Revisiting sensory impairment: a robotic-based training approach with chronic stroke survivors

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ABSTRACT

About half of stroke survivors demonstrate deficits in sensing and perceiving their movements, but sensory retraining focusing on proprioceptive and kinaesthetic senses is often overlooked. The current work presents an evidence-based programme to retrain upper limb proprioception and motor functions post-stroke using a compact and portable robotic device. A total of 9 community-dwelling stroke survivors were recruited to undergo 15 robotic training sessions, with each session lasting an hour. The training involved forward reaching as an interactive game, in which the view of the affected forearm was blocked. Robot-generated haptic guidance was provided along the movement path as sensory cues while participants actively moved towards the target location. Audio-visual feedback was given following every successful movement as positive feedback. Baseline, post-day 1, and post-day 30 assessments were conducted, where the last two sessions were done after the last training day. Robotic-based performance indices and clinical assessments of upper limb functions after stroke were used to acquire outcome measures respectively. Throughout the training sessions, all participants showed a gradual but significant improvement in accuracy. Although the result was mixed, clinical scores of both sensory and functional outcomes also showed improvement compared to baseline. We observed the presence of occasional endpoint drift during sensorimotor training in all participants. The outcomes of this study will provide preliminary evidence and help inform the translational aspect of the proposed exercise.

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1 INTRODUCTION

Prior studies have established that the limb position and movement senses in space are important for motor control and learning. In stroke rehabilitation, it has been estimated that half of stroke patients demonstrate impaired ability to sense their movements, bringing a reduction in their quality of life. Despite the high prevalence of such impairment, sensory retraining focusing on proprioceptive and kinaesthetic senses receives less attention. Tasks that simultaneously target motor and sensory aspects are thought to be beneficial for relearning sensory functions and increasing the mobility of the affected limb.

For more than a decade, robotic technology has been incorporated into stroke rehabilitation to achieve more controlled therapy in terms of intensity, duration, and frequency. Some upper limb robotic devices have been reported and used in clinical research to assess upper limb proprioception after stroke. Studies by Dukelow and team, for example, employed a robotic-based *position-matching task* between affected and unaffected limbs, and showed how proprioception of stroke survivors is worse than healthy control [1] [2]. Other studies have looked into exercise protocol to retrain proprioception of the distal and proximal joints [3],[4],[5],[6]. Indeed, our past survey on current clinical work locally found that there

Table 1: Demographic information of the stroke survivors

Information	Value
Age	M = 58.44, SD = 12.59 years
Gender	7 males, 2 females
Duration post stroke	M = 3.56, SD = 1.94 years
Nature of stroke	6 haemorrhagic, 3 ischemic
Handedness	9 right-handed
Baseline EmNSA	Total scores = 13.44 / 40

is no agreement at the moment in terms of intervention to deal with sensory impairment after stroke [7]. Robot-assisted rehabilitation would provide a form of standardized intervention in stroke rehabilitation.

In this paper, we present an evidence-based program that aims to retrain stroke survivors' upper limb sensory and motor functions using a compact and portable robotic device. Here, we focus on proprioception and kinaesthetic senses as part of the 'sensory' domains. Data from the participants who completed the programme showed evidence of a reduction in error during the training and a certain degree of improvement as measured by a series of clinical assessments. Consequently, this study serves as a proof-of-concept and helps inform clinicians about the translational aspect of the proposed exercise.

2 MATERIALS AND METHODS

2.1 Participants

The study was approved by the Institutional Review Board of Nanyang Technological University, Singapore (IRB-2019-10-022). Community-dwelling stroke survivors were recruited through word of mouth by the therapists at local rehabilitation centres. Twenty-four stroke clients were registered and screened by a certified therapist. This therapist is different from the person who will be responsible for the routine intervention. From this batch of patients, N = 9 fulfilled the eligibility criteria and completed the study without dropouts. Participants were included if they (1) had first-ever ischemic or haemorrhagic stroke survivors > 6-month ago; (2) were between 21-75 years of age; (3) had sensory impairments as assessed by the Erasmus MC modifications of the Nottingham Sensory Assessment (EmNSA) (score ≤ 6 out of 8 in at least two categories); (4) had shoulder abduction and elbow flexion of motor power grade > 2 according to the Medical Research Council (MRC) scale for muscle strength. However, they were excluded if they were found to have (1) bilateral impairment; (2) high upper-limb spasticity (Modified Ashworth Scale for spasticity > 2); (3) unilateral neglect as assessed by the Star Cancellation Test (score < 44); (4) cognitive impairment (memory, attention, and language) as examined by Mini-Mental State Examination, and (5) known history of mental disorders, and the inability to perform upper limb activity due to excessive pain were excluded.

2.2 Equipment

The study employed a planar or two-dimensional (2D) table-top rehabilitation robotic device (Articares Pte Ltd) [8] which was placed on a height-adjustable table. The device had a handle resembling an ergonomic computer mouse, and was connected to a computer which also served as a 24-inch LCD display. The 2D coordinate of the handle was recorded by the computer through a custom-made game written in MATLAB R2019b (MathWorks Inc., Natick, MA, USA), which also offered an interactive gamified interface shown on the LCD display. Participants were seated on a clinical chair in front of the robot, with their affected shoulder in a neutral position and the hand gently placed on the handle, fastened with a Velcro strap.

2.3 Study design

Eligible participants went through a series of interventions using their affected UL for 15 regular sessions. Each session lasted for about 45-60 minutes and took place 3 days per week for a total duration of 5 weeks. Robotic and clinical assessments were carried out at baseline, post-day 1, and post-day 30; where 'post-' means after the last training session. All sessions were conducted in a clinic by a certified therapist. Each training began with a warm-up exercise, after which they continued with the actual training task. In the initial session, the therapist provided some familiarization trials with instructions to let the participants understand each task. The therapist also kept a patient diary containing feedback or incidental observation from the trials.

2.3.1 Warm-up exercise. In the warm-up exercise, participants familiarized themselves with the robot by moving freely under the therapist's guide. This was followed by 16 repetitions of the *joint approximation technique*. Here, the task was to move the handle towards a given visual target 10 cm away from the start position, but the robot produced a spring-like resistive force (with a stiffness k = 900 N/m) in the opposite direction of the movement. This force was position-dependent, meaning the resistance would increase as the handle got nearer to the target location. Participants were instructed to pay attention to the resistive force.

2.3.2 Sensorimotor training task. During training, a gaming interface was shown on the LCD display with the start indicator. The handle position was shown as a white circle on the display panel, which would disappear once the handle moved 2.0 cm away from the centre of the start position. There were 4 visual target locations 15 cm equidistant from the start position at an angle of 30°, 60°, 120°, and 150° with respect to the horizontal axis. Each position was shown an equal number of times in a block. A visual target of a cartoon character appeared at one of the positions. After a movement initiation cue, they began to do center-out reaching to the

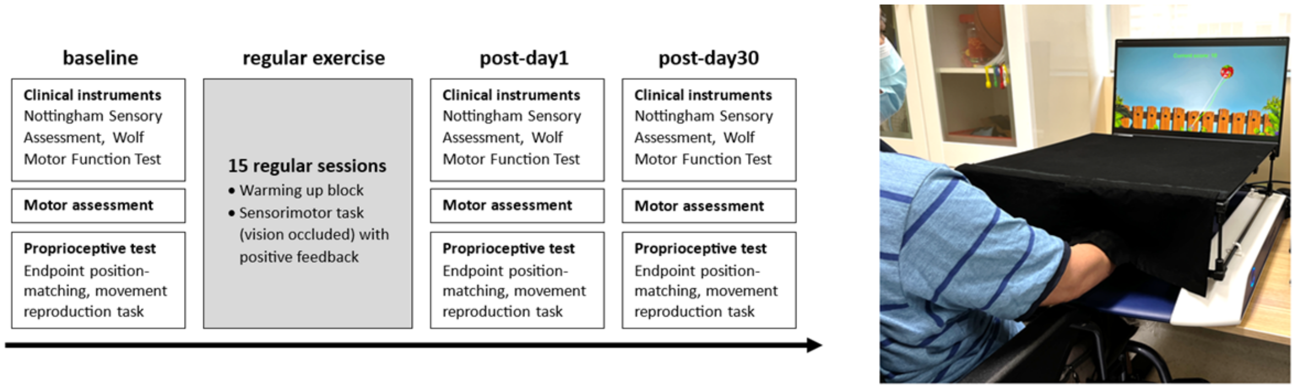

Figure 1: Block diagram of the whole study (*top*); and the training setup shown with terminal feedback (*bottom*)

target as straight and direct as possible within 5.0 sec. The view of the active forearm was occluded using a specially built rectangular box, and there was no visual indicator of the handle whatsoever on the display (Figure 1). After the movement finished, the robot kept the position for 1.5 seconds while receiving two different types of augmented feedback. The robot subsequently moved the hand back to the start position at 10 cm/sec, and the next trial continued. The returned trajectory travelled along a straight and smooth path (stiffness = 3500 N/m, damping = 20 N.s/m). In each training session, there were 10 blocks of 24 repetitions with a brief pause to let them rest.

2.3.3 Augmented feedback. The training was facilitated by different types of feedback that were provided throughout the whole session. As the participants performed the movement, online feedback in the form of a 'virtual channel' was produced by the robot handle (stiffness = 1000 N/m), connecting the start position and the target. If the movement deviated too much from the trajectory, they felt a cushion-like force preventing the handle from moving further away from the ideal path. The virtual channel was available along the reaching path but not in the radial direction, beyond the target position. In this way, participants had to estimate where the target was. Two types of terminal feedback were also given at the completion of each movement to inform the participants how well the latest movement was performed. This feedback appeared visually as a handle 2D trajectory, shown together with an ideal or reference line (white color) connecting the start position and the target. Another terminal feedback was provided as an audio tone and a text ("Good job!") only after every successful movement outcome as a reward.

2.4 Outcome measures

Clinical assessment and robotic-based performance measures were collected at baseline, post-day 1 training, and post-day 30 after the training. Only training performance is presented herewith. The learning effect was estimated from the reaching accuracy, defined as the Euclidean distance between the target centre and the participant's perceived target location.

2.5 Statistical analysis

Instantaneous 2D hand position (x, y) holding the robotic handle was recorded at 200 Hz and analysed offline with MATLAB and R. For the training and motor test, endpoint error, lateral error, smoothness, and maximum speed were computed to denote accuracy parameters. For each session dataset, the average accuracy across all blocks formed the within-session performance. A linear fit was subsequently done on the training dataset of each participant over the whole 15 sessions to estimate the change in performance, where a negative slope indicates an improvement. A non-parametric Wilcoxon signed-rank test was used to test the average slope of all subjects. Then, 2-way analysis of variance (ANOVA) was employed to compare differences in accuracy over training sessions and over different target directions. Statistical significance was based on a p-value threshold of 0.05.

3 RESULTS

Performance during the regular training sessions was the focus of the current report. Figure 2 shows the progression of endpoint error over the for individual participants. This error represents the difference between the actual target centre and the position that the participant felt to be the location. Each data point represents an average performance within a session across all blocks, and a blue represents the linear fit. On average the slope was found to be negative, denoting improvement in accuracy over training sessions (Wilcoxon signed-rank test, $p < 0.01$). To test if the change in accuracy differed across different sessions and target location, 2-way ANOVA was conducted on accuracy data from each session. It was found that while there was a significant effect of training session ($p < 0.01$), there was no reliable effect of the target location. This suggests that participants on average improved in a similar fashion across different target locations or reaching direction.

4 DISCUSSION

The work presented a repetitive robotic-based exercise that retrained proprioception, while at the same time promoting the active use of the affected upper-limb of community-dwelling chronic stroke survivors. The study assessed if the proposed exercise was

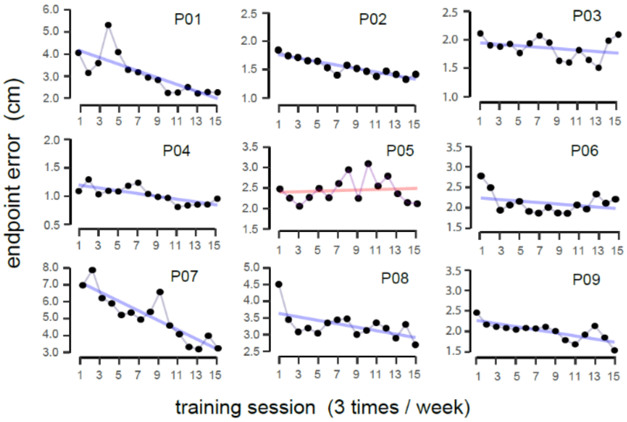

Figure 2: Deviation between the actual target location and the subject's perceived target location during all training sessions (where Pxx represents the participant number).

effective in improving reaching accuracy over the course of training and clinical scores a month later. While some earlier studies emphasized the tactile or haptic aspects of distal joints [9], [10], this work focused on the proprioception and movement-induced cutaneous sensation of proximal joints (elbow and shoulder). The tasks presented here encouraged the active participation of the stroke survivors, unlike some prior studies which make use of a purely passive exercise [11]. A recent systematic review of the evidence [12] suggested that exercises that synchronously combine motor and proprioceptive retraining tend to elicit stronger connections between the sensorimotor regions compared to a paradigm that combines two tasks sequentially, leading to increased neuroplasticity in the associated brain regions.

Although the current design was a one-arm study with no control group, the results show that the exercise is beneficial to improve reaching accuracy in participants with proprioceptive deficits. The outcomes of this study suggest that robotic-based proprioceptive training using a portable robot is feasible in the clinical setting. Our earlier survey on current practice locally did not find common practice agreement on the type of sensory assessment administered in the clinic and the intervention prescribed to the patients [7]. As such, portable rehabilitation robotics can provide a more objective and unifying ground for standardized assessment and intervention in the clinic. Price, usability of the machine, and space availability are still barriers that need to be addressed. Further investigation is warranted to understand how much reduction in error is acceptable in order for the patient to have no more problems in daily life. One way is to invite stroke clients to perform instrumented upper limb tasks of activity of daily living (ADLs) as outlined in [13].

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