction for all subjects. For each trial, a two-second baseline period was followed by a target matching period, a maximum of seven seconds. A successful target match required the subject to maintain the center of a force-driven cursor within a target for 1 second. The motor assessment consisted of two sessions: 1) a "habitual" session and 2) a "conscious" session. In the habitual session, no restriction was applied in performing the task, therefore, the subjects used their habitual motor strategy for target matches as performed prior to the six-week isometric exercise. For the conscious session, the subjects were instructed to consciously use the trained muscle coordination as they practiced during the exercise. At week 0 assessment (prior to training the activation of each targeted muscle in isolation), verbal guidance on behaviors mapped to activation of the targeted muscles was provided prior to the conscious session.

D. Data Analysis

The raw EMG data were pre-processed with a wavelet filter to suppress any electrocardiogram (ECG) artifact visually observed. Following the ECG removal, the EMGs were demeaned to eliminate DC offsets and the mean baseline was subtracted from the processed signal. To obtain the envelope of the signal, full-wave rectification and a low pass filter (4^{th} order Butterworth filter with cutoff frequency at 10Hz) were applied. For the force data, the mean amplitude of the baseline force was subtracted to further analyze task-dependent activities. The force onset was computed to identify both EMG and force data collected during target matching.

An NMF algorithm was applied to the pre-processed EMG data, concatenated across the 54 target matches as a single matrix per each assessment, to identify muscle synergies expressed during the isometric task. All the negative components of the EMGs were set to zero to meet the non-negativity constraint of the NMF. Lastly, the data were normalized to have unit variance to avoid any bias in synergy extraction toward the high-variance muscles [8]. EMGs were modeled as a linear combination of a muscle synergy set (W) and its corresponding activation coefficients (C):

$$EMG_{reconstructed} = W \cdot C \quad (1)$$

W is an M (number of muscles) × N (number of muscle synergies) matrix, and C is an N × B (number of data samples) matrix. To obtain the optimal number of muscle synergies (N) for each subject, the variance-accounted-for (VAF) value for the entire muscle set (gVAF) was calculated. In addition, the difference in gVAF acquired by adding an additional synergy (diffVAF) to a given number of synergies was also considered to estimate the number of muscle synergies. The VAF value was defined based on the ratio between the summation of the squared errors (SSE) and the total sum of the squared and uncentered EMG data (SST):

$$VAF = 100 \times \left(1 - \frac{SSE}{SST}\right) \quad (2)$$

For the synergy analysis, the number of synergies that satisfied gVAF>90% and diffVAF<3% was selected. The similarity of composition between two different muscle synergy sets was calculated using a scalar product [8,15].

III. Results

Typically, five synergies were identified to reconstruct the spatial characteristics of the EMG signals from twelve muscles of the three subjects across six weeks; for one subject with the recording from eight muscles, typically four synergies were required (Figure 1). When the subjects were instructed to use their trained strategies ("conscious" session), a relatively less number of synergies tended to be identified. Compared to the result from a conscious session of the early stage of the training (week 2), the number of synergies expressed during habitual force matches after week 6 of the training decreased significantly (p=0.047), but not in other weeks.

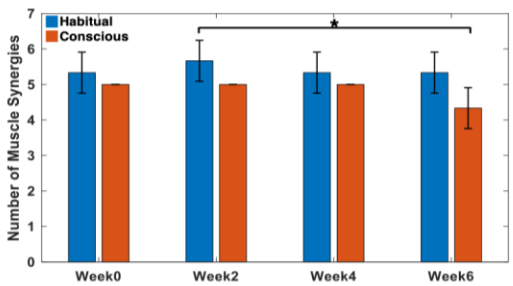

Figure 1. The number of muscle synergies identified from twelve muscle activation across the weeks for the habitual and conscious sessions (, p<0.05).*

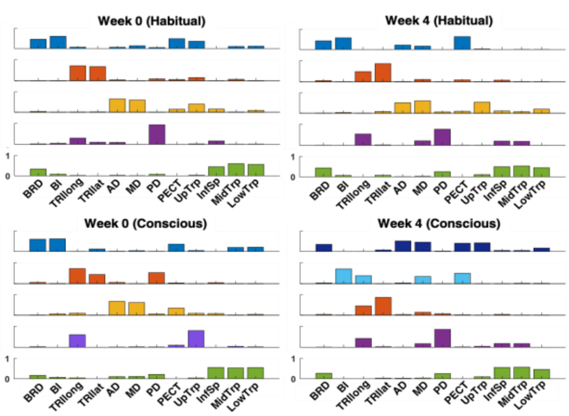

Figure 2. The representative muscle synergy sets of a subject exacted from week 0 (before training; left) and week 4 (right) EMG data.

After four weeks of the training, when the participants intended to use the newly learned motor skill, they were able to activate the targeted muscle pair, BRD and BI, in isolation from each other and induce the formation of new synergistic muscle groups. Before the training, the repertoire of intermuscular coordination patterns was similar between habitual and conscious sessions. Figure 2 shows that the habitual muscle synergy set at week 0 consisted of five synergies including 1) elbow flexor (BRD and BI) with PECT, 2) elbow extensor (TRIlong and TRIlat), 3) shoulder adductor/flexor (AD, MD, PECT, and UpTrp), 4) shoulder abductor/extensor (PD) with TRIlong, and 5) scapula retractor (MidTrp, LowTrp, and InfSp). During the conscious session at week 0, PD contributed more to the elbow extensor and UpTrp was dominating in the shoulder abductor/extensor. The composition of the rest of the muscle synergies, especially the coupling of BRD and BI in elbow flexor synergy, remained consistent. However, through the training, BRD was decoupled from BI and formed a new synergy with shoulder adductor/flexor, while BI was newly coupled with TRIlong, PD, and PECT when the subject consciously tried to use the trained motor control strategy. Despite the emergence of newly developed intermuscular coordination patterns, the habitual muscle synergies were conserved.

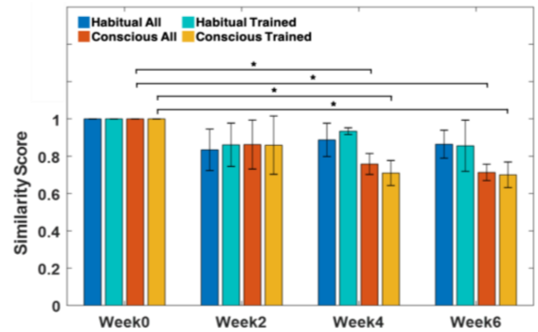

Figure 3. Similarity of muscle synergy composition between week 0 and the post-training weeks (2,4, and 6), when the all the synergies were considered (blue: habitual; red: conscious) and when only the BRD & BI dominant synergies were considered (green: habitual; yellow: conscious).

The composition of synergies expressed during the conscious session after training was significantly different (two-way ANOVA; p<0.05) from that of the pre-training (week 0) as the newly acquired intermuscular coordination patterns emerged (Figure 3). The other synergies, however, activated during the pre-training habitual session, were conserved throughout the training. Once the altered synergies were activated at week 2 or 4, they were consistently activated until week 6.

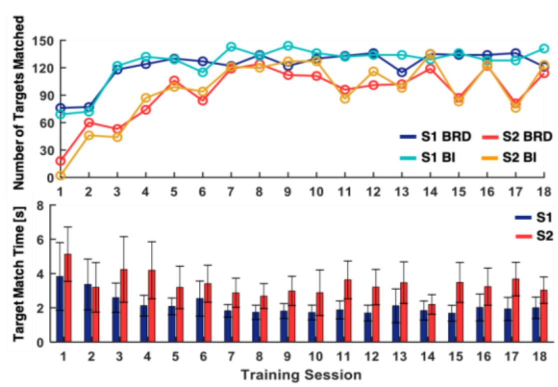

Figure 4. Number of targets matched for muscles BRD and BI (top) and the average target match time for each training session (a representative male subject, S1, and a female subject, S2).

Through the EMG-guided training, the accuracy and efficiency of motor control of the trained UE improved, which led to better isolation of each targeted muscle activation. Figure 4 showed that the number of successful trials for both BRD and BI targets increased during the first two-to-three weeks of training and plateaued from around week 4 of the training in representative male and female subjects, S1 and S2, respectively. The average task duration for each trial decreased accordingly.

IV. Discussion

Despite the relatively small sample size, to date as the first study, our pilot work showed its feasibility in altering the composition of a targeted muscle synergy observed in healthy subjects through a novel EMG-guided training exercise that has its potential to be applied to stroke UE rehabilitation as a next step. Considering that muscle synergies can underlie prescriptive neural strategy for motor control [10], we expect that the motor function of the impaired UE can be improved by targeting or normalizing the stroke-induced abnormal intermuscular coordination patterns. Moreover, since reducing abnormal co-activation of a muscle pair in stroke-affected UE through rehabilitation training can improve motor function [16], targeting the alteration of stroke-induced intermuscular coordination pattern may affect a greater impact on post-stroke motor recovery in UE.

Across the weeks of training, five and four muscle synergies, on average, were required to reconstruct at least 90% of the total variance of the EMG patterns recorded from 12 and eight muscles, respectively. The number and composition of the habitual synergies from eight muscles were matched to those observed in our previous study [5]. When the four back muscles (UpTrp, MidTrp, LowTrp, and InfSp) were added to the eight arm muscles, one more set of synergy, mainly contributing to retract the scapular, was newly identified. The number and composition of muscle synergies can vary depending on which muscles were recorded and what type and condition of the task were given to the subject [17].

After three-to-four weeks of the training, the subjects learned a new motor strategy to decouple the targeted muscle pair in the elbow flexor synergy and induce a formation of new synergies accordingly. The new synergies were able to be expressed for the rest of the training period when the subjects intended to use their newly learned motor skill during the task (conscious session). Even though the targeted muscle pair was neurologically intact, the subjects were not able to intentionally activate the muscle in isolation from the other before the training, since the muscles are synergistically coupled and form a synergistic muscle group. However, through our EMG-guided training under isometric conditions, the subjects could successfully activate the pair of BRD and BI in isolation by practicing a new motor behavior and use it as a strategy to complete the assessment task during the conscious session. Given the same instruction and guidance on the training, the subjects freely developed their own way to map an isolated activation of a muscle with a behavior (see Experimental Design in Methods), therefore, either or both composition and number of newly emerged synergies could possibly vary across the subjects.

As the new muscle synergies emerged, the task performance, represented as the number of targets matched and task duration, was improved, which implied the enhancement of motor control of the trained UE. In conclusion, the preliminary results suggest that our proposed training protocol may modulate the stroke-induced abnormal UE muscle synergy (e.g., a synergy with a co-activation of three heads of deltoid muscles), which can lead to normalization of affected synergies, improvement of survivor's performance in activities of daily living (ADLs) and, eventually, the quality of life.

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