Upper extremity intervention for stroke combining virtual reality, robotics and electrical stimulation

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***Abstract*— Approximately 80% of individuals with chronic stroke present with long lasting upper extremity (UE) impairments. We propose the perSonalized UPper Extremity Rehabilitation (SUPER) intervention, which combines robotics, virtual reality activities, and neuromuscular electrical stimulation (NMES). The objectives of our study were to determine the feasibility of the SUPER intervention in individuals with moderate/severe stroke. Stroke participants received a 4-week intervention (3x per week), based on their functional level. Their level of corticospinal tract recovery was assessed using the Predict Recovery Potential algorithm, involving measurements of motor evoked potentials and manual muscle testing. Those with low potential for hand recovery (shoulder group) received an intervention focusing on elbow and shoulder movements. Those with a good potential for hand recovery (hand group) also received EMG-triggered NMES. Outcomes included the Fugl-Meyer UE assessment, the Motor Activity Log and the Stroke Impact Scale. Approximately 40% of participants in either the hand or shoulder group showed changes in the Fugl-Meyer UE assessment superior to its minimum clinically important difference. This indicates that our personalized approach may be effective in improving UE function in specific individuals with moderate and severe impairments due to stroke.**

Keywords—stroke, upper extremity, rehabilitation, virtual reality, robotics, electrical stimulation

I. INTRODUCTION

Approximately 80% of individuals with stroke experience hemiparesis of the upper extremity (UE) [1] leading to chronic impairments such as weakness, loss of motor control, edema, pain and spasticity. These have important consequences for quality of life as impairments in hand and arm function limit participation in daily living activities [2, 3]. Accordingly, recovery of UE function is seen as highly important by individuals with chronic stroke, caregivers and rehabilitation professionals [4].

According to the Canadian Stroke Best Practice Recommendations [5], UE rehabilitation should encourage the affected limb in "training that is meaningful, engaging, repetitive, progressively adapted, task-specific and goal-oriented". Advances in rehabilitation technology, in particular robotics, virtual reality (VR) and neuromuscular electrical stimulation (NMES), have been shown to be effective for improving UE function of individuals with stroke, through the provision of such repetitive and task-oriented training. Robotic devices can be used to assist individuals who are unable to complete arm movements by themselves [6]. Robotic rehabilitation has demonstrated functional gains in individuals with mild and moderate stroke impairments [7, 8]. Likewise, recent work by our team [9] has shown that individuals with severe, chronic stroke can improve their arm range of motion and clinical scores after 10 sessions of robotic therapy. However, it should be noted that functional gains in robotic therapy are not

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greater that those obtained with similar intensity conventional therapy [8]. This could be because robotic devices currently focus on shoulder and elbow movements, ignoring the hand.

VR activities constitute another approach to UE stroke rehabilitation, where patients typically perform movements without physical assistance. Reviews examining the use of VR for the improvement of UE function show promising results [10, 11]. In our view, VR could consolidate the UE functional gains obtained through robotic rehabilitation. While most VR activities typically focus on shoulder and elbow movements, some recent technical advances now allow the inclusion of hand movements as well. Specifically, the Microsoft Kinect version 2, used to track movements in VR, can detect hand opening and closing in addition to shoulder, elbow and wrist movements. These capabilities have been included in a new rehabilitation application, targeting UE reaching and grasping movements [12], which was part of our rehabilitation approach.

Electromyographically (EMG)-triggered NMES is a muscle stimulation modality that has been used to facilitate motor recovery of the hand after stroke [13]. The individual with stroke needs to volitionally activate the muscle(s) to trigger the NMES [14]. Thus, EMG-triggered NMES provides wrist and/or finger extension time-locked to the cognitive intent to actively extend the wrist and open the hand, making the training ecological and functionally relevant. EMG-triggered NMES has been shown to improve voluntary activation of isolated muscles, particularly in task-specific patterns [15].

While advances in robotics, VR and NMES have led to new treatment modalities targeting UE function post-stroke, further progress is needed for these technologies to have a true impact. Despite numerous studies attempting to identify the most effective rehabilitation interventions, post-stroke UE recovery remains disappointing [16] with sensorimotor deficits persisting in a large proportion of stroke survivors for more than 6 months (up to 62% [17]). Improvements in clinical scores have been small and often fail to meet the criteria for minimal clinically important differences [18]. There is a need to look beyond the 'one-size-fits-all' approach, where a single UE modality is applied to a group of post-stroke individuals. Another possible reason for the relatively small gains in UE function, and in particular the low gains in hand function [16], is that an individual's potential for recovery is not always considered. In clinics, therapists typically prescribe UE exercises to their clients based on initial clinical measures, which turn out to be poor predictors of future UE function [19]. However, assessing the integrity of the affected corticospinal tract (CST), by means of motor evoked potential (MEPs) elicited by non-invasive transcranial magnetic stimulation (TMS), was found to strongly predict the changes in UE function that could be elicited by rehabilitation [20]. In particular, the work by Milot et al. [21] showed that amongst several brain measures (e.g., magnetic resonance imaging, diffusion tensor imaging), baseline MEP amplitude was the best predictor of the response to robotic training of the affected UE in chronic stroke survivors. The presence of an MEP indicates that the CST, linking the motor areas of the brain to the hand musculature, is at least partially preserved.

Considering that 1) an individualized intervention to post stroke UE rehabilitation is desirable and 2) CST integrity is a strong predictor of hand function recovery, our proposed approach was to combine multiple modalities in an individualized intervention, tailored to each stroke participant's functional status and recovery potential. Recovery may be enhanced by first assessing CST integrity in order to determine the potential for recuperating hand function, and then combining multiple purposefully selected combinations of modalities to target motor deficits of each individual. Specifically, our **perSonalized UPper Extremity Rehabilitation (SUPER)** program included: 1) robotic activities to work on physically assisted UE reaching movements; 2) VR activities to work on unassisted reaching and grasping movements; and 3) NMES to facilitate hand opening and closing movements. The frequency of each modality during the intervention was determined according to the individual's potential for hand recovery. Our **objective** was to determine the treatment effect of the SUPER program in individuals with moderate/severe chronic stroke. Our hypothesis was that stroke participants with a low potential for hand recovery would benefit from a shoulder/elbow-centered intervention, while those with a high potential would benefit from an intervention involving the whole arm.

II. METHODS

A. Study Design

We used a pre/post, single-subject design with multiple baselines (AAAB). Baseline assessment was repeated three times within one week (T0-A, T0-B, T0-C), while post intervention took place immediately following the end of the SUPER program (T1). All assessments were conducted by a therapist blinded to participant allocation.

B. Participants

We recruited 28 individuals with chronic stroke. The inclusion criteria were: (1) ischemic or hemorrhagic stroke; (2) moderate to severe UE impairment (score between 2 and 4 out of 7 on the Chedoke-McMaster Arm and Hand Scales); (3) at least 3 months post stroke; and (4) no longer receiving rehabilitation services. Exclusion criteria were factors that may have limited participation or understanding of instructions: (1) medical instability; (2) marked cognitive deficits (MiniCOG score <3); (3) uncorrected visual impairments; (4) shoulder pain (score ≥4 on the visual analog scale); (5) severe spasticity in wrist flexors (score >3 on the Modified Ashworth Scale); (6) contraindications to NMES. The participant's potential for UE recovery was first determined by TMS to measure CST integrity (see below). Participants were recruited from two rehabilitation centers in Quebec, Canada: CISSS Laval; Jewish Rehabilitation Hospital and CIUSSS de l'Estrie - CHUS. All participants provided informed consent, as established by the IRB of the Center for Interdisciplinary Research in Rehabilitation (Montreal, Canada).

C. Potential for hand function recovery.

The integrity of the affected CST was assessed using MEPs elicited by TMS, as per the PREP procedure [22]. Surface electrodes were placed in a belly-tendon montage over the affected first dorsal interosseous muscle (FDI) and the extensor carpi radialis (ECR). TMS was performed with the coil held tangentially over the primary motor cortex (C3/C4 according to 10-20 system). We tested at 100% intensity. If needed, a different scalp location was also tried (2 cm posterior to C3/C4). MEP was considered absent if no response higher than 50 μV could be obtained in either muscle after 3 stimuli at each location. The presence or absence of an MEP was used to classify participants as having a high or a low potential for the recovery of hand function, respectively. In participants where TMS was contraindicated (due to medical conditions such as epilepsy), the level of CST recovery was evaluated through manual muscle testing of shoulder abductors and finger extensors [22].

Fig. 1. Robotic rehabilitation system.

D. SUPER intervention.

Participants received the SUPER intervention 3 times per week for 1 hr, for 4 weeks. For participants with a low recovery potential for hand function (*shoulder* group), the SUPER intervention consisted of robot-assisted reaching movements only. For those with a good recovery potential (*hand* group), the SUPER intervention also included VR activities combined with NMES, in addition to robotic therapy. The weekly amounts of robotics and VR/NMES sessions were based on the ability of participants to produce unassisted reaching movements with their affected arm against gravity. The robot-assisted activity consisted of an underwater fishing game, where participants had to reach for targets placed at their maximal voluntary arm extension (Fig. 1). The robot provided weight support of the arm by creating a virtual hard surface between the starting location and the reaching target. If a participant was unable to reach for a target on their own, the robot could prevent backwards movement (movement away from the target. It could also provide a pushing force to physically assist the movement. The type of robotic assistance (if any) was decided upon by the attending therapist. At the end of each trial, participants received feedback on the percent of movement that was performed independently (without robotic

assistance) and was encouraged to keep that number as low as possible.

Fig. 2. VR grocery shopping activity.

For VR, we used a reach and grasp VR activity based on a grocery shopping task (Fig. 2). Participants interacted with the VR activity through arm reaching movements and hand opening/closing movements, which were recorded by a Kinect V2 camera (Microsoft, USA). Participants were required to reach for grocery items placed on a shelf, grab them by closing their hand, bring them near their body and release them in their virtual shopping cart by opening their hand.

Thirty minutes of EMG-triggered NMES treatment was also incorporated in the VR sessions of reaching and grasping for participants in the hand group. Two-inch diameter surface electrodes attached to a NMES device were placed over the motor points of the Extensor Digitorum Communis for activating finger/wrist extension. Stimulation intensity (pulse amplitude) was set to produce maximal finger extension without discomfort. The electrical stimulation was triggered when the instrument detected an EMG signal exceeding a pre-set threshold, determined earlier during practice. The muscle stimulation was triggered when the participant attempted to grasp an object on the computer screen during VR activities. Thus, as the participant attempted to reach for an object, the stimulator picked up the EMG signal generated by the attempted wrist extension movements and stimulated the extensors to assist with hand opening during the reaching attempt. At the end of the reach, the stimulator was turned off until the next attempt.

To summarize, participants in the shoulder group received 60 min of robot therapy. Some, who were able to move the arm against gravity, also received the VR intervention (e.g., 30 min of robot therapy and 30 min of VR therapy). Participants in the hand group received approximately 30 minutes of robot therapy, followed by 30 minutes of VR therapy combined with NMES.

E. Outcomes.

The primary outcomes consisted of: 1) the Fugl-Meyer Assessment, upper extremity section (FMA-UE), a performance-based measure of UE impairment describing motor recovery. 2) the Box and Blocks Test (BBT), a measure of gross motor dexterity; 3) since low functioning individuals with stroke who are unable to grasp were not able to perform the BBT, we also used the ABILHAND, a questionnaire to assess active function of the upper limbs. All measurement tools have excellent psychometric properties.

As secondary measures, we used: 4) the Motor Activity Log (MAL-14), which rates the quality and frequency of use of the UE in 14 everyday tasks; 5) the Stroke Impact Scale (SIS), a stroke-specific health status measure featuring 33 items capturing daily activities grouped in 6 sub-scales; 6) Hand Grip Strength of the affected UE, measured with a dynamometer.

F. Analyses.

For the efficacy outcomes (primary and secondary), our criteria for quantifying the importance of a difference was based on the established minimally important clinical differences (MCID) of 5.25 for FMA-UE [23], 0.26 for ABILHAND [24] and 1.0 for MAL [25]. For the SIS, analyses focused on three specific subscales: strength (SIS-strength; MCID: 9.2); activities of daily living (SIS-ADL; MCID: 5.9) and hand tasks (SIS-Hand; MCID: 17.9) [26]. For each outcome, we first computed the difference between the post-evaluation measure and the mean of the three baseline measures. We then counted the number of participants who displayed a change greater than the MCID.

III. RESULTS

A. Participants

A total of 28 participants were recruited between June and December 2018. Of these. 26 completed all sessions of the SUPER intervention and all the evaluations. Two participants did not initiate the intervention due to medical or personal reasons

unrelated to the study and were therefore excluded from the analyses. As can be seen in Table 1, after classification with the PREP algorithm, 9 participants were included in the hand group (good CST recovery), while 17 where in the shoulder group (poor CST recovery). Both groups were similar in terms of sex (chi-square; p=0.83), age (t-test; p=0.52) and onset of stroke (t-test; p=0.78). Baseline FMA-UE, BBT and ABILHAND were understandably lower in the shoulder group than in the hand group (t-test; p<0.05).

TABLE I. DEMOGRAPHICS

	Hand group	Shoulder group
n	9	17
F/M	3/6	6/11
Age (years) (range)	64.5 (49.5 – 76.3)	64.9 (57.3 – 76.8)
Stroke onset (years) (range)	5.7 (0.8 – 25.8)	6.6 (0.6 – 24.2)
FMA-UE (/66) (range)	41.5 (26 – 54)	14.2 (9 – 23)
BBT (n blocks) (range)	14.1 (0 – 33)	0.4 (0 – 3)
ABILHAND (-6 to 6) (range)	1.8 (0.2 – 3.9)	0.4 (-2.4 – 4.3)

B. UE Recovery

As illustrated in Figure 3, 10 participants showed changes exceeding the MCID of 5.25 for the FMA-UE. Of these, 4 were in the hand group and 6 in the shoulder group, representing a similar proportion within the two groups (44% and 35%, respectively).

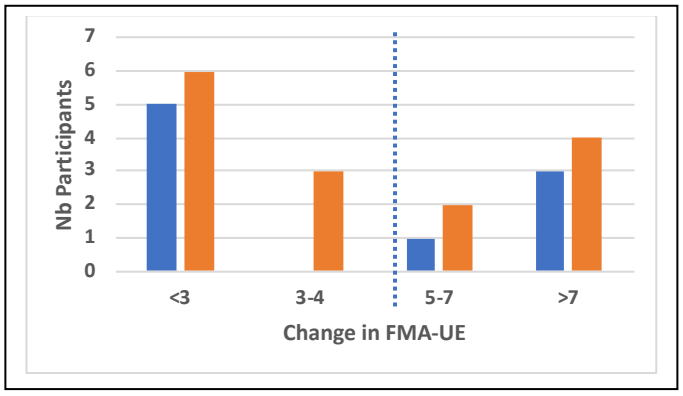

Fig. 3. Changes in FMA-UE from baseline for the hand (blue bars) and shoulder (orange bars) groups. Dotted line indicates MCID.

C. Dexterity

Almost all participants in the shoulder group were unable to perform the BBT with their affected hand during baseline evaluation. No changes were observed after the SUPER intervention in this outcome. In the hand group, there were no differences in performance of the BBT with the affected hand, before and after the intervention. As for the ABILHAND (Fig. 4), 6 participants in the shoulder group and 6 in the hand group showed improvements greater than the MCID following the intervention.

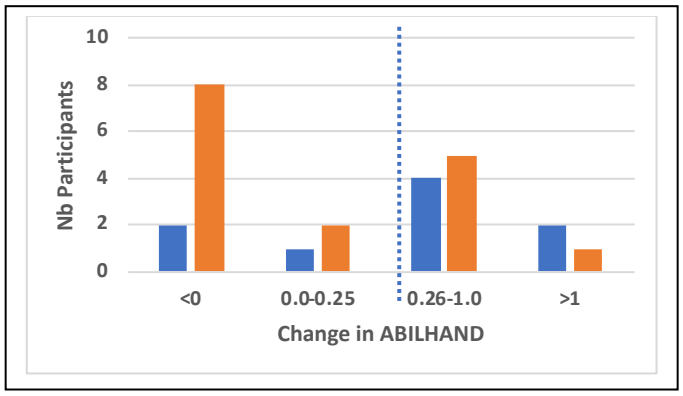

Fig. 4. Changes in ABILHAND from baseline for the hand (blue bars) and shoulder (orange bars) groups. Dotted line indicates MCID.

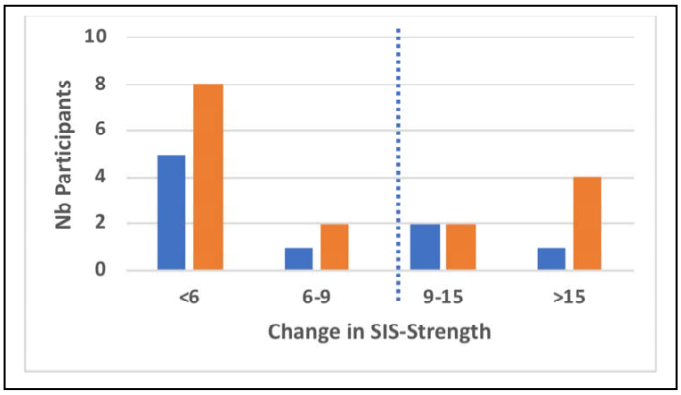

Fig. 5. Changes in SIS-Strength from baseline for the hand (blue bars) and shoulder (orange bars) groups. Dotted line indicates MCID.

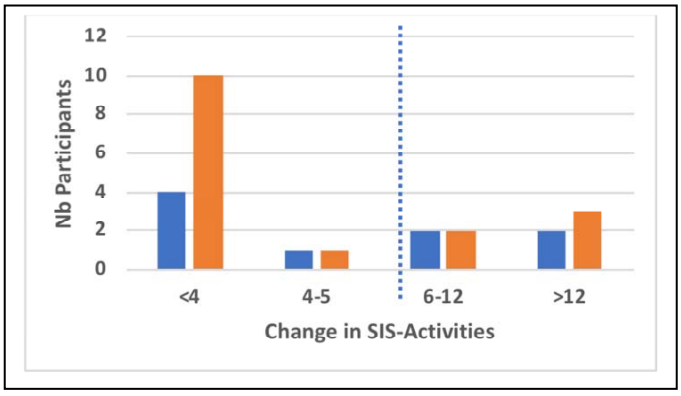

Fig. 6. Changes in SIS-Activities from baseline for the hand (blue bars) and shoulder (orange bars) groups. Dotted line indicates MCID

D. Secondary outcomes

Three participants showed improvements in the MAL-14 superior to the MCID, following the SUPER intervention. All 3 were in the hand group.

For 9 participants, the SUPER intervention resulted in improvements in the SIS-strength subscale

(four in the hand group and 5 in the shoulder group) greater than the MCID (Fig. 5). Likewise, as seen in Fig. 6, 9 participants showed improvements in the SIS-ADL subscale (3 in the hand group and 6 in the shoulder group). As for the SIS-hand subscale, only 1 participant (hand group) displayed changes above MCID.

None of the participants changed their grip strength following the SUPER intervention.

IV. Discussion

In this study, we measured the effectiveness of the SUPER intervention, combining robotics, VR and NMES, to improve UE function in individuals with chronic stroke. The intervention was personalized according to each participant's potential for hand recovery, as assessed by the PREP algorithm. Our results showed that 10-12 participants (40-46%) improved in terms of our primary outcomes (FMA-UE and ABILHAND) following the SUPER intervention. Most also improved in other measures related to the performance of UE activities (SIS or MAL-14). However, few or no participants improved in measures specific to hand strength or dexterity (BBT, grip strength, SIS-hand). While this was expected for participants in the shoulder group, who did not perform any hand related exercises, it seems the SUPER program only had limited impact on hand function for participants in the hand group as well.

Participants in the hand and shoulder groups improved in UE function in similar proportions, indicating that our personalized approach was beneficial to all. This suggests that a personalized intervention, focusing on either shoulder/elbow or the whole UE depending on the level of CST recovery, may be more appropriate than a "one-size fits all" approach where all participants receive the same intervention. The benefits of a personalized intervention are that participants can spend more time practicing tasks that target their specific impairments. Such an approach is also closer to what is done during stroke rehabilitation, where clinicians use clinical reasoning and employ a combination of tasks and activities to promote recovery. One limitation of our study design, however, is that we cannot determine the relative importance of one or another component of the SUPER intervention.

While 40% of our participants improved FMA-UE and 46% improved ABILHAND scores, 18, or 81%, showed improvements in at least one other outcome measure (FMA-UE, ABILHAND, MAL-14 or SIS) greater than MCID values. It is, however, difficult to explain an improvement in activities involving the UE, as measured by the MAL and SIS, without a decrease in the underlying impairment level, as measured by the FMA-UE. We prefer therefore to keep the more conservative estimate of 40% of participants showing improvements following the SUPER intervention.

It is unclear as to why participants in the hand group did not show improvements greater than MCID in the hand-related outcomes. This could have been due to an insufficient number of trials or a lack of variability in hand tasks. Future studies could incorporate another VR/NMES and/or robotic task (e.g., grasping objects of different shapes and sizes) to address these limitations.

Another limitation is the absence of a control group making it harder to attribute improvements in UE function specifically to the SUPER intervention. For example, as our participants were all in the chronic stage of stroke, some may have suffered from physical deconditioning of their affected UE due to disuse. A rehabilitation intervention based on usual care (e.g., exercises and ADL tasks) may have yielded similar results. Indeed, research indicates that both robotics and VR lead to similar improvements in UE function as regular therapy when practice time is matched [8]. In addition, we did not assess if gains in UE function were maintained in the months following the intervention. A follow-up study could include a control group receiving time-matched conventional therapy and reassessment after 3-6 mo.

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