Muscle Synergy-Guided Exercise through Human-Machine Interaction Can Improve Neuromuscular Coordination and Decrease Motor Impairment after Stroke: a Pilot Study

Manuel Portilla-Jiménez, Gang Seo, Michael Houston, Yoon No Gregory Hong, Sheng Li, Hyung-Soon Park, Sean Savitz, Emily Stevens, José Contreras-Vidal, Yingchun Zhang, and Jinsook Roh

***Abstract*— This study aimed to develop a novel neuromuscular coordination-guided rehabilitation exercise through human-machine interaction under isometric conditions and tested its effects on muscular coordination and clinical scores to improve motor function post-stroke. Six post-stroke survivors participated in a muscle synergy-guided exercise as a test group (n=3) and a force strengthening-guided training as a control group (n=3). One complete training set consisted of 18 one-hour training sessions for six weeks. Pre- and post-training assessments and one-month and three-month retention tests were performed using a custom-designed robotic device under isometric conditions. While the muscle synergy-guided test group improved intermuscular coordination and Fugl-Meyer Assessment scores, the force strengthening-guided control did not. This pilot study shows that abnormal intermuscular coordination can be malleable to be similar to healthy patterns through human-machine interaction, even for severely impaired survivors, and the therapeutic exercise has the potential to improve motor control in the upper extremity after stroke.**

I. Introduction

ROBOTICS has been used to improve motor function post-stroke. However, stroke survivors with severe impairment are often unable to benefit from robotic rehabilitation that requires goal-directed movement because they usually cannot perform purposeful reaching [1]. In contrast, isometric resistive exercises, i.e., the arm remains stationary while end-point forces are generated, require less motor capability compared to kinematic movement. Thus, isometric exercises can be potentially ideal for stroke rehabilitation with severe impairment. Also, stroke survivors often suffer from a loss of individual multi-joint control, a critical limiting factor of post-stroke motor recovery. We tested a novel neuromuscular coordination principle-guided exercise through human-machine interaction under isometric conditions to improve post-stroke motor function.

II. Methods

A. Participants

Six chronic stroke volunteers were divided into two groups: synergy-guided exercise (test) (P1, P2, and P3) (two males; 68, 47, and 69 years old), and force-guided exercise (control) (P4, P5, and P6) (two males; P4 = 64, P5 = 52, and P6 = 45 y. o.). Volunteers with a single unilateral stroke participated in this study with mild to severe impairment in the upper extremity (UE). Exclusion criteria included another medical history of neurological pathology or orthopedic disorders in UE. The University of Houston Institutional Review Board approved this study conducted in accordance with the Declaration of Helsinki. Before each assessment and training session, participants provided informed consent.

B. Equipment

Isometric assessment sessions and both synergy-guided and force-guided exercises were performed by using KAIST Upper Limb Synergy Investigation System (KULSIS) [2] (Fig. 1). The three-dimensional forces measured at the hand and the non-invasive wireless electromyographic (EMG) signals (Trigno Wireless Biofeedback System; Delsys Inc., USA) were recorded at a sampling frequency of 1kHz. The eight major UE muscles were: brachioradialis (BRD), biceps brachii (BB), triceps brachii (long head (TrLo) & lateral head (TrLa)), the three deltoid fibers (anterior (AD), middle (MD), and posterior (PD)), and pectoralis major clavicular head (PEC).

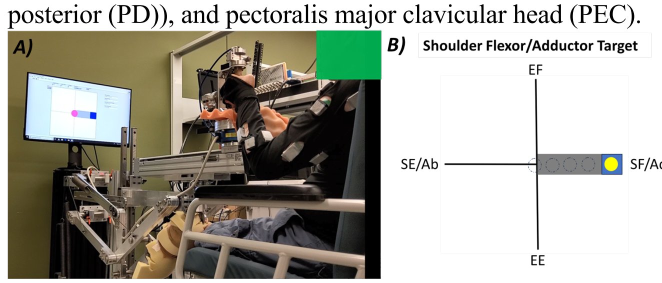

Fig 1. A) A stroke participant performing synergy-guided training by using the KAIST Upper Limb Synergy Investigation System (KULSIS). B) Mapping of four synergies to 2D display and one sample target, Shoulder Flexion/Adduction (SF/Ad). By selectively activating each synergistic muscle group, participants moved the cursor location to one of the four targets (right-SF/Ad, left-SE/Ab, upward-EF, and downward-EE).

C. Muscle Synergy Analysis

As presented in our previous studies [3], [4], muscle synergy analysis was performed during a similar isometric assessment by applying non-negative matrix factorization. The EMG matrix was modeled as $EMG_{isometric} = W \cdot C$, where W was an eight (number of muscles) by N (number of muscle synergies) matrix, and C was an N by D (number of data points) matrix. The W matrix was the time-invariant muscle weights or muscle synergy patterns, while the C matrix was

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J. Roh, M. Portilla-Jiménez, Y. N. G. Hong, and J. Contreras-Vidal are with the University of Houston, Houston, TX 77004, USA (corresponding author: J. Roh; phone: 713-743-2578; email: jroh@ uh.edu).

G. Seo is with the Department of Neurology and Neurological Sciences, Stanford University, Stanford, CA 94305, USA.

Y. Zhang and M. Houston are with the University of Miami, Coral Gables, FL 33146, USA.

J. Park is with the Mechanical Engineering Department, Korea Advance Institute of Science and Technology, Daejeon, 34141, South Korea.

S. Li, S. Savitz, and E. Stevens are with the University of Texas Health Science Center– Houston, TX 77030, USA.

S. Li is with TIRR Memorial Herman, Houston, TX 77030, USA.

their corresponding time-varying activation profile. Finally, to assess changes in intermuscular coordination, muscle synergy patterns were calculated from pre- and post-training isometric assessment. The similarity index (SI) between stroke-affected synergy and individualized targeted synergy vectors was calculated by obtaining their scalar product [4].

D. Designing of Biosignal-Guided Feedback and Protocol

To determine which synergistically activated muscles will be included in each synergy, we referred to our previous study from neurologically intact volunteers [4]. These four synergies and their major muscle excitation were: Elbow Flexor (EF) (BRD & BB), Elbow Extensor (EE) (TrLo & TrLa), Shoulder Flexor/Adductor (SF/Ad) (AD, MD, and PEC), and Shoulder Extensor/Abductor (SE/Ab) (MD & PD, or PD only).

Pre-defined healthy muscle weights from our previous study [5] were not used due to the variability across participants. Thus, to individualize the four-synergy targets, muscle synergies were identified from the EMG data of each stroke participant's less-affected (LA) arm to define the muscle weights of the target muscle synergy matrix for customized training.

Each participant had his or her own target muscle synergy vectors. The muscle weights of the four synergies (EF, EE, SF/Ad, and SE/Ab) vectors were obtained to guide each participant during the synergy-guided exercise. For instance, the elbow flexor target (EF) was matched if the participant generated the following EMG signals (1) while maintaining the rest of the muscles relaxed.

$$EF = \left(\alpha_{LA} \cdot \frac{BRD_{MA}}{MVC_{MA\,BRD}} + \beta_{LA} \cdot \frac{BB_{MA}}{MVC_{MA\,BB}}\right) * \min\left(\alpha_{LA} \cdot \frac{BRD_{MA}}{MVC_{MA\,BRD}}, \beta_{LA} \cdot \frac{BB_{MA}}{MVC_{MA\,BB}}\right) \quad (1)$$

, where α_{LA}, and β_{LA} were the muscle weights for BRD and BB, respectively, identified from the LA arm. Also, BRD_{MA}, and BB_{MA} were the real-time low-pass filtered (Butterworth, 3rd order, 5Hz as cutoff frequency) EMG data of each UE muscle from the more-affected arm (MA). The same idea was applied to define the other three synergy targets. The maximum voluntary contraction of the more affected arm (MVC_{MA}) per muscle and the maximum voluntary synergies (MVS) were determined at the beginning of each training session by assessing the maximal synergy activation three times in each of the four preferred directions of synergies (PDS) [5]. For the control group, instead of using EMG muscle-synergy activation as feedback during training, participants performed the isometric strengthening exercise with their individualized four PDSs as force targets. The six participants performed three one-hour training sessions per week for six weeks (18 training sessions, in total).

Finally, for both groups, to assess potential changes and therapy improvement retention in the clinical motor impairment, the UE FMA was performed pre-, and post-training, respectively. Moreover, for the synergy-guided group, to determine the therapy improvement clinical retention, the UE-FMA was conducted 1 month and 3 months after the last training session.

III. Results

A. Intermuscular Coordination

The synergy-guided group improved the muscle synergy patterns to mimic the targeted vectors. For instance, the lowest SI values and their associated synergy vectors per participant were: P1 (EF from 0.77 pre- to 0.98 post-training), P2 (EE from 0.68 to 0.87), and P3 (EE from 0.84 to 0.98).

B. Clinical Assessment

After force-guided exercise, UE FMA did not change (Fig. 2B). On the other hand, after synergy-guided exercise therapy, UE FMA scores improved in all three participants, P1-P3 (11 ± 1; mean ± std) (Fig. 2A). Moreover, UE-FMA improvement was preserved not only 1 month but also 3 months after the last training session for the synergy-guided group.

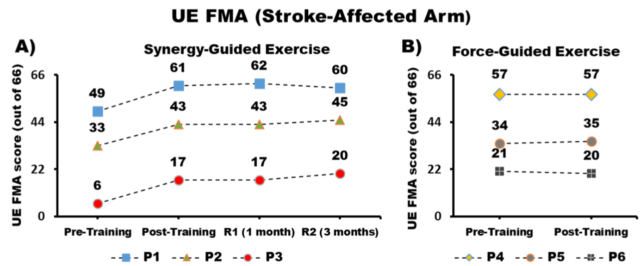

Fig 2. UE FMA scores of the stroke-affected arm from six participants. A) test group (P1-P3) before and after synergy-guided exercise. In addition, retention assessments were performed (1 month (R1) and 3 months (R3) after the last training session). B) control group (P4-P6) before and after force-guided exercise.

IV. Conclusion

We developed a novel muscle synergy-guided exercise (test group) through human-machine interaction under isometric conditions and compared its effects to those of force-strengthening exercise (control group). The test group improved multi-joint coordination and standardized clinical scores while the control group did not. These results suggest that neuromuscular coordination-guided rehabilitation through human-machine interaction can be a novel framework in stroke rehabilitation. Finally, using the muscle weights from the LA arm is a potential limitation since it might create a ceiling on the rehabilitation progress of survivors depending on the impairment level of their LA arm.

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