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Effects of Sensorimotor-integrated (SMI) Wrist/hand Rehabilitation Assisted by a Hybrid Soft Robot Poststroke

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Abstract— **Sensorimotor integration (SMI) is essential for the intentional movement of the upper limb (UL). However, this process is often disrupted poststroke, hindering movement recovery. Previously, a wrist/hand exoneuromusculoskeleton (ENMS) driven by electromyography (EMG) was developed. This work integrated focal vibratory stimulation (FVS) with neuromuscular electrical stimulation (NMES) into the ENMS to achieve electro-vibro-feedback (i.e., ENMS-EVF) for SMI rehabilitation and investigated its functional and corticomuscular effects on chronic stroke participants after UL training. Nine participants with chronic stroke were recruited to attend a 20-session UL training assisted by the ENMS-EVF. The rehabilitative outcomes were evaluated before and after the training program using the Fugl–Meyer Assessment (FMA), monofilament test, EMG activation level, and directed corticomuscular coherence (dCMC). The results showed that the SMI rehabilitation training enhanced sensorimotor functions of the UL, as indicated by significant motor function improvement in the FMA ($p < 0.05$), significant elevation of distal sensitivity in the monofilament test ($p < 0.05$), significant enhancement of the proximal and distal muscle coordination in the EMG activation level ($p < 0.01$), and significant augmentation of ascending sensation feedback and reduction of required descending movement commands in the dCMC results ($p < 0.05$). This study unveils that the SMI rehabilitation assisted by ENMS-EVF is feasible and has neuroplastic effectiveness for benefiting the UL sensorimotor functions poststroke.**

I. Introduction

Sensorimotor integration (SMI) plays a crucial role in the purposeful movement of the upper limb (UL). The ability to move is crucial for performing tasks such as reaching, grasping, releasing, and using the upper limb functionally. Meanwhile, somatosensation plays an important role in recognizing and manipulating objects successfully [1]. Somatosensation is the perception of body parts through identifying body movements, the detection of touch, and discrimination between stimuli [2]. Pioneering research on the motor and sensory mappings within the sensorimotor cortex has elucidated that precise interpretation of somatosensory information before and during movement is vital for proficient motor execution. Hence, the somatosensory and motor networks are closely linked [1, 3].

More than 50% of stroke survivors experience sensory impairments on their hemiplegic side, which disrupts SMI and exacerbates motor function impairments [4]. Based on the crucial rule of SMI in the movement of UL, the somatosensory function is postulated to form an essential factor within the neuroplasticity of motor re-learning feedforward-feedback mechanism after stroke [5].

However, motor and sensory interventions are usually separated in clinical practices, resulting in asynchronization between the desired motor output and therapeutic sensory feedback in the motor relearning process and hindering the neuroplasticity of the close-loop sensorimotor network for SMI after stroke. Among the traditional therapies, Bobath therapy stands out as one that integrates sensorimotor interventions. Nonetheless, it is inferior to task-specific training in efficacy and does not outperform other interventions in enhancing arm activity, mainly because it relies on therapists providing passive movement guidance for stroke survivors focusing on postural control, which also requires more staff time and intensive resources [6].

Robot-assisted stroke rehabilitation can effectively improve the result of rehabilitation by stimulating the related sensorimotor nerves on the cerebral cortex, strengthening the weak muscles, enhancing neuroplasticity for movement relearning, and then recovering the movement functions of the UL to perform activities of daily life [7]. Close-loop stimulation (triggered by voluntary effort) paired with movement training can generate a synergistic effect on neuroplasticity and offer more effective treatment for SMI recovery [5]. Neuromuscular electrical stimulation (NMES) triggered by a voluntary effort could provide timed paired stimulation during movement for sensory feedback and muscle force enhancement on weak muscles, e.g., the extensor digitorum (ED) on the forearm of poststroke individuals. On muscles with sufficient residual force, e.g., flexor digitorum (FD), focal vibratory stimulation (FVS) is more suitable for sensory stimulation because it could evoke more rapid transient involuntary attention for efficient sensory feedback than NMES [8]. In close-loop SMI rehabilitation, synchronous sensory feedback by NMES or FVS during movement could increase the awareness of muscle contraction and elevate timed activation in the related sensorimotor cortex [8], contributing to the neuroplasticity of SMI [5].

In this study, we proposed a robot-assisted SMI intervention for the recovery of movement after stroke, where the synchronous sensory feedback during movement training was provided by the electro-vibro-feedback (EVF) via close-loop NMES and FVS integrated into a hybrid soft robot named exoneuromusculoskeleton (ENMS) [2], i.e., ENMS-EVF, for wrist/hand SMI rehabilitation. This study aimed to investigate the feasibility and rehabilitative effects of the SMI rehabilitation intervention assisted by ENMS-EVF after stroke. We hypothesized that the intervention could improve SMI and

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TABLE I. DEMOGRAPHIC INFORMATION OF PARTICIPANTS

Information	Value
Stroke Type	Hemorrhage = 6, Ischemic = 3
Affected Arm	Left = 5, Right = 4
Gender	Male = 4, Female = 5
Age	Mean ± SD = 54.3 ± 11.3 years
Years after Stroke	Mean ± SD = 9.6 ± 9.75 years

benefit the recovery of UL movement for poststroke individuals.

II. MATERIALS AND METHODS

A. *ENMS-EVF*

The ENMS is an NMES-soft robotic technology for self-help UL rehabilitation after stroke [9]. It integrates NMES and pneumatic actuation to UL joints through a triggering control by residual voluntary motor effort (VME) from a person after stroke, represented by electromyography (EMG) in paretic muscles, i.e., VME triggered but not continuously involved. The EMG electrode pairs were placed on the skin surface of the extensor digitorum (ED) and flexor digitorum (FD) for VME detection. The reference electrode was placed on the skin surface of the olecranon. The skin–electrode impedance was lowered below 5 kΩ by skin preparation. In the ENMS-EVF, NMES through the EMG electrode pairs on the ED assisted muscle contraction and provided sensory feedback during voluntary wrist-hand extension, while FVS by the vibration motor between the EMG electrode pairs on the flexor digitorum (FD) provided sensory feedback during voluntary wrist-hand flexion because of adequate muscle force on FD preserved poststroke.

EVF control was designed based on the EMG-triggered ENMS hand module by collaborating with FVS and NMES in the phasic motions of hand opening and closing [9]. The continuous EMG-driven control was designed to coordinate NMES, FVS, and pneumatic actuation to assist hand movements with enhanced sensory feedback to induce SMI neuroplasticity. The EMG threshold level in each motion phase was set as 10% maximal voluntary contraction (MVC) above the EMG baseline in the resting state. During the extension phase, when the voluntary EMG signal on the ED reached the preset threshold, the ED received NMES while the fingers were mechanically assisted by an inflated pneumatic muscle to aid in finger/wrist extension throughout the motion phase. In the flexion phase, as soon as the voluntary EMG on the FD muscle reached the preset threshold, passive pneumatic deflation and continuous FVS to the FD were provided throughout the voluntary wrist/hand flexion.

B. *Participants*

This study was approved by the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University before commencement (approval number: HSEARS20210320003). A total of 9 stroke participants were screened according to the following inclusion criteria:

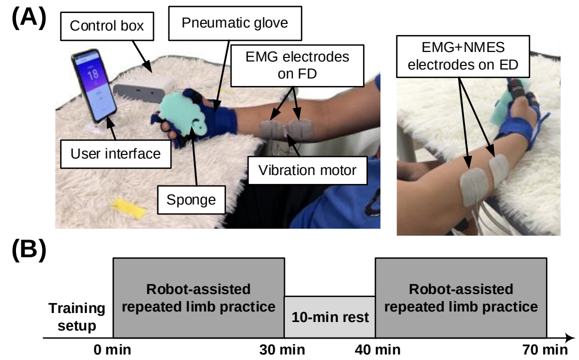

Figure 1. (A) Experimental and training set up. (B) Timeline of the EMG-driven ENMS-EVF-assisted self-help UL training program.

(1) at least 12 months after the onset of a unilateral lesion in cortical or subcortical regions due to stroke;

(2) presence of no visual deficit and sufficient cognition to follow experimental instructions (Mini-Mental State Examination (MMSE) score > 23) [10];

(3) moderate to severe motor disability in the affected UL (15 < Fugl-Meyer Assessment (FMA) < 45) [11];

(4) ≤ 3 spasticity at the wrist and fingers as measured by the Modified Ashworth Scale (MAS) [12];

(5) presence of detectable voluntary EMG signals from the ED and FD muscles on the affected side (three times the standard deviation above the EMG baseline);

(6) presence of a passive range of motion (ROM) for the wrist from 45° extension to 60° flexion, and ability of the metacarpophalangeal (MCP) finger joints to be passively extended to 170°.

(7) no neurological impairments except stroke; and

(8) right-handed before the stroke onset.

The exclusion criteria for the stroke participants were (1) poststroke pain, (2) epilepsy, (3) cerebral implantation, and (4) pacemaker implantation. The demographic information of the recruited participants is shown in Table I. Before the commencement of the clinical trial, written informed consent was obtained from each participant.

C. *Training program*

The program for rehabilitation included a tutorial prior to training and 20 upper limb training sessions, all of which were assisted by ENMS-EVF and lasted at least 60 minutes per session. The training sessions were scheduled at an intensity of 3-5 sessions per week, for seven consecutive weeks, with no more than one session per day.

Each participant received a pre-training tutorial that covered the process of donning and doffing the system, device operation, and the training protocol before the training began. The operator was responsible for setting the training parameters for each training session. These parameters included the EMG triggering levels of the driving muscle unions, the maximum inner pressure of the wrist/hand module, and the applied pulse width of NMES for individual participants. Prior to each training session, the operator would set these parameters to ensure that they were tailored to the needs of each participant. During training, to ensure the stability of the pneumatic muscles under repeated inflations and deflations, the maximal inner pressure of the wrist/hand module was limited to less than 100 kPa.

In this study, first three supervised sessions helped participants to perform self-help training competently according to established procedures [13]. From the 4th to 20th training sessions, the participants performed the self-help training without supervision. During each training session, participants were instructed to sit at a table and maintain a distance of 30–40 cm between their shoulders and the table surface (as shown in Figure 1(A)). To begin, the smartphone with the app was placed on the table in front of the participant. Participants were then required to follow the instructions on the smartphone screen and complete repetitive limb tasks, assisted by the ENMS-EVF on the paretic limb. Finally, participants were asked to complete a 30-minute horizontal task and a 30-minute vertical task at their natural speed, while carrying a spong [13]. To prevent muscle fatigue during training sessions, a break of 10 minutes was permitted between two consecutive tasks (Figure 1(B)).

D. Evaluation of training outcomes

The rehabilitation outcomes of self-help upper limb (UL) training with assistance from ENMS-EVF were investigated by using clinical and electrophysiological assessments. Both pre-training and post-training evaluations were conducted on all participants, with the former taking place before the pre-training tutorial and the latter taking place within 1 day after the last training session.

1) Clinical sensorimotor assessments

The motor functional improvements of each participant were evaluated using clinical assessments in this study. The assessments were performed by an assessor who was blinded to the training. The adopted clinical assessments included (1) motor functional assessment in voluntary limb movements by the FMA with a total score of 66 for the UL assessment [11]; (2) sensation assessment on the affected forearm measured by the Semmes-Weinstein monofilament test [14] on the skin surface above the ED and FD, and six sites on the ventral and dorsal side of the hand (Figure. 2(B)) [15].

2) Electrophysiological sensorimotor assessments

This study used electrophysiological assessments to objectively assess muscle coordination and pathway-specific corticomuscular coherence, including EMG and directed corticomuscular coherence (dCMC) measurements. The electroencephalography (EEG) over sensorimotor cortex and EMG on target UL muscles, i.e., ED, FD, biceps brachii (BIC), and triceps brachii (TRI), during 20% MVC of ED/FD (i.e., extension/flexion) were collected before and after the training. The EMG activation level of the target muscles during the 20% MVC level of ED/FD evaluated muscle coordination in fine motor control [9]. Granger causality was utilized to analyze effective dCMC between the EEG and EMG data [16].

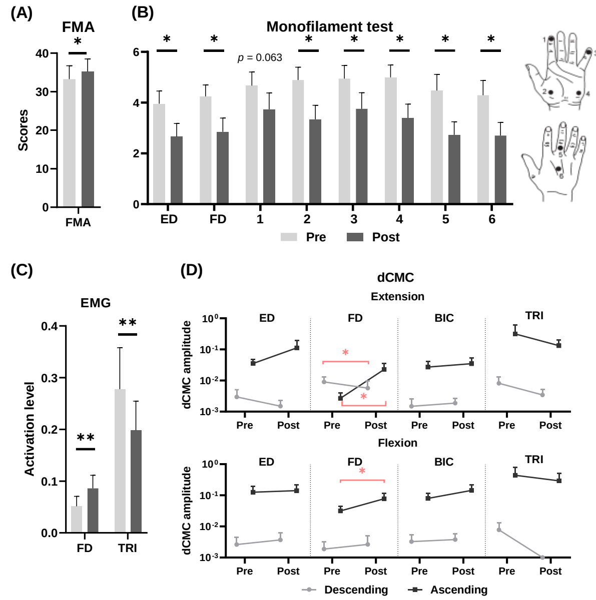

Figure 2. SMI rehabilitation training effects on (A) FMA scores, (B) monofilament scores, (C) EMG activation level, and (D) descending and ascending dCMCs during wrist/hand extension and flexion. *indicates $p < 0.05$, **indicates $p < 0.01$. Wilcoxon signed-rank test.

E. Statistical analysis

The Shapiro-Wilk normality test was used to evaluate the normality of the clinical scores, EMG parameters, and dCMC parameters at a significance level of 0.05. All the parameters, including FMA scores, monofilament scores, EMG activation level, and dCMC amplitude, exhibited significance in the normality test ($p < 0.05$). A paired comparison of the parameters before and after the training was conducted using Wilcoxon's signed-rank test on all the assessment data. The statistically significant level of 0.05 and 0.01 were indicated in this study.

III. Results

All the recruited participants completed the UL training assisted by the ENMS-EVF. After training, significant differences could be found in the increased FMA for the entire UL (Figure 2(A)) and decreased monofilament scores on almost all sites of the hand and forearm (Figure 2(B)) ($p < 0.05$, Wilcoxon signed-rank test). The EMG activation level was significantly increased for FD during extension and decreased for TRI during flexion (Figure 2(C)) ($p < 0.01$, Wilcoxon signed-rank test). The ascending dCMCs on FD muscles during extension and flexion were both significantly increased, and the descending dCMC on FD during extension was significantly decreased after training (Figure 2(D)) ($p < 0.05$, Wilcoxon signed-rank test). Other muscles showed no significance in EMG and dCMC results.

IV. Discussion

The results of this study support the hypothesis that the SMI rehabilitation training assisted by ENMS-EVF could result in improved SMI and benefit the recovery of UL movement for poststroke individuals.

The significant increase in FMA scores indicated improvements in voluntary motor functions of the entire UL. The significant decreases in the monofilament test on almost all sites of the hand and forearm suggested an improvement in cutaneous sensitivity in the distal UL. The significantly increased EMG activation level for FD during extension indicated improved distal muscle control, and the significantly decreased EMG for TRI during flexion suggested reduced proximal muscle compensation. The clinical and EMG assessment results demonstrated that participants with chronic stroke experienced mutually improved motor and sensory functions of ULs and enhanced movement coordination between proximal and distal muscles in fine motor control. These results highlighted the functional benefits of SMI rehabilitation in enhancing sensorimotor functions following stroke.

The dCMC results on FD indicated improved somatosensation conveyance up to the brain and reduced motor commands down to the antagonist muscle during voluntary movements, evidenced by the significantly increased ascending dCMC and the significantly decreased descending dCMC when performing the consistent voluntary contraction level, i.e., 20%MVC. The dCMC results demonstrated that the SMI rehabilitation improved UL motor functions by reconstructing the pathway-specific neuroplasticity in both the ascending and descending pathways of the FD muscle.

V. Conclusion

By incorporating synchronous sensory feedback from EVF during robot-assisted motor training, participants with chronic stroke experienced mutually improved motor and sensory functions of proximal ULs, enhanced movement coordination between proximal and distal muscles in fine motor control, and positive neuroplastic modulation of ascending and descending pathways for improved coordination of sensory and motor functions poststroke. This study highlights the feasibility and neuroplastic effectiveness of SMI rehabilitation training assisted by ENMS-EVF in enhancing sensorimotor functions.

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