# A Wearable Vibrotactile Device for Upper-Limb Bilateral Motion Training in Stroke Rehabilitation: A Case Study

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*Abstract*— **Real-time feedback is essential for motor learning. Automated feedback is especially valuable for at-home stroke rehabilitation in the absence of therapist supervision. This study examined the effect of real-time corrective vibrotactile feedback for training bilateral reaching motions. A bilateral upper-limb motor learning system, comprising a wireless wearable sleeve-armband device for providing vibrotactile feedback, a computer target game, and a customized motion tracking technology, was developed and evaluated on both hemiparetic stroke survivors and able-bodied people. This paper introduces the system and presents preliminary data for one hemiparetic stroke subject and one healthy subject performing bimanual reaching motions in the transverse plane. Vibrotactile training was found to successfully alter both subjects' original trajectories and to improve the motion symmetry of the stroke subject. These preliminary findings indicated the potential efficacy of vibrotactile cues for unsupervised motor learning in both the healthy and the stroke populations.**

## I. Introduction

Physiotherapy speeds functional recovery following a stroke by taking advantage of adult neuro-plasticity [1]; however, repetitive and lengthy therapy usually bores and frustrates therapy clients. Moreover, since therapeutic resources are limited and therapist-administered treatments are expensive, developing engaging, low-cost at-home rehabilitation programs is crucial.

One proposed solution is to employ video games to improve user engagement. A previous study demonstrates that video games that incorporate competitive and social elements into therapy regimens are more effective [2]. However, implementing such virtual reality solutions in the homes is challenging. Since stroke survivors often suffer from proprioception deficits [3], different types of feedback mechanisms need to be investigated for at-home rehabilitation to ensure that users are performing movements that are clinically beneficial. Given that users are likely to be preoccupied with the visual and auditory inputs from the video games, tactile feedback (i.e., force or vibrotactile feedback) is an attractive option for physically guiding the users.

Several studies have shown that the use of force feedback in robotic-assisted systems promotes motor recovery in chronic stroke survivors [4]-[6]. Due to the high cost of the robotic devices employed in such systems, lower-cost systems that use vibrotactile (vibration) feedback are gaining momentum in the stroke rehabilitation field.

Rehabilitation involving bilateral motions is important for stroke recovery, as most daily tasks require coordination of both arms [7], and the skills learned from bilateral arm movements can be transferred to unimanual performance [8]. While a few studies have shown that incorporating vibrotactile cues in motion training can improve trajectory or posture accuracy [9], [10], our literature review did not uncover studies that explore utilizing such cues in bilateral arm training.

This paper introduces a bilateral motion training system comprised of a wearable device that provides real-time vibrotactile feedback, an adapted commercially available tracking technology (the Sony PlayStation® system), and a computer target game. We share preliminary kinematics analysis of one healthy and one hemiparetic stroke subject using this system and evaluate the potential for this system to benefit both the healthy and the stroke population.

## II. Methods

The goal of our study was to assess the potential for real-time corrective vibrotactile feedback as a training regime for simultaneous, bilateral arm motions. For this purpose, we developed a real-time, integrated corrective vibrotactile feedback system for simultaneous, bilateral arm motions in the transverse plane. The system uses the position of the strong hand, i.e., dominant hand of the healthy subject and unaffected hand of the stroke subject, as a reference to generate a task path for the non-dominant/affected (ND/A) hand to follow. The strong hand was assumed to be able to reach in a straight trajectory with intact proprioception, and the vibration cues on the ND/A arm were the only feedback for path guidance. The following sections detail the study tasks, the system, and the study procedures. The protocol for this study was approved by the UBC Research Ethics Board, and participants provided informed written consent.

### *A. Study Tasks*

This study required subjects to perform multiple bilateral reaches while sitting in a fixed chair. Both the healthy subject (P1) and the stroke subject (S1) were required to start at a consistent initial position, i.e., trunk upright against the chair's backrest, upper arms relaxed, elbows and knees bent at 90°, and hands shoulder-width apart (without any support from their thighs). This initial position had the effect of placing both forearms parallel to the sagittal plane.

In order to minimize the impact of trunk compensation, the Required Reaching Length (RRL) was set to be a percentage of the subjects' maximum effective reach, i.e., 85% and 50% for P1 and S1, respectively [11], [12]. The maximum effective

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reach was defined as the distance travelled by the hand from its initial position to the maximum reach at waist level.

Different bilateral reaching tasks were assigned to the subjects based on their proprioception capability. It was assumed that without the aid of visual feedback, P1 could perform vertically symmetric bimanual motions in the transverse plane, i.e., maintaining a constant hand separation distance throughout the reaching motion, while S1 could not. Therefore, P1 was trained to move his non-dominant hand along a line that was at a horizontal angle $\theta_{target}$ (1) from his initial forearm orientation, while S1 was trained to change his neutral reaching angle in order to perform symmetric bilateral reaches (Fig. 1). The value 0.15 meters in (1) was selected to create a condition that required noticeable horizontal movements. Since both subjects' ND/A arm ended up performing an abduction movement, this task design allowed possible comparisons between them.

$$\theta_{target} = \sin^{-1}\left(\frac{0.15\ (m)}{\text{Required Reaching Length}\ (m)}\right) \qquad (1)$$

### B. *System Description*

A personal computer (PC) running Windows® 7 handled all communication between the optical motion tracking technology, the computer game, and the wearable device, and recorded all movement data.

#### 1) *Motion Tracking Technology*

An adapted PlayStation configuration, including two customized controllers and a camera, allowed the subjects to control the computer cursor by holding and moving the two controllers in the transverse plane. The subjects controlled the cursor's vertical movements with the least depth change of their two hands, and they controlled cursor's sideway motions with the horizontal position change of their strong hand.

#### 2) *Vibrotactile Feedback Device*

A custom-made, wearable, sleeve-armband device (Fig. 2) was designed to give corrective vibrotactile cues. The wearable device connected to the PC via Bluetooth. The sleeve was made from a polyamide and polyester material, with eight vibration motors sewn onto it. A removable inner layer prevented contact between the electronics and the user's skin, and an outer layer covered the electronic components. The armband consisted of a LilyPad Arduino microcontroller, control circuits for the microcontroller and vibration motors, and two lithium polymer batteries (3.7V, 2000mAh). Electronic components were connected and sewn onto the device using conductive threads and copper wires.

#### 3) *Target Game*

A simple computer target game was developed for this

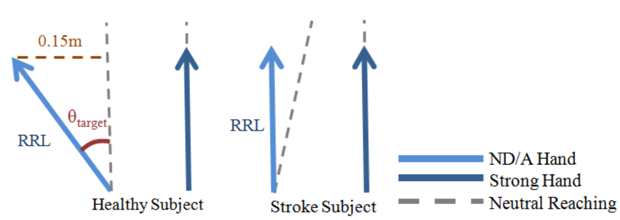


Figure 1. Tasks assigned to the subjects. Light and dark blue lines refer to the task trajectory for their ND/A and strong hand, respectively. Dashed gray lines illustrate the assumed trajectory of their neutral symmetric reaching motion.

Figure 2. A trainee wearing the vibrotactile sleeve-armband device (without the outer layer) while holding onto the two adapted controllers.

study (Fig. 3). Subjects completed one trial by starting at their initial position, clicking on the start target, reaching bilaterally forward, and clicking on the final target. The subjects were instructed to control the cursor within the two vertical lines (Fig. 3, *right*) while reaching bimanually forward.

### C. *Subjects*

One healthy subject (male, 57 years old, right-handed) and one hemiparetic stroke subject (male, 55 years old, with a Fugl-Meyer upper extremity score of 52) were recruited for this study. The stroke subject had a hemorrhagic stroke in the brain stem 47 months prior to this study. Both sides of his body were affected; however, the proprioception and movement of his right arm were judged to be normal by an occupational therapist, and he still presented weakness on his left side. Moreover, this subject could not fully extend both of his arms due to a mild to moderate kyphosis in his thoracic spine, but since the study tasks were tailored to the subjects' motor ability, he was still included in this study. Furthermore, the spasticity in his left arm limited his ability to start at the desired forearm orientation. As a result, S1 was instructed to try his best to start from this initial posture and be consistent.

### D. *Study Procedures*

To create a controlled environment for our optical motion tracking system, both experiments were carried out in the same room with minimal light disturbances. A monitor was placed on a table in front of the subject, and a motion tracking camera was taped upside-down to the bottom of the table. A chair with fixed translational and minimum rotational movement was put 1.5m away from the camera.

Prior to the training session, the study setup was adjusted to create a consistent test condition for both subjects. After the subject was seated in the chair, the chair height was adjusted to allow a 90° bend at the knee, and the top of the computer monitor was adjusted to match the eye level of the subject for minimal physical fatigue [13]. A rack with a cover board on top was placed in front of the subject. The cover board was positioned at ~0.01m in front of the subject's chest to constrain potential trunk movements as well as to occlude the reaching space such that the only visual feedback of the reaching motion available to the subjects was through the monitor.

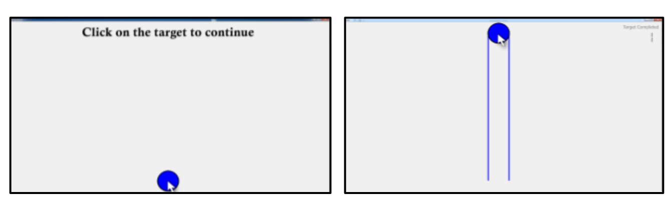


Figure 3. Screenshots of the target game showing the start target (*left*) and the final target (*right*).

Lastly, the tester introduced and put on the wearable device for the subjects, and explained the upcoming training session. The following subsections detail the three main components of the training session.

*1) Part I: Characterizing Reach Pattern*

Each subject's bilateral reaching pattern was characterized to create a personalized target game. The tester first measured the subjects' maximum effective reach using the average of 5 reaches. Then, the tester set the RRL in the game, explained the game to the subject, and let him practice for a few targets.

After the practice trials, the tester calculated each subject's characteristic on bimanual coordination $char_{\text{bim}}$ (2) and the straightness of the strong hand $char_{\text{s}}$ (3) from 30 new trials. Both measures were computed based on the ND/A and strong hand's horizontal positions ($x_{\text{ND/A}}$ and $x_{\text{s}}$) at the initial depth position $z_0$ and the final depth position $z_f$.

$$char_{\text{bim}}(i) = \left( |x_{ND/A} - x_s|_{z_f} - |x_{ND/A} - x_s|_{z_0} \right)_i \ , i = trial\ \# \quad (2)$$

$$char_{\text{s}}(i) = \left( x_{s_{z_f}} - x_{s_{z_0}} \right)_i \ , i = trial\ \# \quad (3)$$

*2) Part II: Vibration Response Training*

Directional vibrotactile feedback can be provided to users as attractive cues (moving towards the stimuli) or repulsive cues (moving away from the stimuli) [14]. To avoid training the subjects with an unintuitive vibration response that could affect the outcome measures, the tester first observed the subjects' reaction towards vibrotactile cues. The tester then informed them of the type of response they showed and tested a few more trials to ensure consistent reaction. Only two vibration motors, one located at the inner elbow and one at the outer elbow, were used in this study for guiding movements of the subjects' ND/A arm.

*3) Part III: Motion Training*

Each subject played a personalized target game to examine the effect of vibration feedback in motor adaptation. The cursor's horizontal sensitivity and the relative position tolerance $tol_{\text{bim}}$ (for setting a vibration-free zone around the ND/A hand's task trajectory) were calculated from $char_{\text{s}}$ and $char_{\text{bim}}$, respectively. In particular, the cursor movement between the two vertical lines (Fig. 3, *right*) was set to be equal to the range of the 95% prediction interval (PI) of $char_{\text{s}}$. The $tol_{\text{bim}}$ was set to be half of the range of the 95% PI of $char_{\text{bim}}$ (4), i.e., a 50% improvement on the precision of their original bimanual coordination. The vibration motors were only activated when the subjects' ND/A hand went outside of their position tolerance $tol_{\text{bim}}$.

$$tol_{\text{bim}} = \pm \frac{1.96}{2} \times \sigma_{char_{\text{bim}}}, \sigma = standard\ deviation \quad (4)$$

The motion training protocol was divided into different testing blocks. Table I lists the number of trials required for each subject in different testing stages. The vibrotactile training block was separated into early-adaptation (EA), mid-adaptation (MA), and late-adaptation (LA). Corrective vibrotactile cues were only enabled in the vibrotactile training and the after-effect trials. One out of 5 consecutive after-effect trials had vibration disabled, namely catch trials (CT). Both participants performed symmetric bimanual reaching motions in the familiarization and baseline stages.

TABLE I. NUMBER OF TRIALS REQUIRED FOR EACH TESTING STAGE. EA, MA, AND LA ARE REFERED TO EARLY-, MID-, AND LATE-ADAPTATION.

| Testing Blocks in Sequence | | P1 | S1 |
|---|---|---|---|
| Familiarization | | 3 | 3 |
| Baseline | | 5 | 5 |
| Vibrotactile Training | EA | 5 | 5 |
| | MA | **30** | **45** |
| | LA | 5 | 5 |
| After-Effect | | 25 | 25 |
| Post-Adaptation | | **10** | **30** |

## III. RESULTS AND DISCUSSION

*A. Training Trajectories at Various Testing Stages*

The relative ND/A hand's trajectory in the transverse plane, i.e., the horizontal position of the ND/A hand after subtracting the strong hand's horizontal position, demonstrated the training effect for P1 (Fig. 4) and S1 (Fig.5). One trial was picked at random from each of the EA, LA, and CT for comparison. Table II lists the maximum deviation from the vibrotactile-free zone for each trajectory. The LA and CT trajectories were similar to each other and with a much smaller maximum trajectory deviation compare to EA. This finding indicates that the subjects learned the task path and retained the adapted internal model even when vibration was removed.

*B. Normalized Distance at Different Testing Stages*

To facilitate comparison between the two subjects at different stages, we defined Index of Curvature (IC) as the ratio of the 3D distance travelled by the ND/A hand to the RRL, and ratio $R_{dis}$ as the distance travelled by the ND/A hand over the distance travelled by the strong hand (Table III). An IC value larger than 1 indicates a longer hand trajectory with respect to the RRL, and a $R_{dis}$ value of 1 refers to perfectly synchronized motion. The ideal bilateral motion is to have $R_{dis}$ and IC both close to 1, i.e., a synchronized motion utilizes the shortest path.

In examining the results, the IC for both subjects in EA was much larger than at the other stages. This was expected since

TABLE II. MAXIMUM DEVIATION FOR TRAJECTORIES AT VARIOUS STAGES.

| Participant | Max. Deviation at Different Testing Stages (m) | | |
|---|---|---|---|
| | ***Early-Adaptation*** | ***Late-Adaptation*** | ***Catch Trials*** |
| P1 | 0.59 | 0.10 | 0.01 |
| S1 | 0.09 | 0 | 0 |

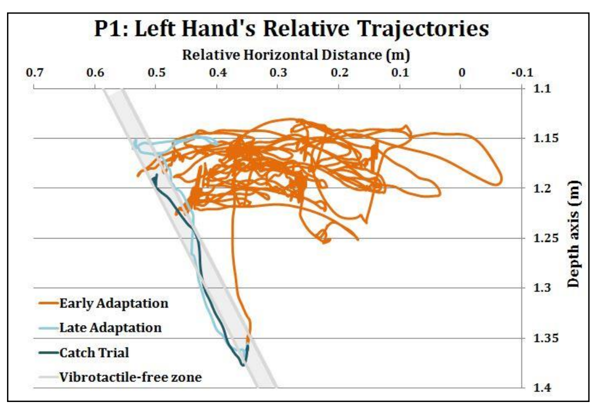


Figure 4. P1 left hand's relative trajectories at different testing stages.

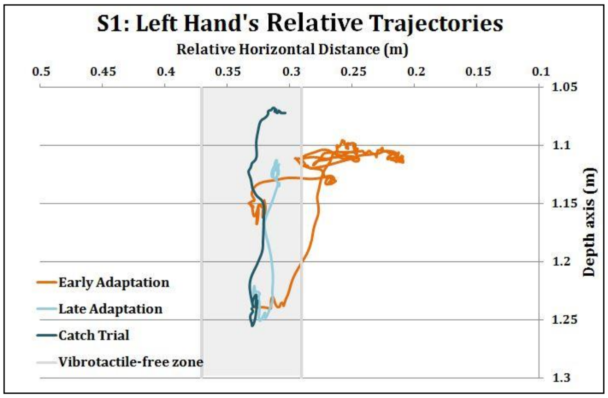


Figure 5. S1 left hand's relative trajectories at different testing stages.

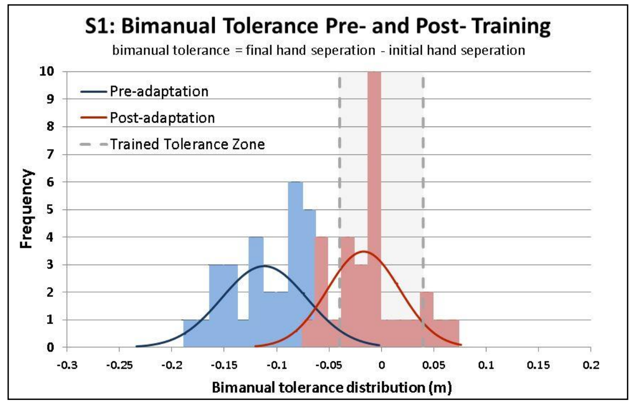


Figure 6. Bimanual coordination tolerance for S1 pre- and post- training.

TABLE III. INDEX OF CURVATURE AND DISTANCE RATIO AT DIFFERENT TESTING STAGES. DEFINITIONS: BA = BASELINE; EA = EARLY-ADAPTATION; MA = MID-ADAPTATION; LA = LATE-ADAPTATION; IC = INDEX OF CURVATURE; $R_{DIS}$ = DISTANCE RATIO.

| Testing Stages | P1 | | S1 | |
|---|---|---|---|---|
| | *IC* | $R_{dis}$ | *IC* | $R_{dis}$ |
| BA | 1.40 | 0.94 | 2.85 | 1.25 |
| EA | 15.08 | 2.12 | 3.84 | 1.41 |
| LA | 2.77 | 1.70 | 2.18 | 1.29 |
| CT | 1.51 | 1.13 | 2.39 | 1.26 |

the users were still discovering the task path. For S1, his $R_{dis}$ in LA and CT trials was similar to the baseline trials (BA), indicating that he had adapted to the task trajectory at the late-adaptation stage and was able to achieve his original bimanual synchronization performance. The ratios for P1 did not show a similar trend, i.e., $R_{dis}$ with larger deviation from 1 was found in LA and CT compared to the one in BA. The difference in the ratios might be due to a limitation on how synchronized people can achieve when performing inherently asymmetric tasks (in LA and CT trials) compared to symmetric motions (in BA trials).

### C. Training Effect on Bimanual Coordination Tolerances

In order to investigate if S1's bilateral reaching motion was more symmetric after the training, the histograms and the theoretical normal distributions of $char_{\mathrm{bim}}$ for the pre- and post-adaptation stage were compared (Fig. 6). His bimanual coordination was found to be greatly improved from a mean of -0.11 meters with a standard deviation of 4.06 to a mean of -0.02 meters with a standard deviation of 3.44. Moreover, 67% of the post-adaptation performance was within the trained tolerance zone $tol_{\mathrm{bim}}$.

## IV. CONCLUSIONS AND FUTURE WORK

A system was developed to investigate the effect of utilizing vibrotactile cues to train bilateral reaching motions. The early results from this study indicated that both a healthy subject and a stroke subject were able to adapt to the designed bilateral motion with the aid of vibration training. The left hand's relative trajectory of both subjects progressed towards the task trajectory over the training period, and the motion symmetry of the stroke subject was improved post-training. We have collected data from a total of 20 healthy subjects and 7 stroke subjects for this study. The next step is to perform a similar analysis on all 27 subjects and to examine the significance of vibration training in motor adaptation.


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