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Expanding the repertoire of intermuscular coordination patterns and modulating intermuscular connectivity in stroke-affected upper extremity through electromyogram-guided training: a pilot study

Gang Seo, Michael Houston, Manuel Portilla, Feng Fang, Jeong-Ho Park, Hangil Lee, Sheng Li, Hyung-Soon Park, Yingchun Zhang, *IEEE Senior Member*, and Jinsook Roh, *IEEE Member*

Abstract— **Abnormal intermuscular coordination is a major stroke-induced functional motor impairment in the upper extremity (UE). Previous studies have computationally identified the abnormalities in the intermuscular coordination in the stroke-affected UE and their negative impacts on motor outputs. Therefore, targeting the aberrant muscle synergies has the potential as an effective approach for stroke rehabilitation. Recently, we verified the modifiability of the naturally expressed muscle synergies of young able-bodied adults in UE through an electromyographic (EMG) signal-guided exercise protocol. This study tested if an EMG-guided exercise will induce new muscle synergies, alter the associated intermuscular connectivity, and improve UE motor outcome in stroke-affected UE with moderate-to-severe motor impairment. The study used the six-week isometric EMG signal-guided exercise protocol that focused on independently activating two specific muscles, the biceps and brachioradialis, to develop new muscle activation groups. The study found that both the stroke and age-matched, able-bodied groups were able to develop new muscle coordination patterns through the exercise while habitual muscle activation was still available, which led to improvements in the motor control of the trained arm. In addition, the results provided preliminary evidence of increased intermuscular connectivity between targeted muscles in the beta-band frequencies for stroke patients after training, suggesting a modulation of the common neural drive. These findings suggest that our isometric exercise protocol has the potential to improve stroke survivors' performance of UE in their activities in daily lives (ADLs) and, ultimately, their quality of life through expanding their repertoire of intermuscular coordination.**

Clinical Relevance— **This study shows the feasibility of expanding the intermuscular coordination pattern in stroke-affected UE through an isometric EMG-guided exercise which positively affects task performance and intermuscular connectivity.**

I. Introduction

In the United States alone, an estimated 0.8 million individuals suffer from a stroke each year [1] and approximately 80% of them experience various motor deficits [2] which include impaired intermuscular coordination [3-5]. Utilizing the concept of muscle synergies, characteristic activation patterns of a group of muscles underlying a motor behavior, previous studies have computationally identified the abnormalities in the intermuscular coordination in the stroke-affected UE [3-6]. Through dimensionality reduction methods, few studies characterized the stroke-affected UE muscle synergies as abnormal coupling of activation between elbow flexors and shoulder abductors [7], as well as the aberrant co-activation of three heads of deltoid [5]. Despite these findings, it remains uncertain whether targeting or normalizing the altered muscle synergy through rehabilitation exercises is feasible, and if so, whether it can decrease stroke-induced motor impairments and improve motor function. Given that intermuscular coordination patterns can underlie prescriptive neural strategies for motor control, it is important to investigate the modification of abnormal UE muscle synergy through rehabilitation exercises and its potential relationship with the improvement of impaired motor function after stroke. Not only the muscle synergies but also the intermuscular connectivity (IMC), which quantifies the common neural drive between muscles in the frequency domain, is known to be affected by stroke, especially in alpha-band (α: 8-12 Hz) [8] and beta-band (β: 13-30 Hz) [9] frequencies. Furthermore, α-band IMC is known to be linked to the temporal control of muscle synergies [10]. Therefore, investigating the impact of targeting muscle synergies on IMC is also vital in the understanding of neuromuscular control with possible implications for the neuromotor rehabilitation of stroke survivors. As a continuation of our recent study, which verified the modifiability of the naturally expressed muscle synergies of young able-bodied adults in UE through an EMG-guided exercise protocol, this study first tested if new muscle synergies can be induced even in stroke-affected UE and if this benefits UE motor outcome and IMC.

II. Methods

A. Participants

Four chronic stroke survivors (two females, two males; 59.3±8.98 years of age) with moderate-to-severe impairment in UE (UE Fugl-Meyer assessment score: 27.0±12.8) and three age-matched, healthy adults (three males; 59.3±11.6 years of

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Jinsook Roh is with the University of Houston, Houston, TX 77004 USA (corresponding author; phone: 713-743-2578; e-mail: jroh@ uh.edu).

Yingchun Zhang is with the University of Houston, Houston, TX 77004 USA (corresponding author; phone: 713-743-6127; e-mail: yzhang94@uh.edu).

Gang Seo, Michael Houston, Manuel Portilla, and Feng Fang are with the Biomedical Engineering Department, University of Houston, Houston, TX 77004 USA.

Sheng Li is with University of Texas Health Science Center - Houston, and TIRR Memorial Herman, Houston, TX 77030 USA.

Jeong-Ho Park, Hangil Lee, and Hyung-Soon Park are with the Mechanical Engineering Department, Korea Advanced Institute of Science and Technology, Daejeon, 34141, South Korea.

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age) with no medical history of neurological disorder in UE participated in the study. For the training and assessment, the stroke survivors used their impaired UE, and the healthy participants used their dominant UE. The study was performed in accordance with the Declaration of Helsinki, with the approval of the University of Houston Institutional Review Board. Prior to each experiment, informed consent was obtained from each participant.

B. Experimental Setup and Protocol

The EMG-guided training and the assessment of isometric force generation for muscle synergy identification and IMC were conducted using the KAIST Upper Limb Synergy Investigation System (KULSIS) [11]. The end-point forces applied at the gimbal handle of KULSIS and EMGs from 12 major UE muscles were acquired at a sampling rate of 1kHz. The recorded muscle set included 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), pectoralis major (clavicular fibers; PECT), trapezius (upper, middle, and lower fibers; UpTrp, MidTrp, and LowTrp, respectively), and infraspinatus (InfSp).

The general experimental setup and protocol followed our previous study done in the young healthy group [12]. Both groups underwent EMG-guided training for six weeks, three times a week, for one hour each session. While grabbing the handle at the shoulder level in a sitting posture, the participants were instructed to control a cursor to match targets in a two-dimensional square space by modulating the activation of BRD (vertical movement of the cursor) and BI (horizontal movement of the cursor). These two muscles are typically coupled in the elbow flexor synergy, making it challenging to activate them in isolation from each other. The square space in the display was scaled based on 70% of the pre-measured maximum voluntary contraction (MVC) of each muscle. The target zone randomly appearing at either the horizontal or vertical corner of the square was defined as 30% of the scaled space and the cursor needed to remain in the zone for 1s for a successful match. Subjects were encouraged to explore and develop their own strategies for matching the targets under isometric conditions, with verbal guidance provided if needed. In addition, at Week 0, 2, 4, and 6 of the training, participants performed isometric reaching in a three-dimensional force space across 54 directions uniformly distributed around a unit sphere to assess any changes in muscle synergies and IMC. Participants were instructed to isometrically guide a force-driven virtual cursor toward the targets in a 3D force space and remain in the logical radius (30% of the target force) for 1s (Hold period). For the IMC assessment, 10s of Hold period was required, and only two target directions, upward and medial, with 20 repetitions used (200s total data) (These two directions were empirically determined based on the targeted muscles' biomechanical characteristics.). The assessment consisted of two conditions: one where the participants used their habitual motor strategy independent of the training (Habitual condition), and another where they were instructed to use the strategy acquired from the training (As-Trained condition) [12].

C. Intermuscular coordination

Prior to identifying muscle synergies from the EMGs recorded from the matched trials of the assessment, the raw EMGs of each trial were denoised (ECG-filtering using a wavelet method), demeaned, full-wave rectified, and low-pass filtered (4th order Butterworth filter with cutoff frequency at 10 Hz) to obtain the general envelope of the signals. The pre-processed EMGs were further segmented from the onset of the force to the end of the Hold period. The segmented EMGs of each trial were then concatenated across all 54 trials as a single EMG matrix. Lastly, the matrix was normalized to have a unit variance to prevent any bias toward the muscles with high variance [5]. For muscle synergy identification, the non-negative matrix factorization (NMF) algorithm was applied as described in our previous studies [5,12,13,14]. Through NMF, the EMG matrix for each assessment was modeled as a linear combination of time-invariant synergy vectors (W) and their corresponding time-varying activation coefficients (C):

$$EMG_{(M\cdot T)} = W_{(M\cdot N)} \cdot C_{(N\cdot T)} \qquad (1)$$

, where W is an M (number of muscles) x N (number of muscle synergies) matrix, and C is an N x T (number of data points) matrix. To identify the optimal N, the synergy set that yielded the global variance-accounted-for (VAF) over 90% was selected. The composition similarity across different weeks of assessment was computed using the dot product [5,15]. To test the statistical significance of the similarity, the similarity threshold (0.781; α=0.05) calculated through the method described in the previous study was utilized [5,13,14].

D. Intermuscular connectivity

IMC between the BRD and BI muscles was assessed via the magnitude-squared coherence for both target directions (upward and medial) separately. Magnitude-squared coherence between two signals x and y was computed by normalizing the square of the absolute value of the cross-spectral power density of the two signals x and y, P_{xy}, by the product of the auto-power spectral densities of the two signals x and y, P_{xx} and P_{yy}, respectively (2). A multi-taper approach using discrete prolate spheroidal sequence tapers as implemented within the Fieldtrip toolbox [16] was utilized with 3 tapers per data segment (1s duration) resulting in a 4 Hz smoothing box (± 2 Hz).

$$C_{xy} = \frac{|P_{xy}|^2}{P_{xx} \times P_{yy}} \qquad (2)$$

IMC values were subsequently converted to Z-scores [17] by taking the hyperbolic tangent of the square root of the IMC values and dividing them by the square root of 1 divided by 2 times the number of windows used in the magnitude-squared coherence calculation (3). After the Z-score conversion, connectivity values at or above 1.65 exceeded the 95% confidence interval. Connectivity values for the BRD-BI muscle pair were then averaged in the α-band and β-band for comparisons across assessments, conditions, and groups. Reported values of IMC are expressed as the mean accompanied by the standard deviation in parentheses.

$$Z_C = \frac{\tan^{-1}\sqrt{C_{xy}}}{\sqrt{1/_{2L}}} \qquad (3)$$

III. Results

A. Intermuscular coordination

Based on the global VAF, five to six synergies were typically required for both groups to explain at least 90% of the variance of the EMG signal recorded from 12 muscles across different weeks of assessment. When five synergies were identified, the habitual muscle synergies of a representative healthy participant before the training included 1) elbow flexor (BRD and BI), 2) elbow extensor (TRIlong and TRIlat with PD), 3) shoulder adductor/flexor (AD, MD, and PECT) with UpTrp, 4) shoulder abductor/extensor (PD) with scapula retractor (MidTrp and InfSp), and 5) LowTrp. For a stroke participant, the muscle synergies identified during the Habitual condition shared a similar composition with the synergies of the healthy participant, except for the elbow extensor synergy which was included BI. After six weeks of training, the targeted muscle pair, BRD and BI, of both groups was dissociated from the elbow flexor synergy and reformed new synergies. The BRD was newly coupled with the shoulder adductor/flexor while the BI tended to inherit the composition of habitual elbow flexor synergy (Fig. 1). Based on the similarity analysis, these alterations in the general composition of the synergy set after the training were statistically significant in both groups (similarity threshold at 0.781; $p<0.05$). Meanwhile, the composition of habitual muscle synergies in both groups was conserved throughout the six weeks, which implied that the participants expanded the repertoire of the intermuscular coordination patterns via our training protocol and selectively utilized the patterns to perform non-trained tasks.

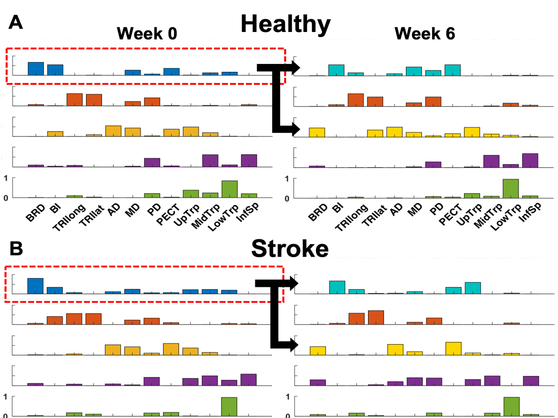

Figure 1. The representative muscle synergy sets of healthy (A) and stroke (B) groups identified from the As-Trained assessment session at week 0 (pre-training) and week 6 (post-training).

B. Intermuscular connectivity

Fig. 2 displays the IMC for age-matched controls and stroke survivors across Week 0 and Week 6 during the Habitual and As-Trained conditions, respectively. As seen in Fig. 2, healthy participants tended to have greater IMC compared to stroke patients due to the lack of corticospinal tract damage. Consistently, α-band IMC in the As-Trained condition trended to increase in healthy participants from week 0 to week 6 during the Medial target direction (week 0: 1.23±0.28; week 6: 2.74±0.77; $p>0.1215$). Similarly, α-band IMC during the As-Trained condition also trended to increase in stroke from week 0 to week 6 for the Medial target direction (week 0, 1.17±0.40; week 6, 1.91±0.43; $p>0.1208$). However, a significant increase in β-band IMC was found in stroke patients when comparing the Habitual and As-Trained conditions at week 6 during the Upward target direction (Fig. 2C; Habitual: 1.27±0.17; As-Trained: 1.43±0.16; $p<0.01$).

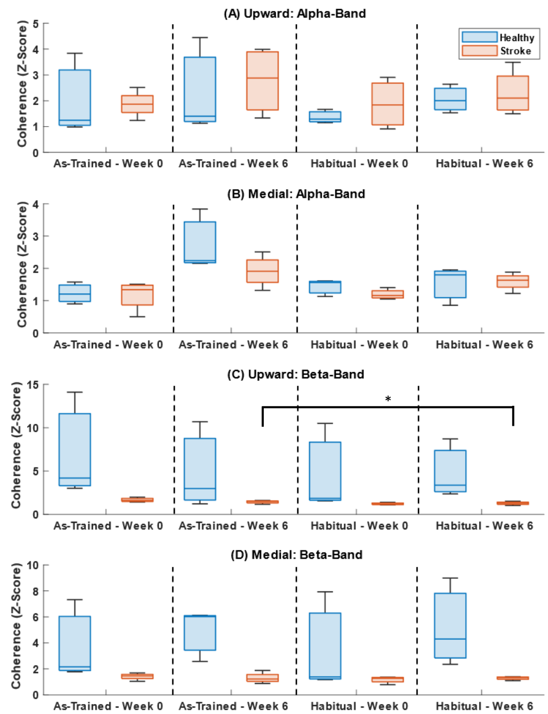

Figure 2. Average IMC of BRD and BI for (A) Upward and (B) Medial target directions in α-band and the same directions for β-band ((C) and (D)) at weeks 0 and 6 for both Habitual and As-Trained conditions. (, p<0.01)*

C. Task Performance

As the repertoire of intermuscular coordination expanded and the IMC of the targeted muscles was modulated after the training, the task performance of the trained UE also improved. Both groups showed a significant increase in the number of matched targets and a significant decrease in the task completion time (Fig. 3; One-way ANOVA, $p<0.05$). These improvements were observed in both BRD- and BI-activation-targeted trials.

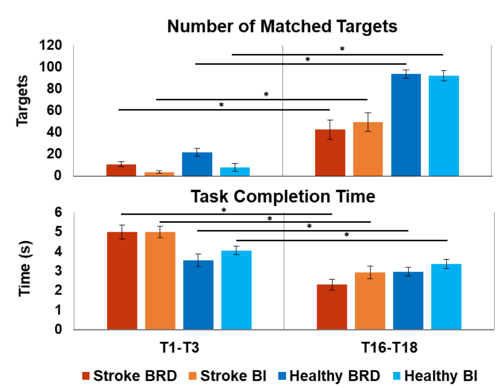

Figure 3. Group means and standard errors of the number of matched targets per session and the task completion time per trial computed from the first and the last three training sessions (T1-T3 and T16-T18, respectively). For each group, the BRD-activation targeted trials and BI-activation targeted trials were measured separately. (; One-way ANOVA, p<0.05)*

IV. DISCUSSION

As a continuation of our previous study [12], this pilot study showed that both stroke and age-matched, able-bodied groups could develop new muscle coordination patterns through the isometric exercise which also affected IMC between targeted muscles in the α-band frequencies. These changes in intermuscular coordination and IMC led to improvements in the motor control of the trained arm which implied the potential of our protocol for stroke rehabilitation.

To the best of our knowledge, developing new intermuscular coordination patterns in the stroke-affected UE to improve motor function has been rarely explored. A few recent studies targeted reduction of pairwise co-activation of muscle pairs, which did not consider the effects of the training on the global intermuscular coordination patterns [18,19], or trained the activation of muscle in the affected UE to mimic the activation of less affected UE muscles [20]. Since we demonstrated the feasibility of developing new intermuscular coordination patterns in stroke-affected UE by targeting a natural elbow flexor synergy, directly targeting the modulation of stroke-induced abnormal intermuscular coordination patterns may lead to improvement of motor function after stroke.

Our EMG-guided exercise appears to be associated with changes in the level of neural drive to UE muscles. Specifically, β-band IMC between the BRD-BI muscles increased significantly at the Week 6 assessment in the As-Trained condition compared to the Habitual condition. This finding suggests that the level of common descending neural drive to both muscles, most likely cortical in origin [21], was increased as the synergy repertoire was newly expanded through the training. Furthermore, since the level of β-band IMC is increasing in the As-Trained condition compared to the Habitual condition at Week 6, it may be viewed as a task-specific modulation of common neural drive to the BRD and BI. Although a previous study showed the association between the activation of muscle synergy and the α-band neural drive [10], neither paired-sample nor two-sample T-tests indicated any statistical significance in the change of α-band IMC, which can be attributed to the low sample size across age-matched healthy controls (N=3) and stroke survivors (N=4). Alternatively, it may be conjectured that the concurrent changes of intermuscular coordination patterns, IMC, and task performance in EMG-guided exercises specifically are more associated with motor strategy changes at the cortical level, and not the sub-cortical level.

Future studies should also consider the effects of EMG signal-guided training on cortico-cortical connectivity as well as cortico-muscular connectivity, which reflects muscle coordination strategies [17]. Investigating the training effect at the cortical and cortico-spinal level would enhance our understanding of the potential underlying mechanism of expanding the repertoire of intermuscular coordination patterns, which can further lead to developing a new therapeutic protocol that targets the disrupted muscle synergy more efficiently.

REFERENCES

[1] A. Go et al., "Heart Disease and Stroke Statistics—2013 Update", *Circulation*, vol. 127, no. 1, 2013.

[2] P. Langhorne, F. Coupar and A. Pollock, "Motor recovery after stroke: a systematic review", *The Lancet Neurology*, vol. 8, no. 8, pp. 741-754, 2009.

[3] V. Cheung, "Central and Sensory Contributions to the Activation and Organization of Muscle Synergies during Natural Motor Behaviors", *Journal of Neuroscience*, vol. 25, no. 27, pp. 6419-6434, 2005.

[4] S. Ferrante et al., "A Personalized Multi-Channel FES Controller Based on Muscle Synergies to Support Gait Rehabilitation after Stroke", *Frontiers in Neuroscience*, vol. 10, 2016.

[5] J. Roh, W. Rymer, E. Perreault, S. Yoo and R. Beer, "Alterations in upper limb muscle synergy structure in chronic stroke survivors", *Journal of Neurophysiology*, vol. 109, no. 3, pp. 768-781, 2013.

[6] D. Reisman, "Aspects of joint coordination are preserved during pointing in persons with post-stroke hemiparesis", *Brain*, vol. 126, no. 11, pp. 2510-2527, 2003.

[7] V. Cheung et al., "Muscle synergy patterns as physiological markers of motor cortical damage", *Proceedings of the National Academy of Sciences*, vol. 109, no. 36, pp. 14652-14656, 2012.

[8] Houston, Michael, et al. "Alterations in muscle networks in the upper extremity of chronic stroke survivors." *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 29 (2021): 1026-1034.

[9] Fisher, Karen M., et al. "Beta-band intermuscular coherence: a novel biomarker of upper motor neuron dysfunction in motor neuron disease." *Brain* 135.9 (2012): 2849-2864.

[10] Laine, Christopher M., Brian A. Cohn, and Francisco J. Valero-Cuevas. "Temporal control of muscle synergies is linked with alpha-band neural drive." *The Journal of physiology* 599.13 (2021): 3385-3402.

[11] J. Park, J. Shin, H. Lee, C. Park, J. Roh and H. Park, "Design and Evaluation of a Novel Experimental Setup for Upper Limb Intermuscular Coordination Studies", *Frontiers in Neurorobotics*, vol. 13, 2019.

[12] Seo, Gang, et al. "Feasibility of inducing new intermuscular coordination patterns through an electromyographic signal-guided training in the upper extremity: a pilot study." *2021 43rd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC)*. IEEE, 2021.

[13] Seo, Gang, et al. "Alterations in motor modules and their contribution to limitations in force control in the upper extremity after stroke." *Frontiers in Human Neuroscience* 16 (2022): 937391.

[14] Seo, Gang, et al. "Myoelectric interface training enables targeted reduction in abnormal muscle co-activation." *Journal of neuroengineering and rehabilitation* 19.1 (2022): 1-12.

[15] L. Pellegrino, M. Coscia, M. Muller, C. Solaro and M. Casadio, "Evaluating upper limb impairments in multiple sclerosis by exposure to different mechanical environments", *Scientific Reports*, vol. 8, no. 1, 2018.

[16] Oostenveld, Robert, et al. "FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data." *Computational intelligence and neuroscience* 2011 (2011): 1-9.

[17] Reyes, Alexander, et al. "Beta band corticomuscular drive reflects muscle coordination strategies." *Frontiers in computational neuroscience* 11 (2017): 17.

[18] E. Mugler et al., "Myoelectric Computer Interface Training for Reducing Co-Activation and Enhancing Arm Movement in Chronic Stroke Survivors: A Randomized Trial", *Neurorehabilitation and Neural Repair*, vol. 33, no. 4, pp. 284-295, 2019.

[19] Jian, Chuyao, et al. "Modulating and restoring inter-muscular coordination in stroke patients using two-dimensional myoelectric computer interface: a cross-sectional and longitudinal study." Journal of Neural Engineering 18.3 (2021): 036005.

[20] Seo, Na Jin, et al. "Use of an EMG-controlled game as a therapeutic tool to retrain hand muscle activation patterns following stroke: a pilot study." *Journal of Neurologic Physical Therapy* 46.3 (2022): 198-205.

[21] P. Brown, S. Farmer, D. Halliday, J. Marsden, and J. Rosenberg, "Coherent cortical and muscle discharge in cortical myoclonus," *Brain,* vol. 122, no. 3, pp. 461-472, 1999.