

**AN EVALUATION OF THE USE OF VIBROTACTILE CUES  
IN BILATERAL UPPER-LIMB MOTION TRAINING  
WITH HEALTHY ADULTS AND HEMIPARETIC INDIVIDUALS**

by

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# Abstract

Due to limited therapeutic resources and the high cost of therapist-administered treatments, victims of neurological trauma such as stroke need alternate solutions, e.g., virtual rehabilitation trainers. Effective virtual trainers can also benefit able-bodied people in tasks involving motor learning or motion refining. Since real-time instructional cues, provided through various sensory channels (visual, auditory, and haptic), function in the same way as human trainers, automated feedback systems are gaining momentum in the motor learning and retraining field.

Given that most daily tasks require coordination of both arms, the aim of this thesis is to evaluate the potential of utilizing real-time corrective vibrotactile (vibration) feedback to facilitate a training regime for simultaneous, bilateral arm motions. To address the research goal, the author designed and developed a low-cost, upper-arm, motion training system consisting of a wireless, wearable sleeve-armband device with embedded vibration motors, a vision-based bimanual motion tracker, and real-time stimulus-response control and data logging software.

Since there are two logical, but different, movement responses a person might have toward directional vibrotactile cues, i.e., moving towards or away from a stimulus, the first study investigated if an intuitive and consistent response exists among participants. This study also investigated if providing stimuli using different actuator configurations could facilitate a more consistent response among participants. The study results showed high variability in participants' motion response to vibrotactile cues regardless of the actuator configurations. Thus, researchers should account for the perceptual differences among individuals and avoid training users with an unintuitive vibration response that could affect the outcome measures.

The second study evaluated the motion training system with both hemiparetic stroke survivors and healthy adults. Prior to assessing the training system, the experimenter set up a customized game and task path based on each participant's reaching pattern and trained the participants' reaction toward vibrotactile cues based on their own preferences. Vibrotactile training was found to successfully alter healthy participants' original trajectories and to increase the end-position precision of the stroke participants' affected hand and bimanual coordination. These results suggest the promising use of vibrotactile feedback in bilateral motion training for both healthy and hemiparetic stroke populations.

# Preface

This research is under the supervision of the author's mentors: Dr. Machiel Van der Loos and Dr. Elizabeth Croft. The author and both supervisors are with the University of British Columbia (UBC) Mechanical Engineering department. The author was responsible for performing the background literature review, developing and integrating the software and hardware for the studies, recruiting subjects, conducting the experiments and data analysis, and writing the manuscript. Dr. Machiel Van der Loos and Dr. Elizabeth Croft provided guidance and review of my study protocols and manuscripts.

The first human-subjects experiment (Study I, Chapter 3) was conducted with the approval of the UBC Behavioural Research Ethics Board under application number H13-02800, "VIBE-Guide". The study protocol of the second human-subjects study (Study II, Chapter 4) was approved by the UBC Clinical Research Ethics Board (H14-02115: "VIBE-Guide Phase II"). The outer case of the adapted motion tracking controllers used in Study II was designed by Mimi Law, a former Emily Carr student, and later modified by the author and Brendan Sexton, a former undergraduate student who worked under the author's direct supervision. Part of the control software of the motion tracking system was adopted from the work by Alida Verster and Nathan Wolfe, former undergraduate students who worked in the author's lab.

A paper reporting preliminary results of Study II was accepted and presented at the 2015 International Conference of the IEEE Engineering in Medicine and Biology Society. Part of the paper was included in Chapter 4. The manuscript was written by the author and reviewed by Dr. Elizabeth Croft and Dr. Machiel Van der Loos.

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# List of Abbreviations

<b>3D</b>	3-dimensional
<b>CI</b>	Confidence interval
<b>CIMT</b>	Constraint-induced movement therapy
<b>CL</b>	Confidence level
<b>CSV</b>	Comma-separated values ( <i>file type</i> )
<b>CT</b>	Catch trials ( <i>testing stage</i> )
<b>D/UA</b>	Dominant/unaffected
<b>EA</b>	Early-adaptation ( <i>testing stage</i> )
<b>IC</b>	Index of Curvature ( <i>performance metrics</i> )
<b>LA</b>	Late-adaptation ( <i>testing stage</i> )
<b>MAS</b>	Modified Ashworth Scale
<b>N/A</b>	Not appropriate
<b>ND/A</b>	Non-dominant/affected
<b>PC</b>	Personal computer
<b>PI</b>	Prediction interval
<b>RRL</b>	Required Reaching Length
<b>SD</b>	Standard deviation
<b>UE-FM</b>	Fugl-Meyer Upper-Extremity Scale

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*This thesis is dedicated to my beloved family  
for their constant support and inspiration throughout my life.  
Your love made me who I am today.*

# Chapter 1

## Introduction

Known to be the second leading cause of death worldwide [1], stroke affects an estimated total of 315,000 Canadians [2]. Stroke refers to the interruption of blood flow to a part of the brain either due to blood vessel blockage (ischemic stroke) or rupture (hemorrhagic stroke). This interruption cuts the oxygen supply to the brain cells of the affected area, causing the brain cells to die. Of those who have experienced stroke, only 10% make a full recovery, while 65% suffer from minor to severe impairment, 10% require long-term care, and 15% of cases result in death [3]. Approximately 75% of stroke survivors suffer from hemiparesis [4], i.e., one-sided weakness of the body. The disability-adjusted life years (DALY) for the Canadian population are 3 years [5], where the DALY is the sum of years of life lost due to premature mortality (death before the predicted optimal age limit) and years of productive life lost due to disability [6]. The DALY serves as an indicator of the impact of a disease and gives a health profile of the population's health status [6]. In addition to impairing the health status of a population, stroke is also a continuous drain on the economy, with an average acute care cost of \$27,500 per stroke incident [3], and a cost of \$3.6 billion a year for physician services, hospital costs, lost wages, and decreased productivity [2]. As the chance of stroke correlates with age, it is expected that these statistics will increase with our aging population.

Physical rehabilitation speeds functional recovery by taking advantage of adult neuroplasticity [7]. Neuroplasticity is the ability of the brain to change function and structure in response to environmental demands, such as sensory input, motor act, and awareness, via modifications of synaptic connections and promotion of neurogenesis [8]. Studies have shown that both healthy adults/animals and their stroke counterparts need to perform hundreds of repetitions in order to learn/relearn specific movements [9]-[11]. For upper-arm stroke rehabilitation, for example, common physical rehabilitation strategies include using only the affected side (unilateral) or both sides (bilateral) to perform repetitive movements. However,

with limited therapeutic resources, the numbers of functional therapeutic tasks of upper and lower limb movements per therapy session are an order of magnitude lower than the numbers of repetitions required for functional improvements from animal studies [12], [13]. In addition, the high cost of therapist-administered treatments, and repetitive and lengthy therapy sessions often bore and frustrate therapy clients, negatively affecting the stroke recovery process. A potential solution to offset these challenges is to develop engaging, low-cost, at-home rehabilitation programs.

The employment of computerized systems that combine virtual reality technology, e.g., video games, and automated feedback (on their game and/or motor performances) aims to alleviate the monotony of rehabilitation exercises and to improve user engagement. A previous study demonstrated that video games that incorporate competitive and social elements into therapy regimens are more effective [14]. Moreover, automated feedback systems resemble the practice of therapists when they make use of various sensory channels to instruct their clients in learning motor exercises. Added advantages of a computerized approach are higher accuracy, greater repeatability, and faster response times [15], [16]. However, implementing such solutions in the home is challenging. Since stroke survivors often suffer from proprioceptive and sensory deficits [17], it is important that researchers investigate appropriate feedback mechanisms for at-home rehabilitation. This investigation is necessary to ensure that users will gain value from the feedback and will perform movements that are clinically beneficial.

Types of feedback include visual, auditory, and haptic (vibrotactile and force) modalities. Visual and auditory types of feedback provide instructions for trainees to follow without high accuracy, and vibrotactile (vibration) and force feedback give direct cues on motion refinement, while force feedback is the only feedback channel that can physically alter trainees' movements. Haptic cues are the desirable alternate feedback mechanism in situations where visual and auditory sensory channels are occupied or unavailable, for example, when users are preoccupied with visual and auditory inputs from virtual reality technology.

In addition to its use in stroke rehabilitation, automated feedback systems that use haptic feedback could also help people who suffer from visual and hearing impairments generally. A Canadian nationwide survey showed that about 0.32% of the population is legally blind [18], 3.2% of the population have visual impairments [18], and 4.6% of the population have hearing

disabilities [19]. Of the people with hearing disabilities, aged 15 years or older, 30.2% also have seeing disabilities [20]; of the people with vision disabilities, aged 15 years or older, 34.9% have hearing disabilities [20]. Moreover, automated feedback systems that use haptic feedback are valuable for able-bodied people when they are in situations of a dynamic training environment, such as outdoor sports and virtual gaming.

## **1.1 Thesis Overview**

The purpose of this thesis is to investigate the training performance resulting from a home-based, upper-limb, stroke rehabilitation system that combines physical therapy, vibrotactile feedback, and video gaming. Specifically, this system intends to correct the upper-arm bilateral reaching movements of users based on a pre-programmed path trajectory by utilizing vibrotactile cues as motion feedback. The motivation behind choosing vibrotactile stimuli as the target of this investigation is detailed in Chapter 2. Video gaming in this system serves as an engaging factor.

This system focuses on bilateral movements since most daily tasks require the coordination of both arms [21], and the lack of arm control negatively affects quality of life and independence [22]. For a person with hemiparesis, the effectiveness of bilateral training, either with both hands in synchrony or in alternation, may be due to a facilitation effect from the non-paretic arm to the paretic arm [23]. Empirical results have shown that bilateral training is equally or more beneficial than unilateral training. In particular, the muscle activations of the paretic limb are similar in bilateral and in unilateral exercises [4], [24], and the skills learned from bilateral arm movements can be transferred to unilateral performance [25]. Additional benefits of bilateral training include forcing functional movements of the affected arm and encouraging inter-limb coordination [4]. Moreover, implementing a bilateral training system in an unsupervised home environment is especially valuable to prevent users from “deceiving” the system using only their unaffected hand.

Chapter 2 of this thesis provides the background literature related to this thesis work, including a review of upper-extremity exercises in stroke rehabilitation and an overview of systems that provide various types of feedback for static or dynamic motion guidance/corrections. In particular, this chapter outlines motor-learning-related studies that utilize visual, auditory,

force, and vibrotactile feedback. This information builds a foundation for the motivation and study design of this thesis work.

Chapter 3 details the first of the two human-subjects studies in this thesis (Study I). Study I examined the feasibility of using vibrotactile cues in motion guidance and the type of motion response that the subjects exhibited to vibrotactile cues. This study also investigated the effect of different vibration actuator configurations on reaction time and motion response consistency, i.e., if the user consistently reacted to directional vibrotactile cues in the same way. The results from this study formed a basis for the implementation of vibrotactile feedback for the next study.

Chapter 4 lays out the experimental design and results of a study that investigated the effect of corrective vibrotactile cues in bilateral reaching motion (Study II). Target populations included healthy younger adults, healthy older adults (45 years old and older), and stroke survivors. This study used a bilateral motion training system to collect data. The system includes a wearable device that provides real-time vibrotactile feedback, an adapted commercially available tracking technology (a modified Sony PlayStation® system), and a computer target game. Based on a system-specific task path, this system guides the movement of healthy subjects' non-dominant hand and stroke subjects' weak hand using real-time vibrotactile cues during a bilateral reaching. This chapter presents both visual and numerical task performance improvements as a result of vibrotactile training.

Chapter 5 concludes this thesis with the interpretations of the study results from Study I and Study II. This chapter also provides recommendations for future work building from the body of knowledge obtained from this thesis.

## Chapter 2

# Background and Literature Review

The prevalence and impact of stroke, as well as the importance of repetitive movements and user engagement in stroke recovery, introduced in Chapter 1, provide the grounding for this thesis. Chapter 2 further describes previous work related to the development of automated feedback systems in motion training and stroke rehabilitation. Specifically, Section 2.1 details the state of the art in stroke rehabilitation treatment for the upper extremity. Section 2.2 gives an overview of motion training systems that utilize automated feedback for healthy and/or stroke users. Section 2.3 introduces the proposed training system for this thesis to examine a less-investigated aspect in the motor learning literature, namely, the effect of using vibrotactile feedback in bilateral arm reaching.

### 2.1 Upper Extremity Exercises in Stroke Rehabilitation

The severity of stroke is dependent on both the degree and the location of cerebral oxygen deprivation. Many stroke survivors experience motor impairment (Chapter 1), of which 80% of cases concern the upper-extremity [26]. Spontaneous recovery from motor deficit tends to occur within the first few months (up to around 6-12 months) after the stroke [27], [28]. Maintaining or regaining motor function after the spontaneous recovery period requires intensive and repetitive physical movements of the affected arm through, e.g., physical and occupational therapies. These therapies help stroke survivors in recovering their range of motion and regaining skills for independent living.

Constraint-induced movement therapy (CIMT) is a common treatment approach in upper-extremity stroke rehabilitation as a supplement to physical task training. By constraining the unaffected limb, hemiparetic stroke survivors are forced to exercise the affected limb. Studies have shown improvements in patients as a result of CIMT [29], [30]. For example, Van der Lee et al. found that stroke survivors who receive CIMT demonstrate greater gains in dexterity and functional use of their affected arm in comparison to the ones who receive an equal amount of

neurodevelopment therapy-based training [29]. Levy et al. found that stroke survivors who receive CIMT show markedly increased cerebral activity of their affected hemisphere, accompanied with improvements in functional scores of their affected hand on weight lift and grip strength [30].

In order to provide a more engaging therapeutic environment, virtual reality technology has been widely adopted in clinics and examined in stroke rehabilitation studies. Virtual reality systems create simulated environments that allow human-computer interaction. The interactions generally require users to accomplish certain tasks, e.g., for stroke survivors, it can be score-related gaming or simulated daily tasks for independent living. System users receive feedback from various sensory channels as instructions or responses to their movements. It has been found that both healthy adults and stroke survivors can learn motor skills from a virtual environment and further translate it to the real world [31]–[34]. Some studies even showed that the performance from virtual reality training can be superior to real world training [33]–[35].

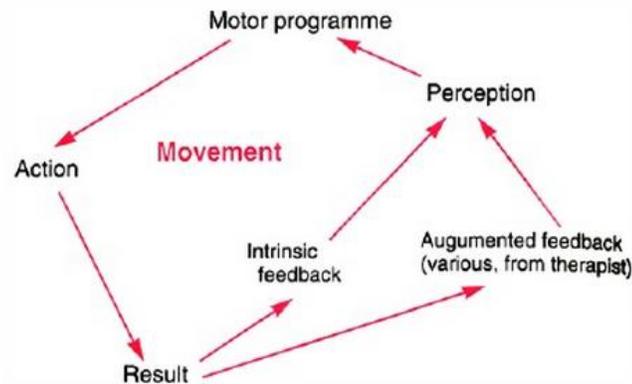
The next section details motor learning studies that implemented various types of automated feedback systems. Most of those studies also included a virtual reality environment.

## **2.2 Developed Systems with Various Types of Augmented Feedback**

One can only acquire new motor skills through environmental feedback that contains information about one's actions [23], [33]. There are two broad categories of feedback: augmented feedback and knowledge of results, where augmented feedback is artificially generated feedback, and knowledge of results is given to people as post-task verbal feedback [33]. As this thesis aims to examine the motor training effect as a result from real-time vibration feedback, this section will focus primarily on literature findings related to augmented feedback in motor learning.

Hartveld and Hegarty used Figure 2.1 to describe the dynamic interactions between action and perception in motor training in physiotherapy, for which feedback is a key component [36]. The trainee receives: 1) augmented feedback from therapists or computerized motion training systems, and 2) intrinsic feedback, i.e., the information that the trainee receives as a natural consequence of the trainee's performances [37]. Both types of feedback contribute to the

trainee's motor action. Based on the result of the trainee's motor action, the trainee then receives the two types of feedback.



**Figure 2.1: Dynamic interactions between action and perception in motor training in physiotherapy using feedback as a key component (© 1996 Hartveld & Hegarty, by permission) [36].**

Similar to human trainers, automated feedback systems are capable of providing feedback through different sensory channels – visual, auditory, force, and tactile – using a computer and corresponding hardware. Automated feedback systems record expert movements or specified task paths in the computer as references. Trainees can then use the systems to learn specified movements, where the system provides feedback upon deviation from the reference task path. Such feedback systems can govern the quality of trainees' movements in real-time and in an unsupervised environment. This advantage is especially valuable for at-home stroke rehabilitation, because it ensures that stroke trainees are performing clinically beneficial movements.

One advantage of an automated system is its capability of simultaneously providing different types of feedbacks. On the other hand, there is a likelihood that multiple sources of feedback may instead become a source of confusion and distraction for trainees. This situation is described as *information overload* [38]. In order to prevent information overload, Huang et al. recommended an information/sensory fusion approach that takes in dynamic data from multiple sources and presents only relevant performance results to trainees in a simple and intuitive way [38]. Sources include processed data from sensor inputs, feedback rules from a rule base, and prior knowledge of movements from a database [38].

This section introduces recent studies that used real-time augmented feedback in motion training systems. The section headings use the main feedback mechanisms (for providing motion guidance) to categorize the studies. Section 2.2.1 presents studies that utilized visual and/or auditory feedback systems. Section 2.2.2 details the work in the robotic-assisted field that examined force feedback. Section 2.2.3 introduces the error augmentation technique in visual or force feedback systems. Section 2.2.4 presents motion training systems that utilize vibrotactile cues, whereas Section 2.2.5 provides an overview of the challenges in integrating vibrotactile cues in motion training systems.

### **2.2.1 Visual and Auditory Feedback Systems**

As mentioned earlier, automated feedback systems require a computer as an integral component for data management and feedback output controls. Computer systems can easily produce visual and auditory feedback with built-in equipment, whereas additional hardware is needed to generate force and vibrotactile cues. Hence, in terms of the system cost, visual and auditory feedback systems are superior to the other two types of feedback systems.

Studies on visual and auditory feedback systems have shown positive results [23], [33]. For example, a study found that healthy subjects, who receive training in a virtual reality environment with real-time visual and auditory feedback, show an accelerated learning rate compared to control subjects, who practice a comparable amount of time with a human trainer [33]. This study task was to train subjects to hit a table tennis ball. Bizzi et al. divided the subjects into three groups, where each group received training from: 1) a human trainer (control group), 2) a virtual trainer with animations of the table tennis ball, and 3) a virtual trainer with no animations of the table tennis ball. The training system used a pre-recorded expert's end-effector trajectory as the training path. The results showed significant improvements of the second group compared to the other two groups, and the training effects retained for at least 3 days. The results also showed that the control group achieved a higher performance compared to the third group. This finding indicates that motion training requires both spatial and temporal information to effectively train a functional movement.

A 6-week study done by Whitall et al. showed that rhythmic auditory cueing can be useful for stroke rehabilitation [23]. They trained the subjects using a bilateral reaching motion. Their

results showed significant improvements in the functional use of the subjects' upper-arm. These improvements were retained for 2 months post-training.

The aforementioned studies demonstrated that visual and/or auditory feedback is effective and can be beneficial for both healthy and stroke populations. However, since visual and auditory feedbacks only provide high-level instructions, the motion training performance that a trainee can achieve is limited. Vibrotactile feedback systems, on the other hand, may be used to overcome such limitations. In particular, a few studies showed that the joint accuracy of the subjects who receive training using combined vibrotactile stimuli and visual cues are higher than the subjects who receive training with only visual feedback [39], [40]. The studies are detailed in Section 2.2.4.

## **2.2.2 Force Feedback Systems**

Force feedback systems require motorized mechanical devices to generate force cues. A common setup in literature for upper-arm motor learning requires the trainee to hold a mechanical device and perform arm movements. Such systems are analogous to the robotic-assisted systems.

Force feedback is unique among all feedback types because of its ability to provide partial or complete mechanical assistance that physically alters one's motion, whereas visual, auditory, and vibrotactile feedback can only cue the users. Force feedback can be used as: 1) an assistive force that aids trainees in accomplishing intended movements, or 2) a resistive force that acts in the opposite direction of trainees' motion and induces larger effort from the users. This section details studies that implemented systems using either type of force. The next section (Section 2.2.3) introduces a few systems that provide resistive force feedback using a technique called error augmentation.

Depending on the level of assistive force from the device, system users perform active movements (no assistive force), active-assisted movements (some assistive force), or passive movements (maximum assistive force). This assisting capability is especially valuable for stroke survivors suffering from moderate to severe motor impairment due to their inability to perform unassisted, repetitive motions [24], [41]. However, whether or not passive movements can aid motor recovery remains in dispute. Lewis and Perreault demonstrated that subjects who perform bilateral voluntary reaching achieve significantly smaller movement distance than the subjects

who receive robotic assistance [24]. In contrast, Marchal-Crespo and Reinkensmeyer pointed out that passive movement reduces the efforts required from the trainees and encourages slacking, which could potentially decrease motor recovery [42]. Krebs et al. also suggested that passive movements cannot alter stroke survivors' motor recovery [43].

Many studies have shown significant influences of force feedback in training both healthy and chronic stroke subjects [41], [44]–[47]. For example, a study trained naïve, healthy subjects to perform a rowing motion based on a predefined path. The study results found that the motion accuracy resulted from training combining force and visual feedback is higher than the result from training with no feedback [44].

The remainder of this section provides short descriptions on three highly influential robotic devices in stroke rehabilitation: the Massachusetts Institute of Technology (MIT)-Manus, the Mirror Image Movement Enabler (MIME) device, and the Assisted Rehabilitation and Measurement (ARM) Guide.

MIT-Manus was the first robotic system that was extensively tested in clinical settings with both acute and chronic stroke populations [45], [46]. A 6-week study that used MIT-Manus showed significant reduction of subjects' motor impairment in performing goal-directed, planar reaching movements [45]. This study also investigated outcome differences between assistive force feedback and resistive force feedback. The magnitude of the resistive force feedback was dependent on subjects' muscle strength. The results showed that the designed resistive force feedback improves functional ability in stroke survivors' wrist and hand motions compared to the assistive force feedback.

The MIME device provides assistance force for point-to-point arm reaching motions in two motion modes, i.e., the unilateral and bilateral training mode [41]. Chronic stroke survivors who received both motion modes of robot-assisted training showed significant improvements in their proximal (shoulder and elbow) functional ability scores after 1 month (mid-treatment) and 2 months (end-treatment) of exercise compared to the control group. The control group received the same amount of conventional therapy [41]. However, the study found no significant differences in the functional ability between the groups after a 6-month follow-up.

A 2-month study using the ARM Guide compared the reaching performance of a control group (with no force feedback) and a robot-assisted training group (with a 1 cm band around the

ideal trajectory that was feedback-free) [47]. The results showed a significant increase in the maximum reaching speed and maximum range of supported movement in both groups. However, the improvements of those two metrics were not significantly different between the two groups.

The finding of the ARM study, along with the results in the aforementioned MIME study, indicate that force feedback systems can provide equal if not greater therapeutic value as conventional therapies. These studies in aggregate suggest that the additional value of robotic feedback systems requires further investigation.

The disadvantages of robot-assisted systems are the high cost of the system, safety concerns related to the mechanical device, and space consumption of the mechanical device – since the device needs powerful motors to provide sufficient physical assistance. Therefore, the adoption of residential robotic-assisted systems remains stagnant despite the positive learning results in automated force feedback systems.

### **2.2.3 Error Augmentation in Motion Training and Stroke Rehabilitation**

Error augmentation is a technique that presents feedback based on amplified or offset position deviations of the user's hand motion from the ideal trajectory. For example, feedback can be resistive force feedback from a mechanical device or visual feedback in a virtual reality environment. The offset error augmentation technique is based on measuring individuals' baseline errors from initial trials, creating an error profile, and adding the error profile to the presented feedback in learning trials. The amplified error augmentation provides feedback that is a multiple of the position deviation in learning trials. These error augmentation techniques are commonly used in parallel with the visual distortion technique, which creates a rotated visual path based on the original target path. The purpose of this combination of techniques is to generate a higher trajectory deviation [48]. This section details a few studies that utilize the error augmentation techniques and the corresponding results.

Patton et al.'s study investigated the existence of the adaptation ability in both healthy and stroke subjects in response to a force field [16]. The study used a two-joint planar robot device to create resistive force fields to perturb subject movements. The results showed significant improvements in stroke subjects who received resistive force with amplified error, but not in subjects who received no force feedback.

Even in the absence of force error augmentation, studies that utilized visual error augmentation showed promising results [49], [50]. For example, a study showed significantly higher learning rates in healthy subjects who underwent training that utilized visual offset error augmentation compared to the subjects who received training with no error augmentation or with visual amplified error augmentation [49]. This study also showed that the visual offset error augmentation technique benefited the alteration of movement patterns for two stroke subjects. Another study showed similar results – offset error augmentation technique results in a fastest learning rate compared to the results from no error augmentation training or amplified error augmentation training [50].

In addition, Shirzad investigated the motor adaptation effect of combining both visual and force feedback using different error augmentation gains in healthy subjects [48]. The results showed significantly higher amount of learning for the group who received training using a high-gain visual and high-gain force feedback than the group who received training with only visual error augmentation. There were no significant differences in comparing the other groups that used different feedback gains.

#### **2.2.4 Vibrotactile Feedback Systems**

Automated vibrotactile feedback systems are still in the early-stage of development, though many concepts have been put forward [51]. Similar to robotics-assisted systems, vibrotactile feedback systems also require hardware to provide vibrotactile stimuli. Most concepts are in the form of wearables. The low cost of vibration motors combined with a light and compact size make vibrotactile feedback systems superior to robotic-assisted systems.

Using vibrotactile feedback is not a new concept in the field of human-computer interaction. In fact, systems that utilize vibrotactile feedback have been widely investigated in the field of postural/motion training [39], [40], [52]–[55], communications [56], and obstacle avoidance [57]–[59]. This section first describes tactile feedback in current stroke rehabilitation practice and then details the relevant work in motion training using such systems.

#### **Tactile Feedback in Current Stroke Rehabilitation**

In current physical therapy practice, tactile cues such as stroking and tapping from therapists, or vibrations from mechanical devices, facilitate the function of weak muscles [60]. For example,

by gently stroking their clients' triceps brachii tendon and anconeus muscle, therapists can stimulate the clients' elbow extensor muscles to elicit elbow extension [55].

Whole body or segmental vibration therapy is widely used in physical rehabilitation to reduce spasticity and to improve muscle strength and proprioception [61], [62]. This type of treatment uses a vibration frequency above 30 Hz [61], with an optimum frequency of 75 Hz to evoke response [63]. One specific example would be the vibration of muscle tendons, resulting in an intense firing rate of the muscle spindles, which is then interpreted by the central nervous system as the vibrated muscle being stretched [64]. A study applied 70-Hz muscle tendon vibration on the forearm flexor to augment proprioceptive input to the central nervous system during goal-directed arm reaches [63]. Working under the assumption that applying tendon vibrations on the forearm during arm movements may influence the sensorimotor pathway around the shoulder and elbow, this study showed that tendon vibrations improve the stability of the proximal arm in hemiparetic stroke subjects [63].

### **Automated Vibrotactile Feedback Systems**

Vibrotactile cues can be offered as prompts of the initialization of a movement (cues with attached meanings), e.g., the experimenter defines the instructions related to different types of vibrotactile stimuli and requests the subjects to memorize and perform. It can also be used as real-time directional feedback in position or joint angle corrections. This section provides descriptions of some studies related to the development and evaluation of vibrotactile feedback systems. The studies include training for directional reaching [55], sports [53], and imitation of arm postures or movements [39], [40], [54]. Since corrective real-time vibrotactile cues in arm movements are closely related to this thesis work, more focus is placed on introducing such studies.

Using vibrotactile cues as a prompt in directional reaching, the results from Lam et al.'s preliminary study was not encouraging [55]. Their study investigated the usability of using eight vibrotactile motors, located above or below the elbow (at the posterior side of the arm), to generate cues to prompt a reach-forward movement in the event where the subjects stopped moving and had not yet achieved the target [55]. The subjects were rehabilitation professionals who confirmed that such stimulation is important in traditional therapy. However, the subjects did not think the vibrotactile prompt was effective and did not agree nor disagree in using this

vibrotactile cue as a replacement of therapists. The reason might be due to the method of implementation and the lack of ability to address individual needs [55].

Another study investigated the effect of using vibrotactile cues as real-time prompt instructions in training snowboarders, since trainees only receive performance feedback from their instructors after each run in current snowboarding lessons [53]. In this study, Spelmezan et al. trained subjects to interpret various vibrotactile stimuli with designed vibration instructions. The vibration motors were located on the subject's torso and legs. The results showed that for all subjects, the number of correctly performed movements in response to vibrotactile cues is slightly lower than the number in response to audio cues. This finding might be a result from requiring the subjects to memorize the designed vibrotactile cues and their corresponding meanings, whereas audio cues are direct verbal commands and are relatively familiar to the subjects. However, subjects reacted to vibrotactile cues with a significantly faster reaction time compared to auditory instructions, which is advantageous for real-time motion training.

Vibrotactile feedback in studies mostly lowers the performance error of hinge joints [39], [40], [65]. For example, a study that investigated the acquisition of martial art postures using vibrotactile cues demonstrated a significant decrease in total joint deviation error, accumulated over each trial, over the course of vibrotactile training [65]. Moreover, Lieberman and Breazeal's study showed that using visual and vibrotactile feedback concurrently results in lower total hinge joint errors (accumulated over each trial) when compared to solely using visual feedback [39]. This result was independent of task difficulty. In addition, a study showed higher final postural accuracy at the wrist, elbow, and forearm as a result of either vibration training or combinatory training using vibration and visual feedback over training that only used visual feedback [40].

In contrast, a study showed that the addition of vibrotactile feedback does not generate a higher postural accuracy compared to utilizing only visual feedback for training. However, subjects showed high preference toward combining the two types of feedback because vibrotactile feedback "pushed them towards perfection" [54].

Though vibrotactile feedback has been researched in a wide range of fields and has shown some promising results, our literature review did not uncover any study that investigated the real-time training effect of vibrotactile feedback in stroke survivors, or in training subjects on synchronized, bilateral arm reaches. Based on the positive results from the aforementioned

automated feedback systems in training chronic stroke survivors to perform bilateral reaching motions, the main goal of this thesis is to provide insights of using vibrotactile cues in similar motion training systems. The next section describes the challenges in developing motion training systems that incorporate vibrotactile feedback.

### **2.2.5 Challenges of Vibrotactile Feedback in Motion Training Systems**

As mentioned in Section 2.2.2, unlike force feedback systems that can provide physical assistance, vibrotactile, visual, or auditory feedback systems are limited to providing instructional cues to the users. Hence, two inherent limitations of vibrotactile feedback systems are: L.1) trainees need to possess a minimal ability to initiate functional movements, and L.2) trainees need to possess reasonable sensory perception to vibrotactile cues [38].

For the healthy population, the first limitation is not an obstacle, whereas the second limitation depends on the subjects' detection sensitivity to vibrotactile stimuli during movements. Specifically, Buckingham et al.'s study demonstrated that for neurologically intact humans, activating vibration stimuli after movement onset results in a lower detection rate of the stimuli compared to activating the stimuli before movement onset [66]. Such suppression of tactile information due to movement is termed *tactile gating* [66]. Since real-time feedback is especially powerful in motor learning because of its instantaneous nature, people who are highly influenced by the tactile gating effect, i.e., unable to detect vibrotactile stimuli during movements, are not suitable for motion training using a vibrotactile feedback system.

Both L.1 and L.2 are severe limitations for the implementation of an automated vibrotactile system in stroke rehabilitation. To illustrate, L.1 confines such systems to stroke subjects with only mild or moderate impairments. However, by combining such systems with other rehabilitation feedback, for example, force feedback, it is possible that vibrotactile feedback can still be useful in correcting movements of users with low motor function while force feedback physically assists them. As for L.2: in addition to the tactile gating effect, a study found that 46% and 35% of their stroke subjects had impaired or absent tactile sensation toward light touches at the wrist and the elbow, respectively. Moreover, 53% and 46% of their subjects showed impaired or absent ability to localize tactile stimuli at the wrist and elbow, respectively [67]. Stroke survivors who have difficulties with tactile localization are not suitable for vibrotactile feedback

systems; however, increasing the intensity of vibrotactile stimuli may still be useful for stroke survivors who have difficulties in sensing light touches.

Prior to implementing automated vibrotactile feedback into training systems, the important question of, “*How would system users subconsciously interpret directional vibrotactile cues during arm motion training?*” remains to be addressed. Two logical responses to directional vibrotactile feedback are the *attractive* response (moving towards the stimulus) and the *repulsive* response (moving away from the stimulus) [68]. Our literature review did not uncover studies that have investigated if people exhibit a consistent motion response to vibrotactile stimuli applied on their forearm. Rather, most studies trained their subjects with one of the two responses [53], [65], [69], and one study divided their subjects into two groups and trained each group with either the *attractive* response or the *repulsive* response [54].

Spelmezan et al.’s study provided the closest answer to this question, except that their study focused on users’ interpretation of vibrotactile cues that were applied on their torso and lower body [53]. They found that about half of their subjects reacted to such vibrotactile cues with the *attractive* response, while the other half responded with the *repulsive* response. However, they proceeded to their second study by training all subjects using the *repulsive* response, and some subjects stated that they expected to move otherwise. Based on the findings from this one study, one can intuit that in other studies in the motion training literature, some subjects were trained with *unintuitive* responses, i.e., moving in the opposite direction as to what they naturally prefer, and that the resultant performance might not be at their optimum.

## **2.3 Proposed Motion Training System**

As mentioned in Section 2.2.4, this thesis aims to assess short-term motor learning, i.e., motor adaptation, using a bilateral arm motion training system that provides vibrotactile cues. Prior to implementing such a system, a key question is whether or not healthy and stroke populations possess the ability to adapt movements using automated motion feedback. This concern has been addressed in current literature. Patton et al. provided part of the answer to this question: both healthy and stroke survivors have the ability to adapt to force feedback training [16]. This study also revealed that healthy subjects have significantly higher adaptation capacity

compared to stroke survivors. In addition, studies have also shown that healthy adults possess the ability to adapt their motions with the aid of vibrotactile feedback [39], [65].

With the assumption that stroke survivors still acquire adaptation capability toward vibrotactile feedback, this section details the proposed system of an upper-arm training system that utilizes vibrotactile cues in an unsupervised environment for both healthy and stroke subjects. Several aspects need to be considered for this system. Huang et al. suggested that effective therapies require that automated feedback systems be motivating, and that the feedback cues should be easy-to-understand to avoid information overload [38]. As mentioned in earlier sections, one solution is to create a virtual reality game, which offers an engaging environment. Such an environment was found to provide system users self-confidence and to sustain attention through immersive displays and interactive training [38]. For design simplicity, a simple computer target game is determined to be suitable for this proposed system.

As for designing vibrotactile cues, users' ability in identifying the correct locations of vibrotactile stimuli, namely, the *localization accuracy*, needs to be considered. Moreover, the detection threshold of vibrotactile frequency is an essential component in determining the choice of vibration motors in this study. Cholewiak and Collins studied younger and older adults' detection threshold on vibration frequency and localization accuracy on seven sites on the forearm [70]. They found that older subjects have a higher detection threshold on vibration frequency than younger subjects, and all seven sites show similar threshold values for both subject groups. This study also demonstrated that the localization accuracy at the wrist and close to the elbow is the highest in all subjects compared to other sites along the forearm. Also, the effect of varying frequency on the localization accuracy is minimal in the range of 100Hz-250Hz. The results from this study built the basis of the vibrotactile feedback aspect of the study design, for which vibration motors have been placed at the wrist and elbow for directional guidance, and the frequency of the vibration motor is within the range of 100Hz - 250Hz.

In addition, taking into consideration of the findings in the literature and the goal of design simplicity, the proposed movement implemented in this study is a bilateral forward reaching motion. In particular, reaching motions are essential for everyday life, especially for stroke survivors, since it is a fundamental movement for activities such as dressing and eating [55]. Since most real-life arm movements involve object manipulation [33], this proposed system will

focus on training the movements of the end-effector (i.e., the subject's hand). Based on the finding that there are no studies that investigated vibrotactile feedback in bimanual motion training and that some studies showed positive results from training bimanual motion using force feedback, this thesis seeks to fill in these blanks in the literature. Specifically, this thesis aims to implement an algorithm that uses vibrotactile feedback to train the stroke or healthy subjects' affected/non-dominant hand, respectively, to follow a designated path based on the movement of their strong hand. This algorithm is similar to the ones in the aforementioned systems using force feedback.

As mentioned in Section 2.2.5, studies in the literature mostly assigned their system trainers with one out of the two types of response to vibrotactile cues, i.e., the *attractive* or *repulsive* response. This approach may have negatively impacted the outcomes due to the possibility of training the subjects with an unintuitive response [53]. Thus, prior to developing and evaluating a bilateral motion training system, the author designed the first study (Study I, Chapter 3) of this thesis to investigate people's natural reaction to vibrotactile cues applied on their forearm. This study hopes to reduce any learning effects (caused by training system users with unintuitive movement instructions) in the subsequent main study (Study II, Chapter 4).

## Chapter 3

# Study I: Motion Response to Vibrotactile Cues and User Preference in Types of Vibrotactile Stimuli

Chapter 2 introduced two logical motion responses to directional vibrotactile cues: the *attractive* response and *repulsive* response. Studies that utilized vibrotactile cues in motion training commonly trained their subjects using only one or the other motion response. However, this approach is not ideal since study subjects might already possess an *intuitive* motion response to vibration cues, i.e., the motion response that they perform subconsciously, naturally without thinking. Training study subjects to move in the opposite direction of their intuitive motion response is likely to affect the outcome measures of motor learning studies. Therefore, it is important to investigate if people possess an intuitive, consistent motion response to vibrotactile cues, and if so – do people prefer one motion response over the other?

This chapter details the design and results of a study that explored whether healthy adults demonstrate a repeatable motion response when their non-dominant arm receives directional vibrotactile cues. In addition, this study also investigated if providing stimuli using different vibration actuator configurations could facilitate a faster reaction time and/or a higher motion consistency. Those two performance metrics are defined later in Section 3.1.

For this study, the author adopted a commercially available motion tracking technology for tracking the motion of subjects' non-dominant hand and developed a wearable device to provide different vibrotactile stimuli. This study also examined the usability of the wearable device. The results from this study were valuable for the implementation of vibrotactile feedback in the subsequent motion training system in Study II.

Section 3.1 introduces the study design and hypotheses. Section 3.2 to Section 3.4 provide information on recruitment of subjects, experimental setup, and study procedures. Section 3.5 details the data analysis approach. Section 3.6 and Section 3.7 discuss the results and findings of this study.

### 3.1 Study Design

The main goal of this study was to observe the subjects' natural movements in response to directional vibrotactile cues, i.e., either moving towards the stimuli (an *attractive* response) or away from the stimuli (a *repulsive* response). The term *intuitive response* will be used throughout this thesis to refer to this natural response, and the term *unintuitive* response refers to the other motion response.

Other goals of this study were to investigate if the majority of the subjects react with the same intuitive response and if different vibration motor arrangements facilitate different reactions in motion guidance. Specifically, this study examined the performance differences between the two designed vibration stimuli: the *point* vibration stimulus, i.e., a single-point stimulus close to the elbow, and the *line* vibration stimulus, i.e., a two-point stimulation, with one stimulus close to the elbow and the other one at the wrist, aligned distally on the forearm. The performance metrics for this study were reaction time and motion consistency. Reaction time is the time difference between the activation of the stimuli and the start of users' movements. Motion consistency is a measure of repeatability of subjects' motion response, since it is possible that subjects react to vibrotactile cues using both *attractive* and *repulsive* response.

The *line* vibration stimuli were valuable because of the "phantom sensation" effect [71]. To illustrate, in the case where two motors are simultaneously activated with equal intensity, the receiver would perceive a vibration stimulus at the midpoint between the motors, with a larger area of sensation compared to the one created by a single stimulus [71]. This effect increases the number of subjective stimulus sites without increasing the number of vibration motors [72]. It was of interest to investigate if the *line* vibration stimulus that utilized the phantom sensation effect provided a clearer instruction in motion guidance than the *point* vibration stimulus.

The hypotheses of this study were: (H1.1) each person possesses an intuitive response, either an *attractive* or *repulsive* response, to vibrotactile cues, (H1.2) healthy adults significantly prefer

one intuitive response over the other, and (H1.3) the *line* vibration stimuli result in a faster reaction time and a higher motion consistency than the *point* vibration stimuli. Confirmation of hypothesis H1.1 would support the position that lesser learning effects result from requiring a person to perform an unintuitive response in short-time motor adaptation studies, e.g., asking a subject to move away from vibration stimuli while the subject's intuitive response is an *attractive* response. Verifications of hypotheses H1.2 and H1.3 could help to determine the type of vibration response and stimulus type to integrate into the system for Study II.

In order to test the hypotheses of Study I, the study design consisted of two 10-trial sessions for each subject. The trials tested subjects' motion performance and their perceived clarity of the two types of vibration stimuli. The experimental setup included the Sony PlayStation® system for motion tracking (detailed in Section 3.3.1) and a wearable device to provide vibration cues on the user's forearm (detailed in Section 3.3.2). The PlayStation system included a PlayStation® Move controller and a PlayStation® Eye camera.

## **3.2 Study Participants**

Subjects were recruited through advertisements on social media, the author's lab websites, mailing lists, and the University of British Columbia (UBC) campus bulletin boards. The inclusion criteria required the subjects to be 19 years old or older (or a UBC student of 17 or older), to be healthy without any movement disorders, and have basic knowledge of computers. Subjects who were unable to communicate in English, had disability that would prevent them from completing the study tasks, or were cognitively impaired were excluded from this study.

A total of 21 subjects, 10 males and 11 females, were recruited for this study. Twelve subjects' age fell within the range of 17 to 25, with 9 in the range of 26-35. All subjects had experience in using computers, and 90.5% of the subjects had experience with game consoles and technologies that provided vibration feedback.

Data collection took place in the Robotics for Rehabilitation Exercise and Assessment in Collaborative Healthcare (RREACH) Lab on UBC's Point Grey campus. The study protocol was approved by the UBC Behavioural Research Ethics Board (H13-02800). All the advertising materials and consent forms are presented in Appendix A.

### 3.3 Experimental Setup

This section introduces the system components, including a motion tracking system, a wearable device, and a control software interface. A personal computer (PC) running Windows® 7 handled all the control and logging software and communicated with the controller and wearable device via Bluetooth.

#### 3.3.1 Optical Motion Tracking Technology

The Sony PlayStation system, with one Move controller and one Eye camera, was the human-machine interface for this study (Figure 3.1). During the initialization of the tracking system, the sphere of the controller lit up in a certain color to allow position tracking of the controller. The sphere color for this study was set to blue for all subjects to create a consistent condition. An open source framework, the “moveframework” [73], performed real-time calculations to derive the 3-dimensional (3D) position data of the controller by using the sphere size and sphere location on captured images. The PC recorded the 3D position data, along with the clicking state of the buttons on the Move controller.



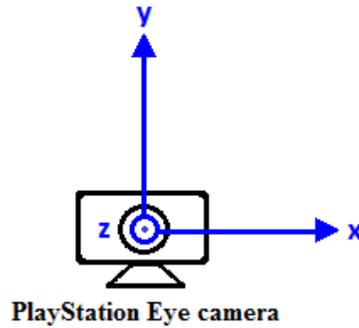
**Figure 3.1: Study I experimental setup. This figure shows the PlayStation system with one controller and one camera and the custom wearable device (detailed in Section 3.3.2).**

The author chose this tracking technology based on its low cost and its acceptable 3D position tracking accuracy<sup>1</sup>. The XYZ coordinate for this system is defined in Figure 3.2. A calibration of this motion tracking system revealed a position tracking error up to a maximum of

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<sup>1</sup> Carse et al. compared 3D tracking error of three commercially optical tracking devices using reflective markers: a 12-camera Vicon MX system (Oxford metrics, UK), an 8-camera Vicon 612 system (Oxford metrics, UK), and an 8-camera Optitrack system (NaturalPoint, Corvallis, OR) [74]. For measurement distances between 9 to 15 centimeters (similar to the minimum reaching distance in Study II), the maximum position tracking errors of the three systems were (in sequence): 1.17%, 16.3%, and 18.3% [74].

15% of the total distance travelled by the controller. This calibration included a tracking space of  $[-0.35, 0.35]$ ,  $[-0.40, 0.40]$ ,  $[0.80, 1.50]$  meters for X-, Y-, and Z- axis, respectively.



**Figure 3.2: Schematic diagram of the frontal plane of a PlayStation Eye camera (the black circle in the centre is the camera lens) and the defined Cartesian coordinate system XYZ with respect to the centre of the lens.**

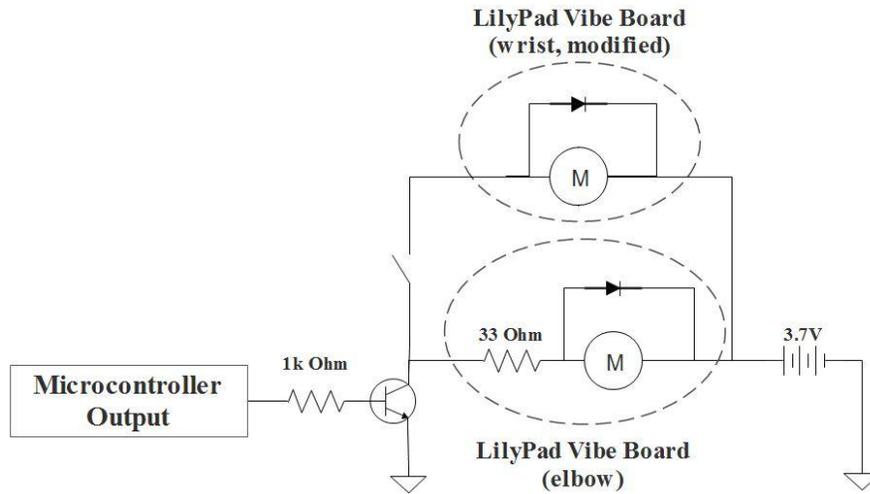
### 3.3.2 Vibrotactile Feedback Device

In order to provide corrective vibrotactile cues on the users' non-dominant arm for motion guidance, the author required a comfortable, wireless, wearable device that was safe, lightweight, easy to put on, and adjustable to accommodate different arm sizes. Based on these criteria, the author proposed a wireless, sleeve-armband design (Figure 3.1), with all the control electronics mounted on the armband and vibration motors mounted on the sleeve. The electronics selected were off-the-shelf LilyPad products, designed specifically for wearable use and widely used in research and individual projects [56], [75], [76].

The wearable device used a Bluetooth module to communicate with the PC using a 115200 bit-per-second serial communication. The sleeve was made from a polyamide and polyester material. A removable inner layer prevented contact between the electronics and the subject's skin. There were eight vibration motors (LilyPad Vibe Board) mounted on the sleeve and connected using conductive threads. Each LilyPad Vibe Board came with a  $33\Omega$  resistor and a diode for motor protection. This vibration motor has an operating frequency range of 115 Hz-235Hz [77], similar to the vibrotactile stimulation received from cell phones (130-180Hz) [78].

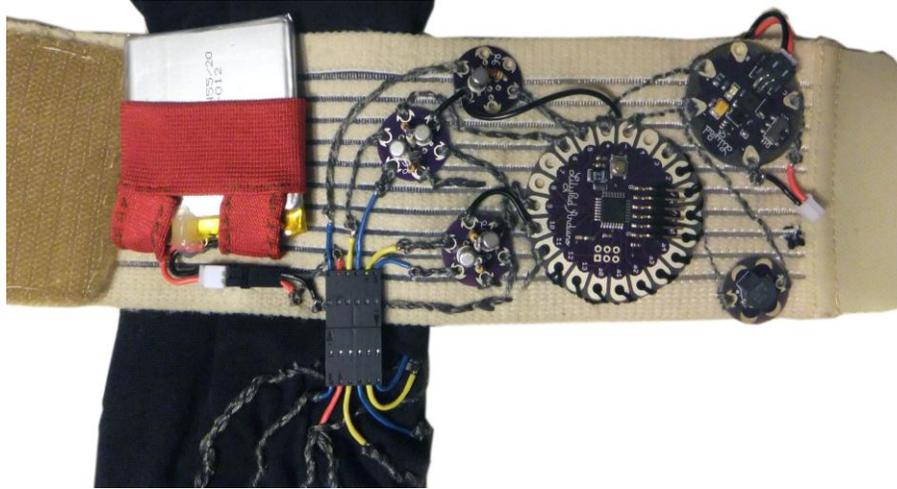
Cholewiak and Collins's study results showed that the localization accuracy of vibration stimuli is the highest at the wrist and close to the elbow compared to other sites along the forearm (Section 2.3). Therefore, four vibration motors were sewed equally distributed around the wrist circumference, whereas the other 4 were sewed close to the elbow. Conductive threads and copper

wire connected the terminals of each elbow motor to its aligned wrist motor's terminals and created a parallel circuit configuration. In order to provide the same vibration intensity at the wrist motor and the elbow motor simultaneously (for the *line* vibration stimuli), the author short circuited the on-board resistor of the LilyPad Vibe Board at the wrist to compensate for the extra resistance from the linking conductive threads. The circuit diagram for each motor pair is shown in Figure 3.3.



**Figure 3.3: Circuit diagram for each motor pair (one close to the elbow and one at the wrist). Dashed circles indicate the on-board components of the LilyPad Vibe Board. The  $1k\Omega$  resistor and transistor are the components for a custom motor control circuit to activate the motor with low-current microcontroller output. The switch is for generating different types of vibration cues.**

The armband consists of a LilyPad Arduino microcontroller, custom control circuits for the microcontroller and vibration motors, two lithium polymer batteries (3.7V, 2000mAh), and a safety switch for emergency shut-down (Figure 3.4). The batteries came with a protection circuit that prevents the battery from over-charging and short-circuited. The control circuit board for the microcontroller is a LilyPad LiPower board, which included a step-up circuit that provides 5V to the microcontroller and a mechanical switch to cut the power supply to the microcontroller. Four output pins of the microcontroller each links to one of the motor control circuits. Each motor control circuit includes a transistor and a  $1k\Omega$  resistor to drive the vibration motors from the low-current microcontroller output, as shown in Figure 3.3. The armband connects to the sleeve via custom connectors. Electronic components were connected and sewed onto the device using conductive threads and copper wires.



**Figure 3.4:** A close-up picture of the control armband. LilyPad Arduino is the largest circular board on the armband. One lithium polymer battery (fixed in a red band) is shown in the picture while the other one is behind the armband and is connected to the LilyPad LiPower board (top right). The safety switch is on the LilyPad LiPower board. Three smaller circular circuit boards contain the control circuits for the vibration motors. A buzzer is shown on the control armband (bottom right), but it was not used in this study. The Bluetooth module is not shown in this photo.

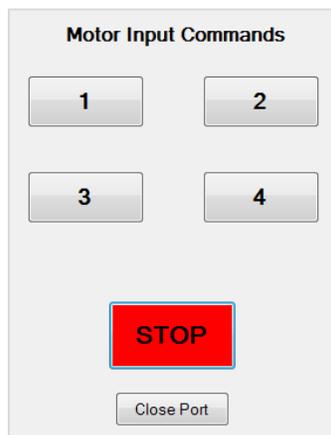
As mentioned earlier in the section, the motors close to the elbow were wired in parallel with their aligned wrist motors. In order to provide *point* vibration stimuli around the elbow, i.e., activating the elbow motors independently, the author sewed four sockets of sew-able plastic snaps close to the terminal at the wrist motor to create an open circuit. By snapping studs of metal snaps onto the plastic sockets, the paired vibration motors can be activated simultaneously and create *line* vibration stimuli.

Since the resistance of each motor circuit is dependent on the type of vibration stimuli and the total length of sewed conductive threads, activating the *line* and the *point* vibration required two different programs that specified different output levels for the microcontroller's output pins. The different output levels were calibrated values that created the same vibration intensity and frequency for all motors.

### 3.3.3 Control Software Interface

Figure 3.5 shows the developed software interface that sends commands to the wearable device and logs the commands and their corresponding timestamps simultaneously. The buttons labeled with numbers 1 to 4 control four different output pins on the LilyPad Arduino

microcontroller for motor activation. Clicking on those buttons changes the output voltage of the corresponding pin to high for 5 seconds and creates an entry in the command log. Clicking on the emergency “STOP” button turns all output pins on the microcontroller to low.



**Figure 3.5: The control software interface for Study I. Buttons labeled with 1-4 are used to activate different paired or single motors. The “Stop” button turns all output pins of the microcontroller on the sleeve to low. The “Close Port” button closes the Bluetooth connection between the PC and the sleeve.**

### 3.4 Study Procedures

Each study session started with the experimenter introducing the study to the subject and asking the subject to sign a written consent form. After the subject provided written consent, the experimenter introduced the motion tracking technology and the wearable device to the subject and asked the subject to sit on a chair right in front of the tracking camera., with upper arms relaxed, elbows bent at 90° with the forearms and hands in their neutral position.

Then, the experimenter helped the subject to put on the wearable device by first sliding the sleeve up the subject’s non-dominant arm and adjusting the motor locations. The motors should face top (+Y-direction), bottom (−Y-direction), left (−X-direction), and right (+X-direction) when the subject had his/her upper arms relaxed, elbows bent at 90° with the forearms and hands in their neutral position. An elastic wrist band secured the motors around the wrist. The experimenter then wrapped the armband around the subject’s upper arm. After making sure that the user was comfortable with the device, the experimenter connected the connector between the sleeve and the armband, plugged in the batteries, and then powered on the wearable device.

For each subject, there were two test sessions in randomized order for investigating the subject's motion response and reaction time to *point* and *line* vibration stimuli, respectively. Each test session included 10 trials that randomly activated the different motors on the wearable device. Before the first session, the experimenter asked the subject to hold onto the Move controller using his/her non-dominant hand and made sure that the subject was comfortable with the vibration cues by applying a few stimuli. The experimenter then started the motion tracking system to record the position data of the controller.

Subjects started each trial from their initial position: trunk upright, upper arms relaxed, elbows bent at 90° with the forearms and hands in their neutral position. Each trial included activation of a motor at a random location, the subjects' movements in response to the stimulus, and return of the subjects' hand to its initial position. Throughout the entire movement, subjects were required to press and hold onto a button on the controller for reaction time calculation.

For each trial, the experimenter asked the subjects to move only in one of the four directions (up, down, left, and right) that they thought the vibration cues were instructing them to do. The subjects also self-reported their confidence level (CL) using a 5-point Likert scale (Figure 3.6) regarding the statement: "*the vibration pattern was clear in indicating the movement direction*". The CL score gave an indication of users' perceived clarity of the designed vibrotactile instructional cues.

In between the two test sessions, the experimenter loaded the program for the second test session to the microcontroller and modified the mechanical snap switch on the sleeve to create different types of vibrotactile feedback.

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**Figure 3.6: A 5-point Likert Scale for subjects' self-reported confidence level. The answer indicates the subjects' perceived clarity of the directional vibration cues.**

At the end of both test sessions and after the experimenter removed the wearable device from the subject's arm, the subject filled out a post-test questionnaire and a demographics form. Both data collection forms are presented in Appendix B. The post-test questionnaire focused on the subject's experiences with the two types of vibration stimuli and the usability of the wearable device.

### 3.5 Data Analysis

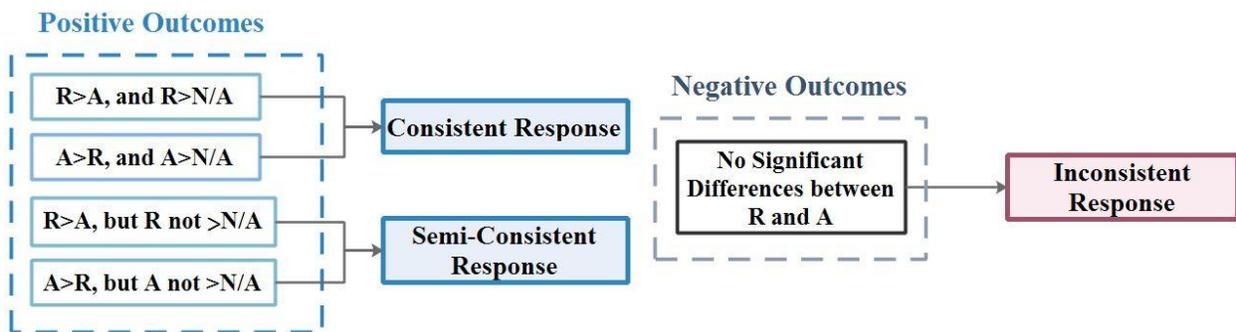
Collected data included time series of position data, button click status of the Move controller, command log of the vibration motor, users' self-reported CL of each trial, and post-test questionnaire answers. This analysis used the calculated reaction time and subjects' motion response for each trial. The reaction time for each trial was the difference between the timestamp of motor activation command and the timestamp when the subject clicked on the controller button. The motor activation command and the movement direction recorded by the system determined the subject's motion response for each trial.

Specifically, the subject's motion response in each test trial could be one of the following: (1) an *attractive* response, i.e., the subject moved towards the vibration stimuli, (2) a *repulsive* response, i.e., the subject moved away from the vibration stimuli, or (3) a *not appropriate* response (N/A), i.e., the subject moved in a direction that is neither towards nor away from the stimulus; for example, the subject moved sideways when the motor facing upward vibrated. Any N/A responses were assumed to be due to confusion, and the other two responses were *valid responses*.

The analysis first examined the percentages of the trials that the subjects perceived as clear in directional indication ("perceived clarity of the vibrotactile cues"), i.e., the percentages of the trials rated with a CL score of 4 or 5, and the percentages of valid responses among those trials. Since subjects were free to move in any direction as a response, these percentages give an indication of the feasibility of using vibrotactile cues as a motion guidance regime as well as the within-subject variability in subjects' intuitive response to vibration stimuli.

Each subject might exhibit responses from all three motion response types. Therefore, in order to determine an intuitive response for each subject, two one-sample two-tail t-tests between proportions [79] were tested using the percentages of each motion response. Specifically, since valid responses were of interest, the percentages between *attractive* and *repulsive* responses were first compared. The null hypothesis was that there was no significant difference in the percentages of the trials where subjects moved towards and away from the vibrotactile stimuli. The response with a significantly higher percentage, if any, was then compared to the percentage of the N/A response. The significance level was adjusted using the Bonferroni correction.

The author defined three consistency levels for each subject's motion response based on the results of the abovementioned two t-tests. Figure 3.7 presents all possible outcomes from these two sequenced t-tests. The three levels were (in the desired sequence): *consistent* response, *semi-consistent* response, and *inconsistent* response. Subjects possessed a *consistent* response when the percentage of their *attractive* or *repulsive* response was significantly higher than the percentages of the other two response groups. Subjects demonstrated a *semi-consistent* response when there were significant differences between the valid responses (the *attractive* and *repulsive* response) but not between the dominant valid response and the N/A response. Subjects showed an *inconsistent response* when there were no significant differences between their *attractive* and *repulsive* response. For all positive outcomes listed in Figure 3.7, the response on the left side of the greater-than sign refers to the response that has a significantly higher percentage than the response on the right side of the sign.



**Figure 3.7:** Defined categorical outcomes from performing two sequenced one sample t-tests on the percentages of the three motion responses for each subject. The greater-than sign indicates a significant difference between the two comparing variables, and the one to the left is the one with significantly higher percentage. For positive outcomes, the left most response in each box is the intuitive response of the subject. Definitions: R = repulsive response; A=attractive response; N/A = not appropriate response.

In order to test the hypothesis that the *line* vibrotactile stimuli are better in motion guidance than the *point* vibrotactile stimuli, the author compared the results from the two vibration stimuli sessions using the consistency level in subjects' motion response and the reaction time. This analysis compared the reaction time using a two-tail paired t-test. The analysis also included an extended McNemar's test to check if there were any differences between the level of consistency in subjects' motion response and the two vibration stimuli. McNemar's test is a statistical test that compares the proportions of correlated nominal data.

The post-test questionnaire included two parts: Part A on users' preference and perception of the two types of vibrotactile stimuli, and Part B on the usability of the wearable device, with one open-ended question on system improvements.

Statements in Part A of the post-test questionnaire were: **A1.** you know which direction to move based on the vibration type, **A2.** you are confident that you are moving in the correct direction, and **A3.** which type of vibration would you prefer to use for motion guidance? For the first two statements, subjects were asked to circle one number from a 5-point Likert scale that best represented their thoughts on the statement regarding each type of vibration stimuli. Question A3 required the subjects to pick either the *line* or *point* type of vibration as their answer.

Statements in Part B of the post-test questionnaire were: **B1.** the device constrained your movement, **B2.** the device is light-weighted and compact, **B3.** the device material is comfortable, **B4.** you feel unsafe wearing the device, **B5.** it is simple to put on the device, and **B6.** you would use this device for arm movement motion guidance. A few open-ended questions in Part B were: **B7.** are there improvements that can be made to this wearable device?, **B8.** do you have any concerns about this wearable device?, and **B9.** are there any other suggestions?

Statements B1-B6 were to examine the underlying belief of: "*the wearable device is well-designed and can be worn while performing arm movement*". The subjects answered each statement on a 5-point Likert scale. The answers to the negative-phrased statements (B1 and B4) were swapped around the neutral value 3, i.e., 2 to 4, 1 to 5, and vice versa. An independent t-test tested the differences between the average value of the six statements and the neutral response, i.e., a score of 3. This analysis used Cronbach's Alpha test to determine the internal consistency of the six questions. An alpha value above 0.7 is reliable [80], whereas a value below 0.5 is not acceptable [81], and a value between 0.5-0.7 is poor and questionable [81].

## 3.6 Results

This section presents the results of the data analysis outlined in Section 3.5. Section 3.6.1 discusses subjects' perceived clarity of the vibrotactile cues. Section 3.6.2 details the results of each subject's consistency level in motion response. Section 3.6.3 compares the performance between the two vibrotactile stimuli. Section 3.6.4 presents the results of post-test questionnaire on user preference in the type of vibrotactile stimuli and the usability of the wearable device.

### 3.6.1 Perceived Clarity of the Designed Vibrotactile Cues

Subjects’ perceived clarity of the vibrotactile cues gives an indication of the feasibility in using the designed vibrotactile cues in directional guidance. Table 3.1 lists the percentages of the trials that were perceived by the subjects as clear directional cues, i.e., a CL score of 4 or 5, for the two types of vibrotactile stimuli, and the percentages of valid responses among those trials. Table 3.1 also includes the overall averaged percentages of both clear instructional cues and valid responses, calculated using the collected data from both the *line* vibration stimuli session and *point* vibration stimuli session.

**Table 3.1: Percentages of the trials that were perceived by the subjects as clear directional cues and the percentages of valid responses among those trials. Definition: CL = confidence level; 4+ refers to a score of 4 or 5 on a 5-point Likert scale.**

Vibration Stimuli	CL Score of 4+	Valid Responses (with CL Score of 4+)
<i>Line</i>	53.8%	80.4%
<i>Point</i>	54.8%	82.6%
<b>Average %</b>	<b>54.3%</b>	<b>81.5%</b>

### 3.6.2 Vibration Response to Vibrotactile Cues

Table 3.2 lists the percentages of the subjects who showed *attractive* or *repulsive* response as their intuitive response, under the three consistency levels, regardless of the type of vibration stimuli. Based on the definition of *inconsistent* response, i.e., there were no significant differences between the *attractive* and *repulsive* response, the corresponding cell contents in Table 3.2 are listed as “not appropriate”. The overall percentages, i.e., the sum of the percentages of the two intuitive responses, of the three consistency levels are also listed in Table 3.2.

**Table 3.2: Percentages of different intuitive response (*attractive* or *repulsive*) in each consistency level category. The overall percentage of *inconsistent* response was 9.52%, and it was not categorized as an *attractive* nor *repulsive* response, so the corresponding cell contents are listed as not appropriate (N/A).**

Intuitive Response	Consistent Response	Semi-Consistent Response	Inconsistent Response
<i>Attractive</i>	28.6 %	38.1 %	N/A
<i>Repulsive</i>	19.1 %	4.76 %	N/A
<b>Overall Data</b>	<b>47.6 %</b>	<b>42.9 %</b>	<b>9.52 %</b>

In order to investigate if most subjects preferred using one motion response to vibrotactile cues over the other, three one-sample two-tail t-tests between proportions were conducted. The t-tests tested the percentages of the *attractive* and *repulsive* response for the *consistent* level, *semi-consistent* level, and the combined *consistent* and *semi-consistent* levels. The significance level was adjusted using Bonferroni corrections to 0.017. Higher percentages of subjects showed an attractive response to vibrotactile cues, with significance found in the *semi-consistent* level ( $t(20) = 2.71, p = 0.013$ ), but not in either the *consistent* level ( $t(20) = 0.636, p = 0.532$ ) or the sum of the percentages of the *consistent* and *semi-consistent* levels ( $t(20) = 2.26, p = 0.036$ ).

### 3.6.3 Comparison between *Line* and *Point* Vibration Cue Patterns

This section presents the comparisons between the two vibrotactile stimuli in terms of the consistency level in motion response and the reaction time. The author used the same statistical analysis detailed in Section 3.6.2 to determine the consistency of each subject’s movement response for the *line* and *point* vibration stimuli. The results are detailed below.

#### Consistency in Vibration Response

The numbers of subjects that showed different consistency levels for the *point* and *line* vibration test sessions are tabulated in Table 3.3, along with the calculated percentages in parentheses. The analysis used the data of *point* vibration test session alone, *line* vibration test session alone, and overall test session (combining both *line* and *point* stimuli data). Using the extended McNemar’s test, there was no significant evidence ( $\chi^2 = 1.53, p = 0.675$ ) to reject the null hypothesis that there was no difference between the two types of vibration stimuli in terms of the consistency levels.

**Table 3.3: The number of subjects and their corresponding consistency levels for the *point* and *line* vibration test sessions and the overall test session. Numbers in parentheses are the calculated percentages.**

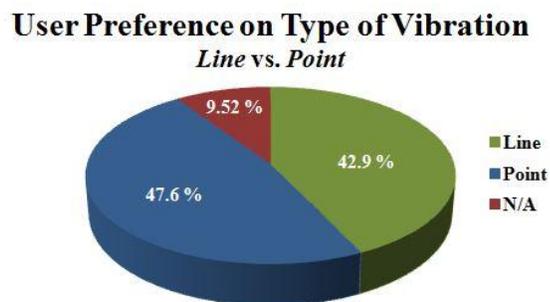
	<i>Consistent Response</i>	<i>Semi-Consistent Response</i>	<i>Inconsistent Response</i>
<i>Point</i>	4 (19.1 %)	11 (52.4 %)	6 (28.6 %)
<i>Line</i>	2 (9.52 %)	13 (61.9 %)	6 (28.6 %)
<b>Overall</b>	<b>10 (47.6 %)</b>	<b>9 (42.9 %)</b>	<b>2 (9.52 %)</b>

## Reaction Time

The average reaction time was  $2.04 \pm 0.840$  seconds for *line* vibration stimuli and  $1.81 \pm 0.800$  seconds for *point* vibration stimuli. A two-tailed paired t-test failed to show any significant differences between the users' reaction time when applying the two different vibration stimuli ( $t(20) = 1.30, p = 0.209$ ).

### 3.6.4 Post-Test Questionnaire Results

Post-test questionnaire analysis reported the modal value of any single Likert-formatted item for each subject group. Based on the questionnaire data, all subjects reported that they knew in which direction to move when they received the two types of vibration stimuli (mode: 4 for both). Subjects were also confident in their movement directions when receiving the *point* vibration stimuli (mode: 4) but felt neither confident nor unconfident for the *line* vibration stimuli (mode: 3). Figure 3.8 shows that slightly more subjects preferred the *point* vibration stimuli ( $t(20) = 0.227, p=0.822$ ).



**Figure 3.8:** User preference on *line* or *point* type of vibration. N/A refers to no preference.

For the wearable device design, subjects agreed that they would use this device for arm movement guidance (mode: 4). In other words, the subjects thought the device was a well-designed wearable device that can be worn while performing arm movements. The average score from statements B1-B6 was tested against the neutral response, i.e., a mean of 3, using an independent t-test ( $t(20) = 9.94, p < 0.001$ ). The Cronbach's Alpha for this analysis was calculated to be 0.568, which failed to achieve the commonly used 0.700 standard but was not unacceptable. This low alpha value may be a result of low number of questions or poor correlations between questions [82].

A total of 19 subjects provided useful comments on potential improvements of the wearable device. Some common suggestions among the subjects were: change motor locations for better distinguishability of the vibrations (14.3%); improve alignment of the wrist and elbow paired motors when using the *line* type of vibration (9.5%); hide the electronics (9.5%); increase vibration intensity (9.5%); accommodate different arm sizes (9.5%). In addition, though there were no questions that asked about the positive aspects of this study, a few subjects stated that the wearable device was compact, light, and comfortable (14.3%).

### 3.7 Discussion

When not given specific instructions, about half of the subjects naturally reacted to vibration stimuli in an inconsistent way, i.e., the motion response of each subject was a combination of *attractive*, *repulsive*, and *not appropriate* response (Section 3.6.2). This result indicates that there is a high variability within each subject's motion response, which was different than the results from Spelmezan et al.'s study [53], where they reported subjects responded to vibrotactile stimuli (on their torsos or legs) with either an *attractive* or *repulsive* response. Even when the subjects perceived the vibrotactile cues as clear in directional guidance, their responses were still not entirely consistent throughout the test session; i.e., they did not move consistently towards or away from the vibrotactile stimuli. Specifically, the results showed that the subjects rated an average of 54.3% of the total test trials as clear directional cues, and among those trials, an average of 81.5% were valid responses (Section 3.6.1). The fact that only slightly over half of the total trials were user-rated as clear directional cues implies that subjects were unfamiliar with such cues and found it hard to interpret them.

In addition to high within-subject variation in the motion response to vibrotactile cues, results from investigating hypothesis H1.2 showed a high between-subjects variability in subjects' intuitive responses. Though most of the subjects showed an *attractive* response to vibrotactile cues, significant differences between the *attractive* and *repulsive* responses were only found in the subjects who showed a *semi-consistent* response (Section 3.6.2). This variability in subjects' intuitive responses was possibly due to the open-ended nature of the task given to the subjects, i.e., any movement direction is correct. This finding was consistent with the observation in

Spelmezan et al.'s study [53], where they found that half of their subjects naturally reacted to vibrotactile cues using the *attractive* response, while the other half used the *repulsive* response.

Although the two types of vibration stimuli did not show significant differences in either the consistency level in motion response or the reaction time, the performances from *point* vibration trials were persistently higher than the ones from *line* vibration trials (Section 3.6.3). To illustrate, both *point* and *line* vibration stimuli led to the same amount of *inconsistent* response (28.6%), while *point* vibration induced a higher percentage of *consistent* response compared to *line* vibration (19.1% vs. 9.52%). Moreover, *point* vibration yielded a faster response time compared to the *line* vibration, which was reasonable because Gallace et al. showed a trend where the reaction time increases with the increase in the number of activated vibration motors [83]. This result is advantageous especially for real-time motion training. Furthermore, results from the post-test questionnaire also suggest a slightly higher user preference to *point* vibration over *line* vibration, as well as a higher confidence in using the *point* vibration for directional guidance (Section 3.6.4).

### 3.7.1 Study Limitations

The inability to reject the three hypotheses (H1.1, H1.2, and H1.3) was due to the unexpected high within-subject variability in subjects' motion response to vibration cues and high between-subjects variability in subjects' intuitive responses. Due to these high variations shown in the data, the author decided to set the motion response for each subject based on individual preferences in the next study. This decision still addressed the study goal of minimizing any learning effects that may affect the outcome measures of the next study.

There were also many limitations related to the wearable device. Firstly, the wearable device only accommodates a certain range of arm sizes to ensure all conductive threads were tight and well-connected throughout the entire path. Secondly, the alignment between the wrist and elbow motor mainly depends on the shape of subjects' brachioradialis, since those two motor sets of four were sewed equally distributed around the sleeve circumferences and the forearm was not perfectly circular. This motor arrangement might have caused confusion for some subjects. Lastly, the vibration intensity was not set at its maximum intensity for this study for *point* vibration in order to create the same vibration intensity as the *line* vibration.

### 3.8 Summary & Conclusion

This chapter investigated the existence, if any, of a single, intuitive motion response to vibrotactile cues in arm motion guidance. This chapter also examined if more subjects preferred one motion response over the other and if different vibration motor configurations could facilitate a more consistent motion response and/or a faster reaction time. The goal of this study was to determine which type of vibrotactile cues and motion response to implement for the next study that investigates motor adaptation using vibrotactile cues. A total of 21 subjects participated in this study. By using two sequenced t-tests, the author determined each subject's intuitive response and the level of consistency of the subject's motion response.

The results from this study form the basis for the next study. The high variances in motion response both within- and between-subjects conclude the need of creating a customized vibration response training session for each subject in Study II. Specifically, the training session should include both trials to observe subjects' motion response and trials to reinforce their own motion response.

Since the *point* vibration stimuli demonstrated more advantages for real-time motion training, i.e., a larger number of consistent responses, a faster reaction time, and a higher user preference, compared to the *line* vibration stimuli, Study II will only utilize *point* vibration stimuli. Moreover, the decision of using *point* stimuli for Study II provides two additional advantages: it solves the alignment problem for the *line* stimuli, and it also allows implementation of vibration with higher intensity. These addressed the second and third hardware limitations detailed in Section 3.7.1. These results provide valuable suggestions for any researcher who wishes to implement real-time vibrotactile cues for upper-arm motion training.

In addition, in response to the concerns addressed by the subjects, two outer layers will be added to the wearable device for use in Study II to cover the armband and the sleeve. Moreover, since vibrotactile cues will be used to direct 1-dimensional movements in Study II (detailed in Chapter 4), only two of the motors on the sleeve will be used, which allows the subjects to better distinguish the vibration locations.

## Chapter 4

# Study II: Effect of Vibrotactile Training in Bilateral Reaching

In Chapter 3, the results of Study I showed high variability in subjects' motion response to vibrotactile cues regardless of actuator configuration. Therefore, in order to avoid training users with an unintuitive response to vibrotactile stimuli, researchers should account for the perceptual differences among individuals.

This chapter<sup>2</sup> presents the results of a study to assess the potential for utilizing real-time corrective vibrotactile feedback as a training regime for simultaneous, bilateral arm movements. This study incorporated the suggestions from Study I by observing individuals' motion response to vibration cues prior to feedback training, and utilizing a single-point vibration feedback for faster responses. To accomplish the study goal, the author developed an integrated gaming system that tracked users' hand movements and provided real-time vibrotactile feedback for two-arm, forward-reaching motion guidance.

Section 4.1 gives an overview of the study design and study tasks. Section 4.2 discusses the recruitment process and demographics of the subjects. Section 4.3 introduces the system components, as well as the flow of the software algorithm implemented in the integrated system. Section 4.4 lays out the study procedures step-by-step. Section 4.5 to Section 4.7 detail the data analysis approach, results, and discussion of this study.

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## 4.1 Study Design

This study investigated if vibrotactile feedback can be used in: (1) training able-bodied people to perform an asymmetric bilateral motion, and (2) training stroke survivors to improve their bilateral reaching symmetry. This study thus recruited subjects from three populations: healthy younger adults, healthy older adults (45 years old and older), and stroke survivors. This study assigned different bilateral reaching tasks in the transverse plane to the healthy and stroke subject groups based on their proprioception capability.

To measure motor adaptation resulting from vibrotactile training, the subjects who participated in this study performed multiple bilateral reaches in a sitting posture while playing a computer target game. Specifically, the author developed and integrated a computer program that allowed subjects to control the cursor using a motion tracking technology and bilateral hand movements, a computer game that increased subjects' engagements, and a wearable vibrotactile feedback device. The system and the control algorithm are detailed in Section 4.3.

For each bilateral reach, all subjects started at a consistent initial position: trunk upright against the chair's backrest, upper arms relaxed, elbows and knees bent at  $90^\circ$  with the forearms and hands in their neutral position, and hands shoulder-width apart (with no support from their thighs). This initial position had the effect of placing both forearms parallel to the sagittal plane.

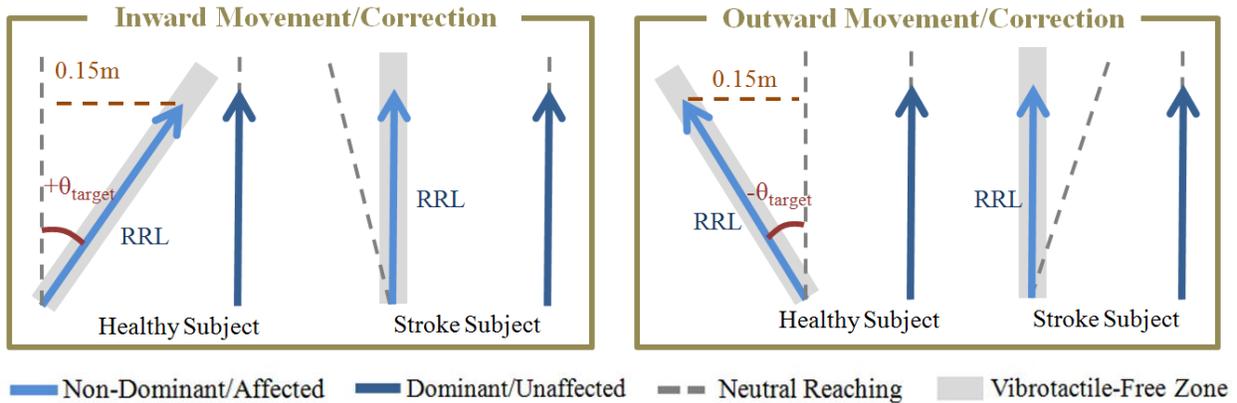
Trunk movement is a common compensatory strategy in arm reaching for stroke survivors with limited arm movement [84] and also for healthy subjects performing a natural reaching task [85]. In order to minimize the impact of trunk compensation on the outcome measures of this study, the Required Reaching Length (RRL) was set to a percentage of the subjects' maximum effective reach, i.e., 85% for healthy subjects and 50% for stroke subjects [84], [85]. The maximum effective reach was the distance travelled by the subjects' hand from its initial position to the maximum reach at waist level.

Both healthy and stroke subjects received instructional vibrotactile cues from a custom wearable device, worn on their non-dominant or affected arm, respectively, to follow a specific path in the transverse plane. In particular, this study assumed that, without the aid of visual feedback, healthy subjects could perform vertically symmetric bimanual motions in the transverse plane – i.e., maintaining a constant hand separation distance throughout the reaching motion and having a neutral reaching angle of 0 degrees – while stroke subjects could not.

Neutral reaching angle was the angle between the subjects' reaching motion path and their initial forearm orientation.

Therefore, this study trained healthy subjects to move their non-dominant hand along a line at a horizontal angle  $+\theta_{\text{target}}$  or  $-\theta_{\text{target}}$ , defined in Equation (1), from their initial forearm orientation in a bilateral reaching motion using two test sessions. A value of 0.15 meters was selected in Equation (1) to create a condition that required noticeable horizontal movements. For stroke subjects, this study trained them to perform symmetric bilateral reaches in one test session that required them to adjust their affected hand's neutral reaching angle (either result in an inward or outward correction<sup>3</sup>). The desired task paths are illustrated in Figure 4.1. The two training sessions for the healthy subjects captured both inward and outward movement in a randomized sequence in order to facilitate possible comparisons between the healthy subjects and stroke subjects.

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



**Figure 4.1: Task trajectory visualization in the transverse plane for Study II for both healthy and stroke subjects. Figures in the left box show the inward movement/correction, whereas figures in the right box illustrate the outward movement/correction. Light and dark blue lines refer to the task trajectory of the non-dominant/affected hand and dominant/unaffected hand, respectively. Dashed gray lines illustrate the assumed trajectory of their neutral “symmetric” reaching motion. Areas shaded with light gray indicate the vibrotactile-free zone of the non-dominant/affected hand. A positive angle sign refers to a clock-wise rotation, and vice versa. RRL is the required reaching length.**

<sup>3</sup> The movement names ‘inward’ and ‘outward’ refer to the ND/A arm’s movement with respect to midline. These were used to describe the multi-joint arm reaching movements that include joint motions such as shoulder flexion, shoulder abduction/adduction, elbow flexion/extension, and wrist flexion/extension.

In all study cases, the system's algorithm used the position of the subject's dominant/unaffected (D/UA) hand as a reference to generate a task path for the non-dominant/affected (ND/A) hand to follow. Based on the subject's neutral reaching patterns, the system set a vibrotactile-free zone around the desired task path in the horizontal direction (detailed in Section 4.4.2). In other words, the subjects received no vibrations as long as their ND/A hand stayed within the vibrotactile-free zone during training.

## 4.2 Study Participants

Subjects were recruited through advertisements in community centers, senior housings, stroke recovery support groups, and local rehabilitation clinics, as well as on social media, the author's lab websites, and the UBC campus. In addition, some subjects, who participated in past studies in the author's lab, were recruited based on their written consent to be contacted for future studies. The advertising materials are presented in Appendix A.

Prior to participating in the study, potential volunteers answered a set of screening questions over the phone for the experimenter to assess their eligibility based on the inclusion/exclusion criteria (Table 4.1). The study took place in a usability laboratory on UBC Point Grey campus in a controlled environment with consistent study setups. Study protocol was approved by the UBC Clinical Research Ethics Board (H14-02115). The list of screening questions and consent forms are presented in Appendix A.

A total of 32 participants: 10 older adults (P1-P10, male: 6, female: 4), 10 healthy younger adults (P11-P20, male: 7, female: 3), and 12 hemiparetic stroke survivors (S1-S12, male: 11, female: 1) were recruited for this study. Five male stroke subjects' datasets were excluded from the analysis: S8 and S9 did not have enough function to reach forward with their affected hand without trunk compensation; S10 did not complete the tasks due to the inability of his affected side to stay stretched long enough to click on the final target; S11 did not complete the tasks due to frustration; S12 could not sense vibrotactile cues while he was moving.

The age of the participants ranged from 19 to 28 ( $23.0 \pm 2.5$ ) for healthy younger adults, from 47 to 88 ( $62.6 \pm 13.5$ ) for healthy older adults, and from 25 to 77 ( $59.7 \pm 17.3$ ) for stroke subjects. The mean time post-stroke of the stroke subjects was 32 months. All subjects except S5 had

experience using computers, whereas 7/10 younger adults, 2/10 older adults, and 1/7 stroke survivors had experience with game consoles.

**Table 4.1: Inclusion/exclusion criteria for all subjects.**

<b>Inclusion Criteria</b>		<b>Exclusion Criteria</b>
<u>Healthy Subjects</u>	<u>Stroke Subjects</u>	<u>All Subjects</u>
<ul style="list-style-type: none"> <li>• 19 years old or older (or a UBC student of 17 or older).</li> <li>• Healthy without any movement disorders.</li> <li>• Have never had a stroke or significant brain injury.</li> <li>• Ability to maintain a sitting posture for 1 hour with minimum supervision and no support from arm rests.</li> <li>• Ability to stretch both of their arms fully around their waist height.</li> </ul>	<ul style="list-style-type: none"> <li>• 19 years old or older.</li> <li>• Hemiplegia as a result of a cerebral stroke</li> <li>• Stroke occurred at least 6 months prior to the study.</li> <li>• Ability to maintain a sitting posture for 1 hour with minimum supervision and no support from arm rests.</li> <li>• Ability to stretch their affected hand forward without help from their trunk or the other hand for at least 15cm around their waist height against gravity.</li> <li>• Ability to stretch their unaffected arm fully around their waist height.</li> </ul>	<ul style="list-style-type: none"> <li>• Uncorrected visual impairment.</li> <li>• Surgery in the hands or arms in the past 6 months.</li> <li>• Orthopedic or neurological conditions that affect arm movement.</li> <li>• Shoulder pain, partial dislocation, or subluxation.</li> </ul>

All healthy subjects except P14 were right-handed. For the stroke subjects, three subjects had left hemisphere damage with right hemiparesis, three subjects had right hemisphere damage with left hemiparesis, and one subject (S7) had a hemorrhagic stroke in the brain stem, which affected both sides of his body. However, a professional occupational therapist judged the proprioception and movement of his right arm to be normal, and he still presented weakness on his left side. Moreover, this subject could not fully extend both arms due to a mild to moderate kyphosis in his thoracic spine, but since the study tasks were tailored to each subject’s motor ability, S7 was still included in this study.

Clinical assessment scores (Fugl-Meyer upper-extremity portion and Modified Ashworth score) for all stroke subjects are listed in Table 4.2, along with the motion correction group that they belonged to as a result of their neutral reaching angle. Both clinical assessments are further detailed in Section 4.4.1.

## 4.3 Experimental System

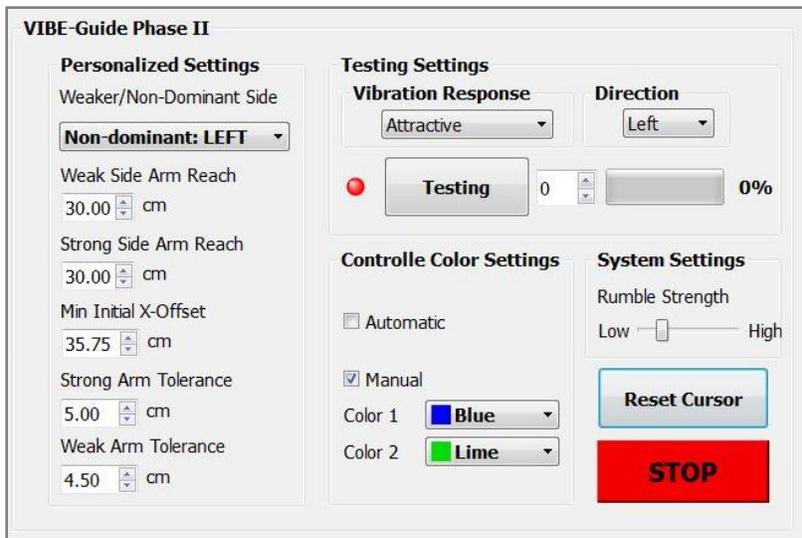
The author developed a system that provides real-time vibrotactile feedback for synchronized bimanual reaching motion. The following sections introduce the system components as follows: a control software interface (Section 4.3.1), a motion tracking system and a wearable device (Section 4.3.2), and a computer target game (Section 4.3.3). Section 4.3.4 and Section 4.3.5 detail the design of the feedback system and the system’s control algorithm, respectively. A PC running Windows® 7 handled all communication between the system components and recorded all movement data.

**Table 4.2: Stroke subjects’ clinical scores and their categorized movement correction group, i.e., if the vibrotactile training trained them to perform an inward or outward correction based on their neutral reach angles. Clinical assessments are detailed in Section 4.4.1. Definitions: UE-FM: Fugl-Meyer score (upper-extremity portion); MAS: Modified Ashworth score.**

	UE-FM	MAS biceps	MAS triceps	MAS wrist extensor	MAS wrist flexor	Movement Correction
S1	39	0	0	0	0	Outward
S2	60	1	2	0	2	Inward
S3	25	2	2	3	2	Inward
S4	64	0	0	0	0	Outward
S5	42	0	2	2	0	Inward
S6	55	2	0	0	0	Outward
S7	52	3	2	1	2	Outward

### 4.3.1 Software Control Interface

A graphical user interface (Figure 4.2) developed in Qt Creator (an integrated development environment) managed data entry of the required parameters to the system’s control and logging software. The parameters included: the type of subject, the ND/A side, the individual’s reaching characteristics, type of vibration responses, and type of movement for healthy subjects (i.e., inward or outward movement). The “Reset Cursor” button resets the computer cursor to its initial location on screen before the start of each reaching motion, and the “STOP” button stops all running processes and turns off all vibration motors as a safety control.



**Figure 4.2: The software control interface for Study II.**

### 4.3.2 Motion Tracking Technology and Vibrotactile Feedback Device

This study employed the same wearable feedback device and motion tracking camera used in Study I (described in Section 3.3.1 and Section 3.3.2), and used two modified controllers to record bimanual hand motions (Figure 4.3). Specifically, we redesigned the cases for the PlayStation® Move controllers and 3D printed them for better ergonomics for the stroke population, e.g., fewer buttons and a tapered base. The design utilized fewer buttons to reduce the user’s cognitive load, and a tapered base design facilitated easier insertion of the controllers into hands with high muscle tone [86]. The white buttons on either controller provide the functionality of a primary (left-button) mouse-click on the PC controlling the experimental task. The red buttons were disabled in this study.



**Figure 4.3: Two adapted controllers and a PlayStation Eye camera.**

This study only used two vibration motors, one located close to the inner elbow and one close to the outer elbow, to apply single-point vibrations to guide subjects’ ND/A hand in the

horizontal direction. Figure 4.4 shows a trainee wearing the feedback device and holding two adapted controllers. The sphere colours of the two controllers were set to blue and green to create a consistent test condition in recording position data.



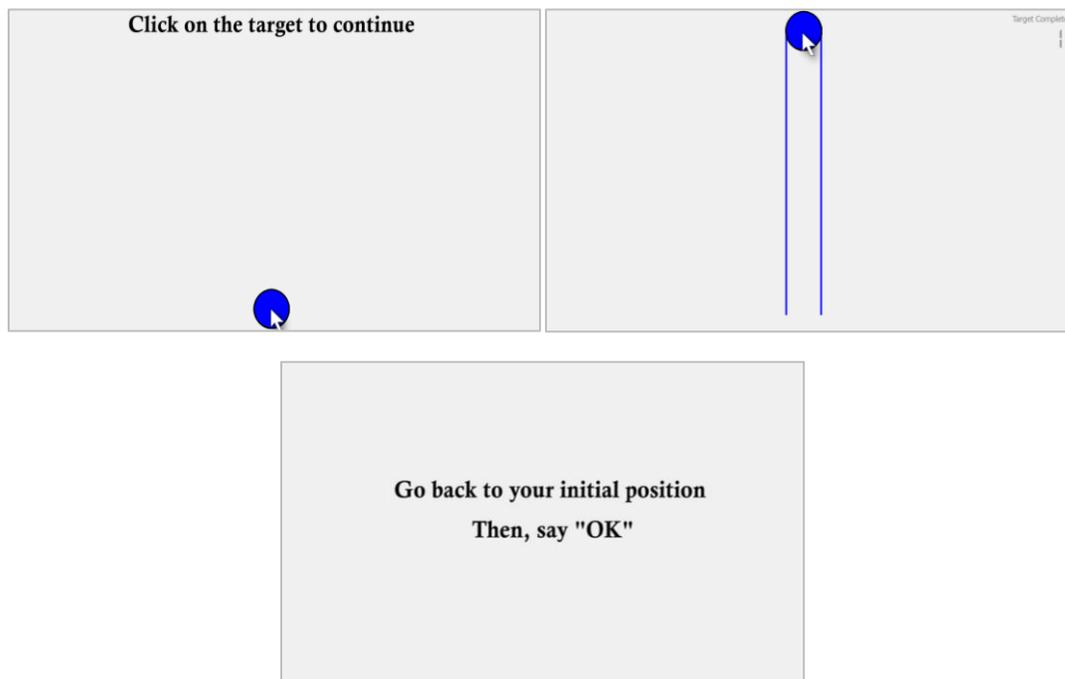
**Figure 4.4:** A trainee wearing the vibrotactile feedback device while holding the controllers. The outer layer of the sleeve is not shown in this figure. This study uses only the vibration motor facing the readers (outer elbow) and the motor facing the opposite direction (inner elbow, not shown in the picture).

### 4.3.3 Target Game

The author developed a computer target game (Figure 4.5) to improve user engagement. Subjects completed a trial by holding the controllers at their initial position, clicking on the start target, reaching bimanually forward, and then clicking on the final target. After the subjects clicked on the final target, the cursor disappeared and a message appeared on the screen instructing the subjects to return to their initial position (Figure 4.5, bottom). This instruction kept the test conditions consistent between trials and subjects. Then, the experimenter reset the cursor to the center of the next start target and instructed the subject to control the cursor within the adjacent parallel boundaries (the two vertical lines in Figure 4.5, top right) while reaching bimanually forward.

In this game, the colour blue referred to “*correct/ready for the next step*” while yellow indicated “*not yet ready*”. For example, if the subject kept the cursor within the sideways boundaries, the two vertical lines turned blue; however, if the subject moved the cursor outside the boundaries, the lines turned yellow. In addition, when vibrotactile feedback was enabled, if the subject had not yet reached the final target with the cursor, or failed to have both hands at the correct relative positions in space, the final target stayed yellow to indicate that the user had not

yet completed the trial. The final target would only turn blue and disappear after clicking when both conditions (reaching the target with correct relative hand positions) were met.



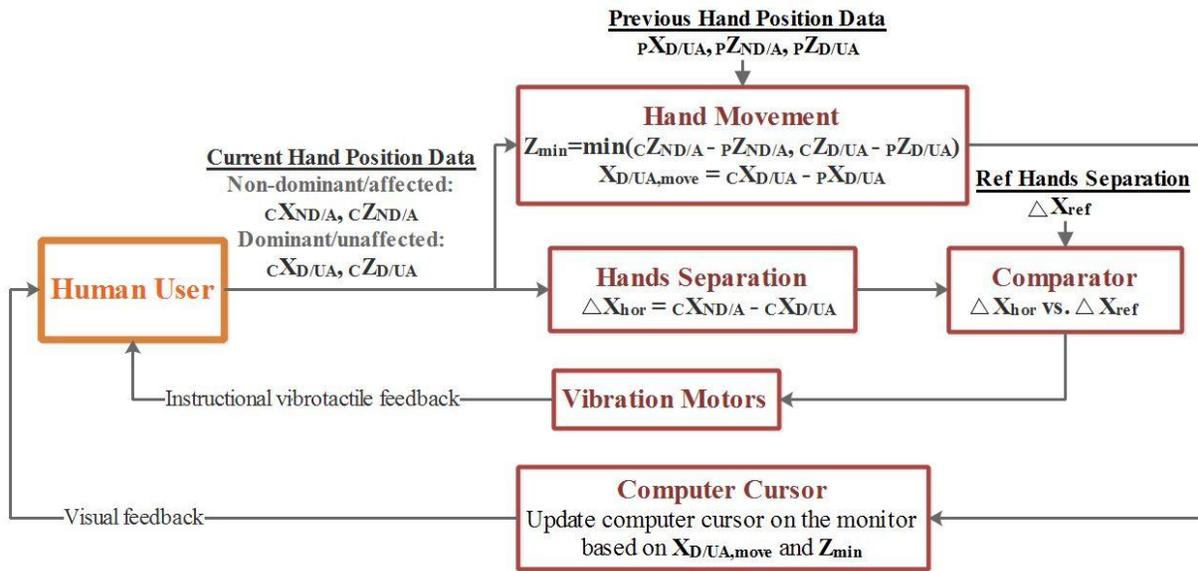
**Figure 4.5:** Screenshots of the target game. Top left figure shows the initial instruction and the start target; top right figure shows the sideways boundaries and the final target; the bottom figure shows the between-trial instruction. A click on the start target indicates the beginning of a trial, and the between trial instruction shows up after successful completion of a trial.

#### 4.3.4 Human-in-the-Loop Feedback System

In each training session, subjects held two controllers and performed bilateral reaching motions while the motion tracking system provided time series of 3D position data to a computer algorithm. The computer algorithm controlled the application of: (1) instructional vibrotactile feedback on the horizontal movement of the ND/A hand, and (2) visual feedback of the cursor movement based on the bilateral reaching forward motion. In addition, the target game provided visual feedback by changing its graphics as described in the previous section.

Figure 4.6 provides an overview of the designed human-in-the-loop feedback system based on the position data. In every iteration, the computer algorithm accepts the latest X- and Z- position data, the hand position data from the previous iteration, and the reference horizontal distance between the two hands, i.e., the horizontal hand separation recorded at the beginning of

each test trial. The algorithm then calculates suitable vibrotactile and visual feedback to present to the users. Specifically, the wearable sleeve provides instructional vibrotactile feedback based on the differences between the current and reference hands separation, and the computer updates the cursor location vertically and horizontally based on the minimum depth movement of the two hands and sideways movement of the D/UA hand, respectively. The author designed such horizontal mapping to constrain the feedback of the ND/A hand's horizontal position to only vibrotactile feedback.

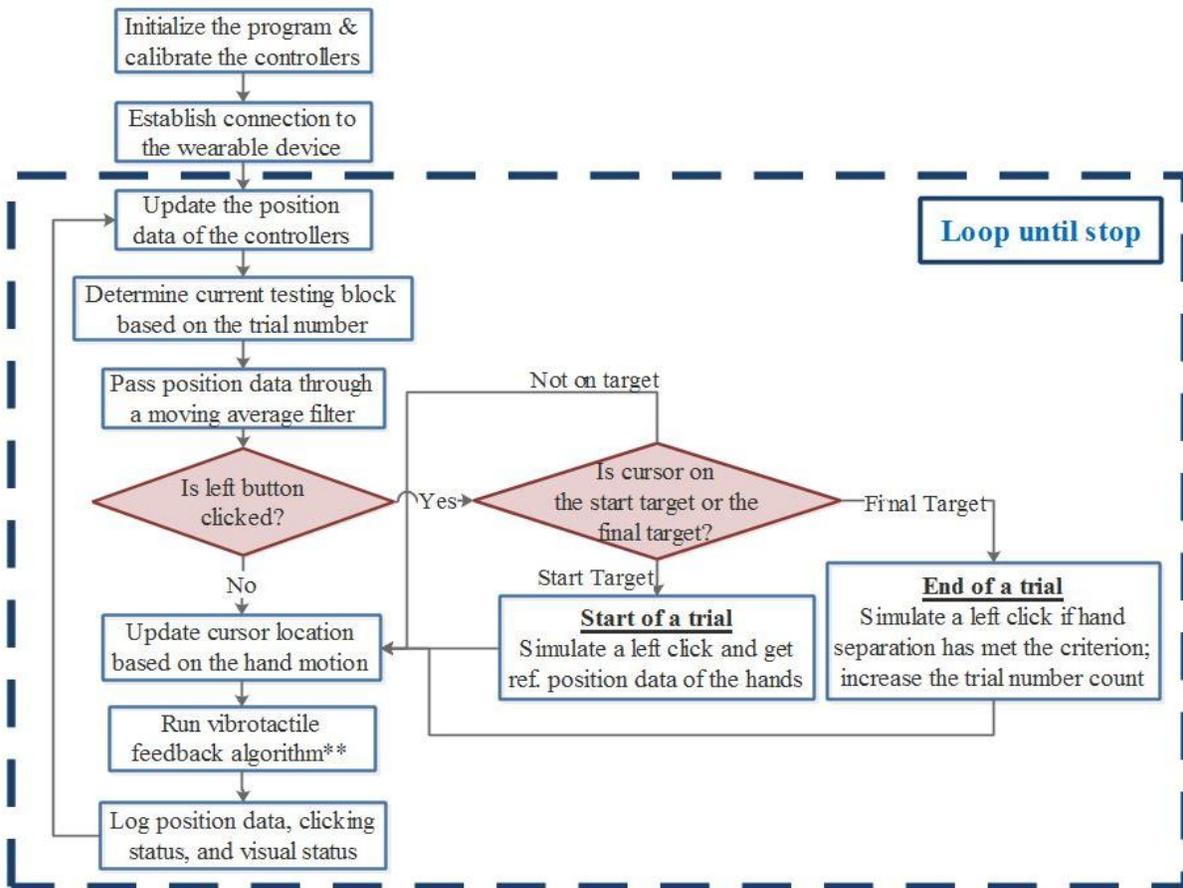


**Figure 4.6: Human-in-the-loop feedback system design based on the input position data.** In addition to current hand position data, the system requires two more inputs to complete the feedback loop: the previous hand position data and the reference hands separation, defined as the horizontal distance between the two hands recorded at the beginning of each trial. The precripts ‘C’ and ‘P’ refer to the current and previous position data, respectively. The subscript ND/A refers to non-dominant/affected hand for the healthy and stroke subjects, respectively. Similarly, the subscript D/UA refers to dominant/unaffected hand.

### 4.3.5 Code Architecture: Motion Tracking & Feedback Control

The main program algorithm handles the position data updates from the controllers and provides desired visual feedback on game progress and vibrotactile feedback on motion training. The author programmed the microcontroller on the wearable device to activate different motors, and programmed the target game to change game graphics, e.g., the colour of the final target, upon receiving commands.

Figure 4.7 shows the process flow of the main program as well as two decision nodes. After initialization, the program updates the controller data until the experimenter stops the program. After updating the controller positions, this program first determines if vibrotactile feedback should be enabled for the current trial (see Section 4.4.2 for detailed test design). The program then passed the position data through a 5-term symmetric moving average filter, as shown in Equation (2) [87], to reduce system noise. A 5-term moving average gives a value of 2 to the window length parameter  $q$ . The author set the moving average weight parameters  $W_i$  as  $1/8$  for  $i = \pm q$  and  $1/4$  on the others. The algorithm then proceeds to check the button click status and applies any visual or vibrotactile feedback if required. Then, the data are stored in a comma-separated values (CSV) file.



**Figure 4.7: Motion tracking and feedback algorithm. For the process labeled \*\*, please refer to Figure 4.8. This process is skipped for test trials with vibrotactile feedback disabled.**

Figure 4.8 details the logic flow of the vibrotactile feedback algorithm, referenced in Figure 4.7. The algorithm processes different case scenarios to send out commands to both the

vibration device and target game. The commands are based on whether the current horizontal distance between hands has met the ideal hand separation criterion.

$$M_{x,t} = \sum_{i=-q}^q W_i X_{t+i}, \quad q < t < N - q \quad (2)$$

where  $M_{x,t}$  is the moving average value calculated from  $X_t$  and the weights  $W_i$  are the moving average weight parameters, where  $\sum W_i = 1$   
 $X_t$  is a time series  
 $q$  is the window length parameter. A moving average filter with odd-numbered terms has a window length of  $2q+1$ . Hence,  $q=2$  for a 5-term moving average filter.

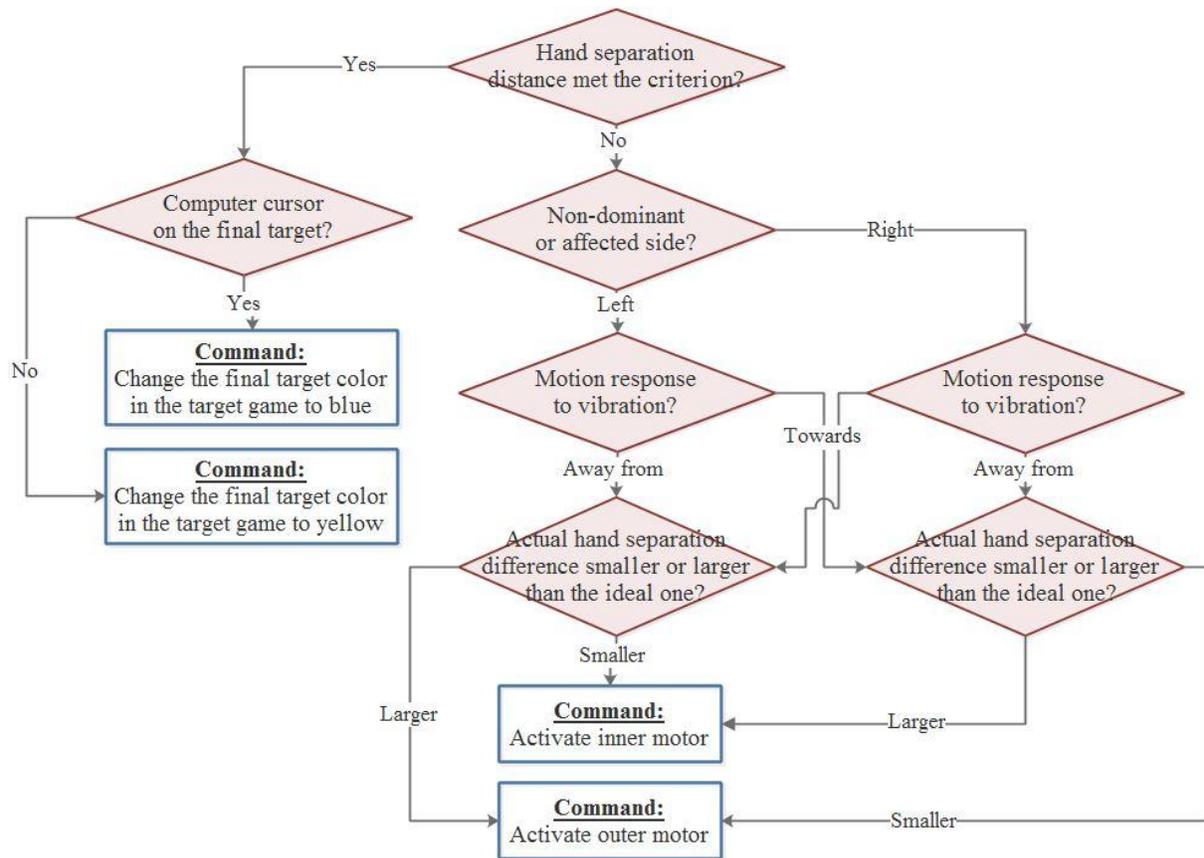
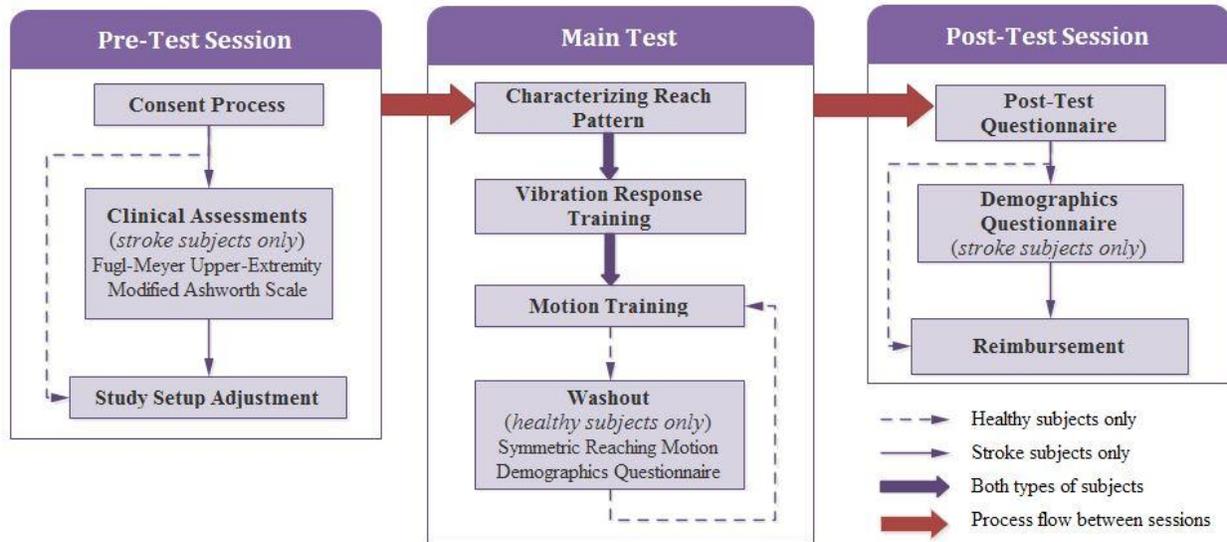


Figure 4.8: A flowchart of the vibrotactile feedback algorithm.

## 4.4 Study Procedures

Study II consisted of three parts: the pre-test session, main test session, and post-test session. Figure 4.9 gives an overview of the experiment process for both healthy and stroke subjects. The following sections explain each session in detail.



**Figure 4.9: Overview of the Study II experimental process. All arrows were followed only once for stroke subjects, whereas for healthy subjects, the dashed arrow between the *Motion Training* and *Washout* under the *Main Test* was followed twice since the study tasks required them to perform both inward and outward movements.**

#### 4.4.1 Pre-Test Session

The pre-test session consisted of: the consent process, clinical assessments, and study setup for stroke subjects, and only the consent process and study setup for healthy subjects. The pre-test session gave an overview to the subjects of the study and equipment.

##### Consent Process

At the beginning of each study session, the experimenter explained the study and the consent forms in detail, which included study-related information, contact information, and subjects' right to withdraw from the study at any time. All subjects gave written consent before proceeding to the study.

##### Clinical Assessments (Stroke Subjects Only)

A professional occupational therapist administered the upper-extremity portion of Fugl-Meyer assessment (UE-FM) and Modified Ashworth Scale (MAS) for characterizing each stroke subject. The UE-FM is a common measure in stroke rehabilitation assessments [88], and it has been shown to have high intra-tester, inter-rater, and test-retest reliability [23], [89], [90]. The UE-FM consists of ordinal scales that measure reflex activities, motion observation, wrist and hand function, and coordination. A complete assessment question can be found in [91]. There are

33 assessment items in total, with a possible score of 0 (unable to perform), 1 (able to perform in part), or 2 (able to perform). The total score is 66: a score below 20 indicates a severe impairment; a score between 21 and 50 refers to a moderate impairment; a score above 51 indicates a mild impairment [92]. There are three additional sections that measure sensation, passive joint motion, and joint pain. For this study, the sections assessing coordination, sensation, reflex, and motion observation are of the highest relevance.

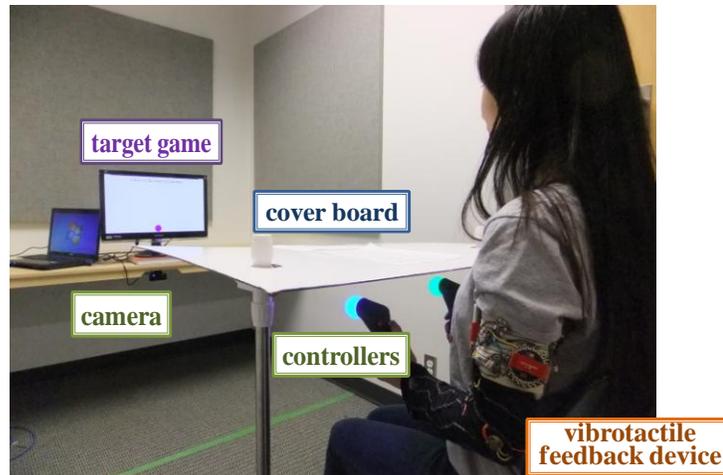
The Modified Ashworth Scale grades spasticity based on resistance measurement during passive soft-tissue stretching [93]. It has been shown to have high inter-rater and intra-rater reliability [94]. Considering the level of relevance of arm muscles to the reaching task for this study, our collaborated therapist suggested using biceps, triceps, wrist flexor, and wrist extensor as the target measurements. The scale ranges from 0 to 4, indicating a normal muscle tone (0) to a high muscle tone (4).

## **Study Setup**

To create a controlled environment for the optical motion tracking system, the experimenter carried out all experiments in the same room with minimal light disturbances. Figure 4.10 shows the experimental setup. The subject sat on a chair with fixed translational and minimum rotational movement that was 1.5m away from the camera, facing a computer monitor on the table and a mounted tracking camera on the bottom of the table.

Prior to the main test session, the experimenter adjusted the experimental setup to create a consistent test condition for all subjects. The experimenter adjusted the chair height to allow a 90° bend at the subject's knees, and adjusted the top of the computer monitor to match the eye level of the subject for minimal physical fatigue [95]. Then, the experimenter placed a rack with a cover board on top in front of the subject. The edge of the cover board was approximately one centimeter away from the subject's chest to constrain potential trunk movements. This cover board occluded the visual of the reaching space so that the only visual feedback of the reaching motion available to the subject was through the monitor. Additionally, the cover board created a low-light condition for the reaching space, which increased contrasts of the data imaging and thus improved the accuracy of the optical tracking system.

Lastly, the experimenter introduced the wearable device to the subject, put the device on the subject, and explained the upcoming test session.



**Figure 4.10: Experimental setup for Study II. A trainee holds the two adapted controllers and focuses on the target game displayed on a computer monitor. The trainee is wearing the vibrotactile feedback device on her left arm. The motion tracking camera is taped underneath the table. The cover board is placed on top of the reaching space and in front of the trainee.**

#### **4.4.2 Main Test Session**

The main test session consisted of three parts (Part I - III) where subjects interacted partially and/or fully with the system. Healthy subjects repeated the motor adaptation training (Part III) twice – one for inward and one for outward movement – with a washout period (Part IV) in between. The sequence of inward and outward movement for healthy subjects was randomized to avoid order effects [96]. For all subjects, the experimenter first measured each subject's reach pattern for creating an individualized study task path, and observed and trained each subject's vibration response. The experimenter made sure that the subject was comfortable with playing the target game and reacting to vibration cues before starting the motor adaptation training.

##### **Part I: Characterizing Reach Pattern (*Pre-Training Performance*)**

This study characterized each subject's bilateral reaching pattern to create a personalized target game and task path for Part III. The experimenter first asked the subject to perform 5 reaches by holding the controllers at the initial position, clicking on the controller button, reaching symmetrically forward to the maximum limit at waist level, and then clicking on the controller button. Each subject's maximum effective reach was the minimum average reaching length of the two hands. Then, the experimenter set the RRL in the game, explained the game to the subject,

and allowed the subject to practice up to 5 game trials. The distance between the center of the start target and the final target was mapped to the RRL.

After the practice trials, the experimenter calculated each subject's bimanual coordination characteristic  $char_{bim}$  using Equation (3) and the straightness of the D/UA hand  $char_{D/UA}$  using Equation (4) from 30 new trials. The 30 trials represented the *pre-training* performance of each subject and were later used in the data analysis. The instruction for the subjects was to reach forward with both of their hands at a comfortable speed. The experimenter computed both measures based on the ND/A hand and D/UA hand's horizontal positions ( $X_{ND/A}$  and  $X_{D/UA}$ ) at the initial depth position  $z_0$  and the final depth position  $z_f$ .

$$char_{bim}(i) = \left( |X_{ND/A} - X_{D/UA}|_{z_f} - |X_{ND/A} - X_{D/UA}|_{z_0} \right)_i, i = trial \# \quad (3)$$

$$char_{D/UA}(i) = \left( X_{D/UA}_{z_f} - X_{D/UA}_{z_0} \right)_i, i = trial \# \quad (4)$$

## Part II: Vibration Response Training

Implementing this training session was a suggestion from Study I to address the high within-subject variability in motion responses to vibrotactile cues. As mentioned in previous chapters, subjects may possess an *attractive* response (moving towards the stimuli) or a *repulsive* response (moving away from the stimuli) to vibrotactile cues. To avoid training subjects who possessed an *attractive* response with a *repulsive* response and vice versa, the experimenter first observed each subject's reaction to vibrotactile stimuli. In particular, the experimenter applied a single-point vibration stimulus through the vibrotactile feedback device and asked the subject to perform a symmetrical reaching motion with the subject's ND/A hand moving either inward or outward.

After six trials<sup>4</sup>, the experimenter then informed the subject of his/her intuitive response to vibrotactile stimuli. Stroke subject S2 was the only subject who had no preference in movement directions to vibrotactile stimuli, so he was instructed to move towards the vibration stimuli. After knowing the subject's intuitive response to vibrotactile stimuli, the experimenter put an instruction sheet on the cover board. The instruction sheet explicitly indicated how the subject should react to vibrations. Table 4.3 shows the instruction for subjects whose ND/A side was

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<sup>4</sup> The author decided on the number of trials based on Study I data. In Study I, analyzing each subject's intuitive response to vibrotactile cues using the initial six trials gave the same results as using all ten trials. Note that this analysis used data from both *consistent* and *semi-consistent* responses.

right/left and consistently moved towards/away from vibration cues, respectively. Then, the experimenter reinforced the subject's motion response using their intuitive response, and trained the subject until the subject performed 5 consecutive movements with the correct response.

**Table 4.3: Movement instructions to vibrotactile stimuli for subjects whose right/left side was their non-dominant or affected side and who showed an attractive/repulsive response to vibrotactile cues, respectively.**

<b>Vibrating Motor</b>	<b>Movement Direction</b>
Inner	LEFT
Outer	RIGHT

### Part III: Motion Training

In order to examine the effect of vibration feedback in motor adaptation, each subject played a personalized target game. The experimenter used characteristics  $char_{D/UA}$  and  $char_{bim}$  to calculate the cursor's horizontal sensitivity and the relative position tolerance  $tol_{bim}$  (for setting a vibration-free zone around the ND/A hand's task trajectory), respectively.

The study design was that the position change of the D/UA hand controlled the sideways movement of the computer cursor. Thus, the system set the cursor movement between the two vertical lines (Figure 4.5, right) equal to the range of the 95% prediction interval (PI) of  $char_{D/UA}$ , i.e.,  $2 \times 1.96$  times the standard deviation of  $char_{D/UA}$ . This setting allowed subjects to only focus on the horizontal movement of their ND/A hand. The system set the  $tol_{bim}$  to be half of the range of the 95% PI of  $char_{bim}$ , as shown in Equation (5), i.e., a 50% improvement on the precision of their original bimanual coordination. Subjects received vibration stimuli whenever their ND/A hand went outside of their position tolerance  $tol_{bim}$ .

$$tol_{bim} = \pm \frac{1.96}{2} \times \sigma_{char_{bim}}, \sigma = \text{standard deviation (SD)} \quad (5)$$

There were five testing blocks for the motion training protocol. Table 4.4 lists the number of trials required for each subject in different testing stages. The first few trials in the familiarization and baseline stage allowed the subjects to regain familiarization with the target game again after the completion of vibration response training. Both healthy and stroke subjects were instructed to perform symmetric bimanual reaching motions in the familiarization and baseline stages. The vibration training block had the vibration feedback enabled for guiding the subjects' ND/A hand along the study task path (Figure 4.1). All subjects were not aware of the

actual study task path. The instruction for the healthy subjects was to have their dominant hand reaching straight forward and their non-dominant hand following the instructional vibration cues to discover the task path. The instruction for the stroke subjects was to perform symmetric bimanual reaching movements. Moreover, as mentioned in Section 4.1 and Section 4.3.4, the cursor movements were the only visual feedback available for the subjects, showing the D/UA hand's horizontal movement and both hands' movement along the Z-axis, and vibrotactile cues were the only feedback for the subjects' ND/A hand movement. The vibration training block was separated into three stages for data analysis purposes. The three stages were: early-adaptation (EA), mid-adaptation (MA), and late-adaptation (LA) stage. Post-training trials provided data of the stroke subjects to observe any significant improvements in motion symmetry post-training.

Corrective vibrotactile cues were only enabled in the vibration training and the after-effect trials. The after-effect trials had vibration disabled for one out of five consecutive trials (namely, the catch trials) in order to observe if the subjects would retain their performance from vibration training. The trial numbers of the catch trials were randomized, but the trial numbers were the same for inward movements/corrections and for outward movement/corrections to allow between-subjects comparison.

There were scheduled resting periods for all subjects: younger adults had two resting periods, each around 30 seconds; older adults had three resting periods, each around 1-2 minutes; stroke subjects had four resting periods, each around 1-5 minutes. In addition to the scheduled resting breaks, subjects could request to rest at any time during the data collection. The time duration of each rest was flexible for older adults and stroke subjects due to different physical demands.

**Table 4.4: Number of trials required for each testing stage in sequence. This table also indicates the activation of vibrotactile feedback in each testing stage. EA, MA, and LA refer to early-, mid-, and late- adaptation.**

Testing Blocks		Vibrotactile Feedback?	Younger Adults	Older Adults	Stroke Survivors
Familiarization		No	3	3	3
Baseline		No	5	5	5
Vibration Training	EA	Yes	5	5	5
	MA	Yes	<b>20</b>	<b>30</b>	<b>45</b>
	LA	Yes	5	5	5
After-Effect (catch trials)		Yes (no for catch trials)	25	25	25
Post-Training		No	<b>10</b>	<b>10</b>	<b>30</b>

## Part IV: Washout (Healthy Subjects Only)

In between the inward and outward training sessions for healthy subjects, there was a washout period to prevent any carryover effect [96]. After the first training session, the experimenter asked the subjects to perform five symmetric reaching forward motions and fill out a demographics form. Both actions took less than 5 minutes for all subjects; however, the subjects were instructed to rest until the total washout time reached 5 minutes.

### 4.4.3 Post-Test Session

After all subjects completed the main test, they filled out a post-test questionnaire regarding the study task, wearable device, and system usability. In addition, stroke subjects also filled out a demographics form (Appendix B). Part A of the questionnaire examined the difficulty level of the study tasks and evaluated the ease-of-use of each system component. The questions are listed in Table 4.5 for both types of subjects. There were two questions worded differently for healthy subjects and stroke subjects considering the differences in the study tasks (A3 & A4). Note that questions A5 and A6 for stroke subjects were relabeled to A6 and A5, respectively, to match to the question sequence for healthy subjects.

**Table 4.5: Questions in Part A of the post-test questionnaire. Questions A3 and A4 are phrased differently while others are the same.**

Healthy Subjects	Stroke Subjects
<b>A1.</b> It was easy to control the cursor	<b>A1.</b> It was easy to control the cursor
<b>A2.</b> It was difficult for me to reach the target.	<b>A2.</b> It was difficult for me to reach the target.
<b>A3a.</b> The vibration cues provided clear guidance for my hand to move to the specified locations.	<b>A3b.</b> The vibration cues corrected my movement to be more symmetric
<b>A4a.</b> I cannot feel the vibration on my forearm during the reaching task.	<b>A4b.</b> I can feel the vibration on my forearm during the reaching task.
<b>A5.</b> The controllers were easy to hold on to.	<b>A5.</b> The controllers were easy to hold on to.
<b>A6.</b> I felt tired after completing the session.	<b>A6.</b> I felt tired after completing the session.

Part B of the questionnaire was related to the wearable device and was intended to address the underlying belief that: “*the wearable device is well-designed and can be worn while performing arm movements*”:

- B1.** The wearable device constrained your movement.
- B2.** The wearable device is light-weighted and compact.

- B3.** The wearable device material is comfortable.
- B4.** You feel unsafe wearing the device.
- B5.** It is simple to put on the wearable device.

Part C of the questionnaire was adopted from the System Usability Scale (SUS) developed by Brooke [97]. The SUS scale is widely used in the human-computer interaction field to test system usability and has been proven to be able to detect differences at small sample sizes than other questionnaires [98]. Part D of the questionnaire asked for further comments regarding the study and the system. In particular, the questions were: **D1)** are there any improvements that can be made to the system components?, **D2&D3)** what is your favourite feature and least favourite feature of the system?, and **D4)** are there any other suggestions? The complete list of questions is presented in Appendix B.

The last part of the study involved reimbursing the subjects for their transportation costs as well as their time in participating in the study.

## **4.5 Data Analysis Approach**

This section details the data analysis approaches to examine the effect of vibrotactile training for healthy subjects and stroke subjects. The analyses focused on the subjects' performance change in the vibrotactile training test block and in the pre- and post-training test block. Custom-developed MATLAB<sup>TM</sup> scripts were used to process all the kinematics-related data and output the results to Microsoft® Excel.

Section 4.5.1 details the data processing procedures on the raw data, including segmentation, resampling, filtering, and calculation on performance metrics. Section 4.5.2 introduces the methods on investigating the vibrotactile training effect in the vibration training stage over trials and improvements post-training. Section 4.5.3 lists additional correlation tests based on stroke subjects' motor ability. Section 4.5.4 discusses the statistical tests used for post-test questionnaire results.

### **4.5.1 Post-Test Data Processing**

The system recorded data, such as position data, button click and visual status, trial number, etc., in CSV files at a sampling rate of  $74.9 \pm 5.34$  Hz. Custom MATLAB scripts read in all CSV

files from a user-specified folder, and then processed the files one by one. The script first identified the segments of different trials in each data file. Each segment then underwent calculations on time-related performance, interpolations, resampling, filtering, and calculations on trajectory-related performance.

The scripts implemented a low-pass filter to reduce noise with high frequency and retain the low-frequency arm movements. Given that the sampling rate of the tracking system was varying, in order to filter the data, the script linearly interpolated and resampled all data before filtering. This section provides the methods for the data interpolation, resampling, and filtering. Performance metrics are defined and detailed later in Section 4.6.2.

### **Interpolation & Resampling**

To address the high variation in the system's sampling frequency, the analysis script resampled all subjects' data using linear interpolation. To select the resampling frequency, the author calculated the mean frequency  $f_{avg}$  and standard deviation (SD)  $\sigma_f$  using each subject's data file with major outliers removed. Major outliers are the data that are above or below three times the interquartile range, i.e., the difference between the first and third quartile, adding to the third quartile and subtracting from the first quartile, respectively. The lower bound frequency  $f_{lower}$  was calculated using Equation (6) for each subject file. The minimum computed  $f_{lower}$  among all subject files, 62.8 Hz, was used as the resampling frequency. Using the MATLAB built-in function `resample()`, the MATLAB analysis script linearly interpolated and resampled all data to 62.8Hz.

$$f_{lower}(j) = f_{avg,j} - 1.96 \times \sigma_{f,j}, \quad j = \text{data file \# and } \sigma = SD \quad (6)$$

### **Filtering**

The analysis script used a low-pass, fourth-order Butterworth filter, a common approach in studies related to human arm motion post-stroke [99]–[100]. Butterworth filters hold a moderately high rate of attenuation beyond the cutoff frequency and the flattest possible passband magnitude response [101]. In other words, Butterworth filters do not alter the signals in the passband range. In order to determine a cutoff frequency for the filter, the author carried out residual analysis for all files [102]. A sample residual analysis is detailed in Appendix C. Residual analyses gave a maximum cutoff frequency of 6.2 Hz. Therefore, the analysis script

low-pass filtered all data at 6.2 Hz using a fourth-order zero-lag Butterworth filter using the MATLAB functions `butter()` and `filtfilt()`.

#### **4.5.2 Methods for Examining Vibrotactile Training Effects**

In order to investigate the effect of vibrotactile cues on bimanual motion training in both healthy and stroke populations, the analysis examined the ND/A hand's relative position trajectory change at four different testing stages, training effects during the vibration training stage, and improvements post-training. This section lists the approaches used in finding evidence of improvements resulted from vibrotactile training.

The remaining of this section is laid out as follows: firstly, the author discusses the methods to generate trajectory charts of the ND/A hand's relative position in the transverse plane. Secondly, the author defines five performance metrics and motor adaptation curves. Thirdly, the author introduces the methods for quantifying the training effects during the vibration training stage for all subjects, and for examining improvements post-training for stroke subjects. Lastly, the author discusses the data analysis methods for post-test questionnaire data.

##### **Position Trajectories in Four Testing Stages**

The author picked the data from four testing stages – baseline, early-adaptation, late-adaptation, and the catch trials – to visually demonstrate progressions of the ND/A hand's relative position trajectory over the test period. Plotting the differences between the X-position of the ND/A hand and the X-position of the D/UA hand at different reaching depth generated the trajectory of ND/A hand's relative position. The average trajectory of the five position datasets in each testing block represented each testing stage.

Given that position changes in the horizontal direction showed the effect of vibration training, segmented position data of each test trial were time-normalized and depth-normalized. Scaling each position dataset to [0, 1] using its reaching duration allowed resampling a fixed number of position data points. This approach allowed averaging across trajectories. Then, the author scaled the Z-position data to [0, 1] using the average depth positions of the first and last 0.5 seconds of each test trial.

## Performance Change during the Vibration Training Stage

To quantify adaptation in the vibration training stage, the author defined five performance metrics. The performance metrics include: RMS error, maximum deviation, reaching duration, index of curvature [84], and distance ratio. All metrics except distance ratio were normalized with respect to the RRL of each subject to facilitate comparison between individuals and examine the overall effects between groups. A MATLAB script was used to calculate and output the performance metrics associated with each test trial. The metrics are defined as follows:

### (1) Normalized RMS Error

RMS error is the square root of the sum of squared X-position deviations, i.e., the differences between the X-position data of the relative ND/A hand and the task path, divided by the number of data points. This metric is normalized by each subject's RRL, as defined in Equation (7). This metric sums up deviation error throughout the entire trajectory, and thus it is a good representation of the subject's overall trajectory performance.

$$\text{Normalized RMS} = \frac{1}{\text{RRL}} \sqrt{\frac{\sum_1^n (y_{ideal} - y_{actual})^2}{n}} \quad (7)$$

where  $y_{ideal}$  is the X-position data of the ideal trajectory  
 $y_{actual}$  is the recorded relative X-position data of the ND/A hand  
 $n$  is the data points of each trajectory.

### (2) Normalized Absolute Maximum Deviation

Absolute maximum deviation is referred to the magnitude of the maximum X-position deviation of subjects' ND/A hand from the ideal path, normalized by each subject's RRL. While RMS error calculates the accumulated error throughout the entire trajectory, the absolute maximum deviation refers to the largest deviation within the trajectory.

### (3) Normalized Reaching Duration

Reaching duration is the time difference between the time when the subjects clicked and left the start target, and the time when they clicked on the final target. Similar to previous metrics, calculated reaching duration was normalized with respect to each subject's RRL to facilitate between-subject comparison.

### (4) Index of Curvature & Distance Ratio

Index of curvature ( $IC_w$ ) for the ND/A hand is the total distance travelled by the ND/A hand

divided by each subject's RRL, as defined in Equation (8). An  $IC_w$  value larger than 1 indicates a longer hand trajectory with respect to the RRL. The distance ratio  $R_{dis}$  is the ratio of the distance travelled of the ND/A hand over the distance travelled of the D/UA hand, as defined in Equation (9). A  $R_{dis}$  value of 1 refers to a motion where the subjects moved both of their hands over the same 3D distance. An ideal bilateral motion is to have both  $IC_{ND/A}$  and  $R_{dis}$  close to 1, i.e., a perfectly synchronized motion that utilizes the shortest path.

$$IC_{ND/A} = \frac{\text{Distance Travelled}_{ND/A}}{RRL} \quad (8)$$

$$R_{dis} = \frac{\text{Distance Travelled}_{ND/A}}{\text{Distance Travelled}_{D/UA}} \quad (9)$$

Averaging the calculated performance metrics across subjects over the test trials in each group facilitated comparison of the overall performance in different subject groups and for different types of motion. Based on the definitions of the performance metrics, it was expected that all metrics would be higher at the beginning of the vibration training block and would gradually decrease – as subjects were still exploring the task path. Based on this expectation, the author performed correlation analyses between the metrics and trial number using the Spearman's Rank-Order Correlation test<sup>5</sup>. Furthermore, in the current motor learning literature, a decreasing exponential curve is a common fit for correlations between errors and time [39], [49], [50]. Celik et al. defined such fit as an *adaptation curve* (Equation (10)) [50]. Therefore, the analysis of this study included generating the adaptation curve for different subject groups and movement types by fitting the normalized RMS error and trial numbers using Equation (10).

The coefficients  $a$ ,  $b$ , and  $c$  for this fit represent the characteristics of learning. Specifically, the learning coefficient  $a$  defines the amount of learning,  $b$  defines the rate of learning, and  $c$  defines the steady-state performance, i.e., the converged value after practicing [50]. For example, a curve with small positive learning coefficients  $a$ ,  $b$ , and  $c$ , refers to a fast learning that achieves a small steady-state performance but with a small amount of learning. Calculating the learning

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<sup>5</sup> The Spearman's Rank-Order Correlation test measures the level of any monotonic association between two variables. The test outputs the significance of the correlation using  $p$ -values as well as the Spearman's correlation coefficient  $r_s$ . The coefficient has a range from  $-1$  to  $+1$  and gives an indication of the strength of the correlation between the two variables. For example, a negative  $r_s$  value refers to negative correlations, and vice versa. A larger  $r_s$  magnitude indicates a stronger correlation.

coefficients for different subject groups and movement types facilitated possible comparison between the groups.

$$y_{fit} = ae^{\frac{-x}{b}} + c \quad (10)$$

where  $y_{fit}$  is performance metric  
 $x$  is trial number  
 $a$ ,  $b$ , and  $c$  are the learning coefficients

Finally, to quantify the improvements over the vibration training period, paired t-tests (or its non-parametric version, the Wilcoxon Signed-Rank Test) were used to provide comparisons of the average performance data from the late-training stage to the early-training stage.

### **Improvements on End-Position Accuracy and Precision Post-Training**

This analysis used the pre- and post-training data from stroke subjects. The analysis investigated if bimanual coordination  $char_{bim}$  improved post-training, and if the affected hand characteristics  $char_A$  achieved a smaller horizontal deviation between its end position and its initial position, as defined in Equation (11). A positive finding indicates that stroke survivors are capable of building an internal motion model of their hands' end-position, and vice versa. A perfect end-position performance is when both characteristics are equal to zero, i.e., both the affected and unaffected hand reached the end position with zero deviation from the initial position.

Moreover, this analysis investigated both *accuracy* and *precision* of the motion characteristics. Accuracy examines how close the measured data values are with respect to the expected value  $\mu$ , and it can be calculated using Equation (12) by subtracting the expected value from the mean of each subject's measured dataset  $\bar{m}_j$ . The expected value was set to be 0 in this case to represent a perfectly straight symmetric motion. Precision indicates how close the measured data are to each other, and it can be calculated using Equation (13) by averaging the absolute deviations from  $\bar{m}$  for each data point in each subject's measured dataset.

$$char_A(i) = \left( X_{A_{z_f}} - X_{A_{z_0}} \right)_i \quad (11)$$

where  $X_A$  is the X-position data of the affected hand  
 $z_0$  and  $z_f$  is the initial and final depth position, respectively  
 $i$  is the trial number

$$Accuracy_j = \overline{m}_j - \mu, \quad \mu = \text{expected value}; j = \text{dataset \#} \quad (12)$$

$$Precision_j = \overline{abs(Measurement_i - \overline{m}_j)}, \quad i = \text{data points}; j = \text{dataset \#} \quad (13)$$

### 4.5.3 Additional Correlation Analyses for Stroke Subjects

To investigate whether improvements in motor performance are correlated to motor abilities of the stroke subjects, correlation analyses were conducted for all performance improvements (include accuracy and precision) of  $char_A$  and  $char_{bin}$ , and other factors, such as the collected UE-FM score, MAS score, age, etc. Since UE-FM measures a wide variety of motor functions, it is possible that subjects with lower UE-FM scores showed similar motor performances as the ones with higher UE-FM scores in this study. Hence, correlation analyses also included examining the performances versus scores of spasticity in different muscles for MAS and specific sections of UE-FM. Specifically, the author identified the following sections in UE-FM that are the most study-related: (1) section D that tests the subjects' coordination and speed when blindfolded (proprioception), (2) section H that assesses the subjects' ability to sense touch on the arm and small position change of the joints when blind-folded, (3) a combined score of section D and section H, and (4) section A on motion observation.

### 4.5.4 Post-Test Questionnaire Analysis

Post-test questionnaire analysis reported the modal result of any single Likert-formatted item for each subject group. Similar to Study I, the author used the Cronbach's Alpha test to check the internal consistency of the five wearable-related questions. This analysis also included the calculation of the SUS scores and compilation of subjects' comments to examine system usability.

## 4.6 Results & Discussion

This section presents the results from the data analyses outlined in the previous section. Section 4.6.1 shows sample position trajectory progressions over different testing stages for both types of movements (inward and outward motion). Section 4.6.2 examines the training effect during the vibration training stage. Section 4.6.3 presents the data analysis on the pre- and post-training motion characteristics of stroke subjects. Section 4.6.4 explores the correlations between individual stroke subject's performance improvements and clinical assessment scores.

Section 4.6.5 provides the compiled post-test questionnaire results. All statistical analyses used a significance threshold of  $p=0.05$ .

#### **4.6.1 Trajectories at Various Testing Stages**

The author chose four random subjects (P7, P17, S5, and S7) to visually show the changes in their average ND/A hand's relative position trajectory over four testing stages, i.e., baseline, early-adaptation, late-adaptation, and the catch trials, for the two types of movements. Sample charts for each subject are shown in Figure 4.11 and Figure 4.12 for inward and outward movement, respectively. For each chart, the author shifted the average trajectories to start at a common initial point. The range of the horizontal axis for all charts was 0.3 meters to allow easy comparisons.

The RRL for subjects P7, P17, S5, and S7 were 23, 21, 10, and 11 centimeters, respectively. As shown from those charts, the baseline trajectories of the healthy subjects were relatively straight, with the end position deviating an average of 1 centimeter from the start position. For S5 and S7, their end positions deviated, respectively, 4 and 9 centimeters away from and towards the midline of their body even when they performed shorter reaches. This observation confirms the previously-mentioned assumption that: healthy subjects are able to perform a symmetric motion without visuals of their hand movement, while stroke subjects are not.

Looking at all plots, as expected, the EA trajectories are longer and less straight compared to the ones in other testing stages – possibly because the subjects were still figuring out the set task paths. The trajectories for the late-adaptation and catch trials are similar to each other, with a maximum end-position difference of 6 centimeters and straighter/smooth trajectory compared to EA. The EA trajectory for P17 was close to the final task path – indicating that P17 had learned the task path within a short number of trials.

#### **4.6.2 Measure of Motor Adaptation in the Vibration Training Stage**

Section 4.6.1 showed that there were improvements of a few subjects' position trajectories over time, i.e., trajectory became smoother, straighter, and closer to the ideal task paths. This section details the correlation results of the five performance metrics, defined in Section 4.5.2, and presents the motor adaptation curve for different subject groups and motion types using

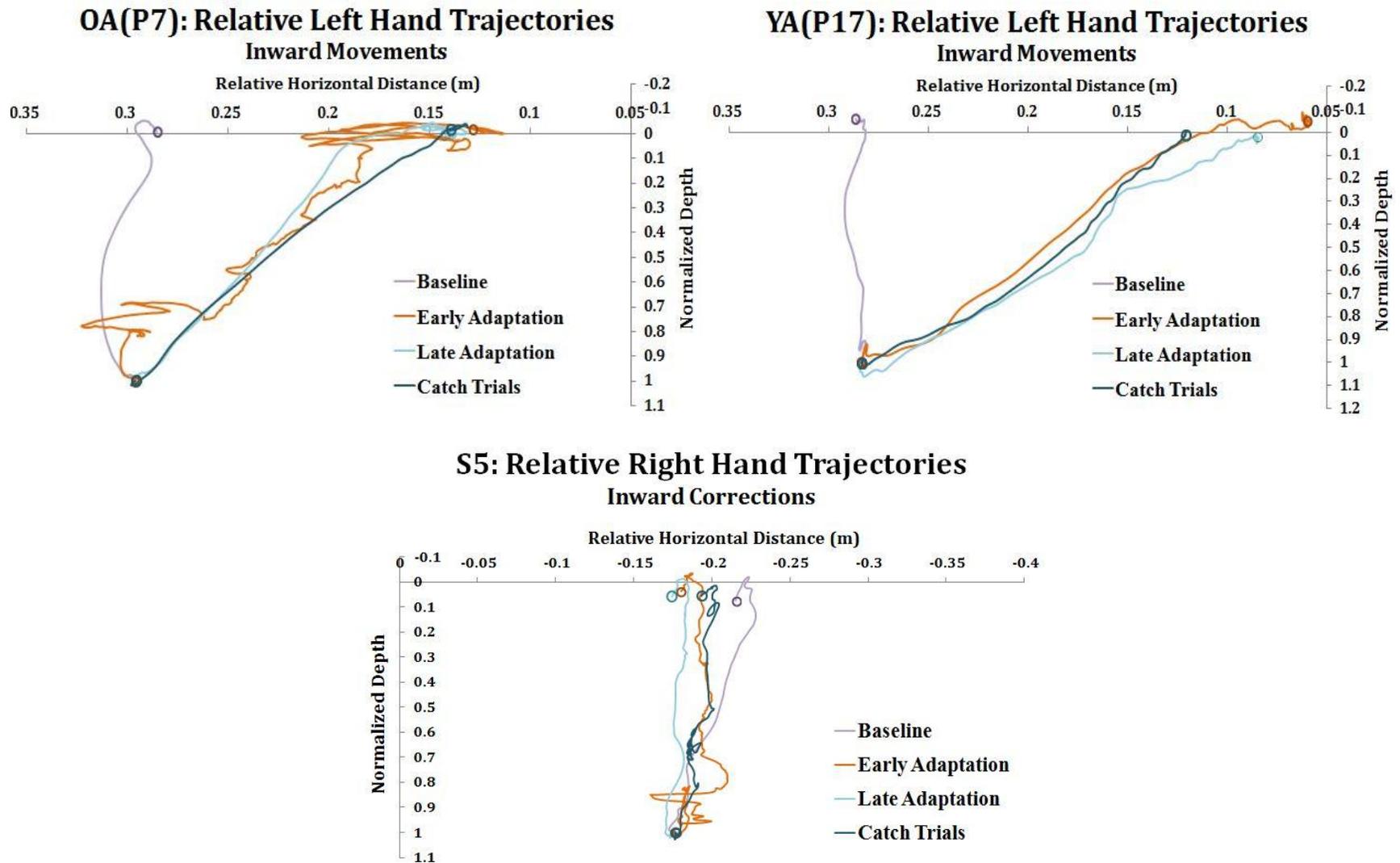


Figure 4.11: Sample trajectory for inward movement/correction of one older adult (P7), one younger adult (P17), and one stroke subject (S5). Both healthy subjects have their left side as their non-dominant side, whereas the right side of the stroke subject is his affected side.

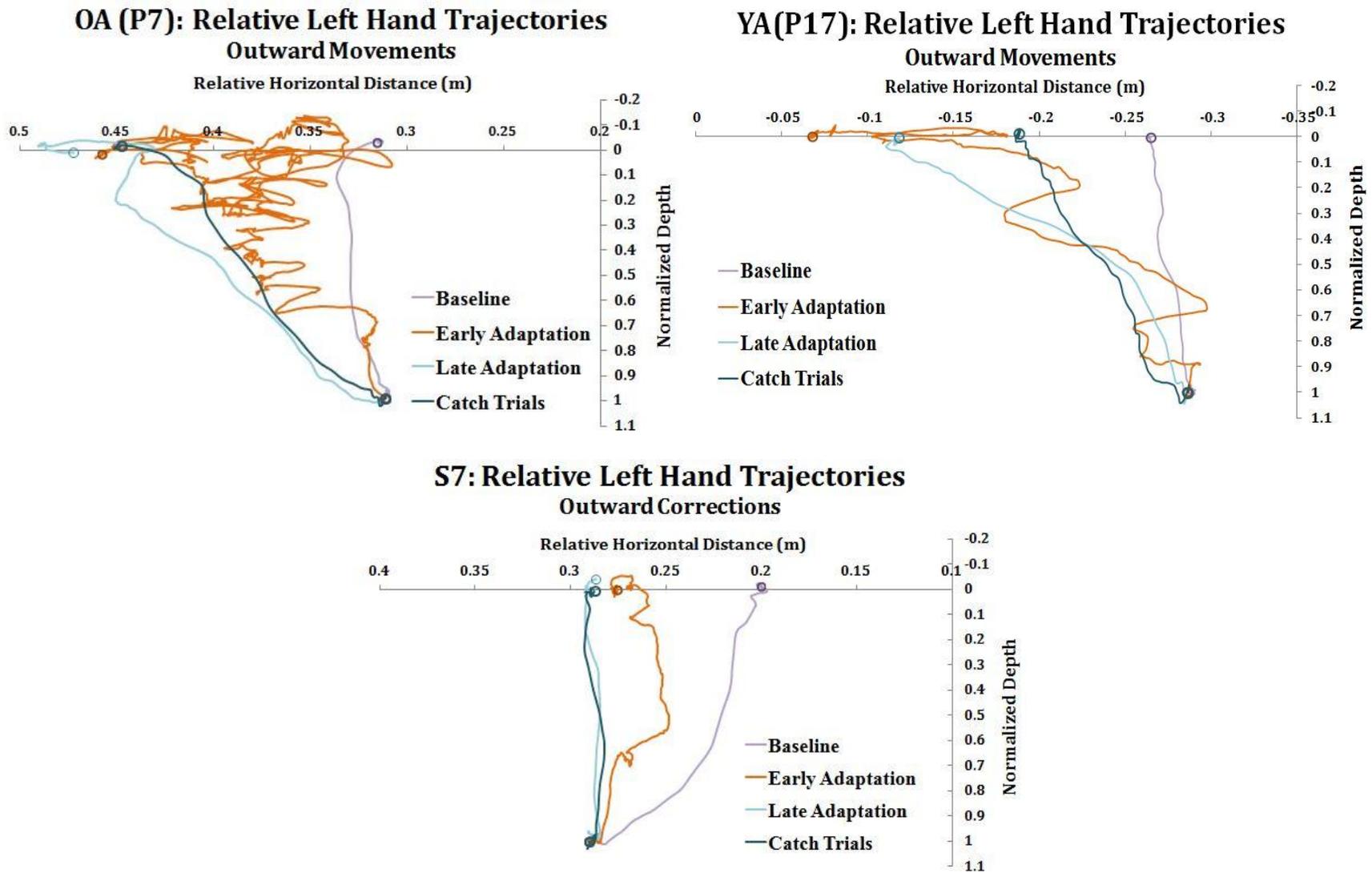


Figure 4.12: Sample trajectory for outward movement/correction of one older adult (P7), one younger adult (P17), and one stroke subject (S7). All subjects have their left side as the non-dominant/affected side.

normalized RMS error over trial. The performance change between the early-adaptation and late-adaptation was then analyzed statistically.

## Correlations

All five performance metrics were significantly negative-correlated with trial number for older adults, younger adults, and stroke subjects who practiced inward correction ( $p < 0.05$  for all, and all except one significance value were smaller than 0.01). However, the same correlation analysis revealed no significant correlations for stroke subjects who performed outward correction. The complete test results and Spearman's correlation coefficients  $r_s$  for each performance metric and each group are presented in Appendix D.

## Motor Adaptation Curve

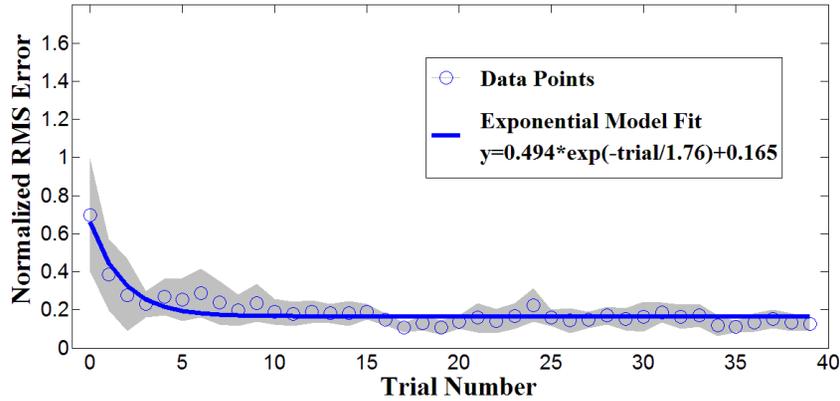
Many motor learning studies with feedback on motion performances showed that the motion error over time followed a decreasing exponential trend, as defined in Section 4.5.2. All metrics showed a similar decreasing exponential trend. This analysis only plotted normalized RMS error over trials as an example for all subject groups and for both types of arm movement. Figure 4.13 and Figure 4.14 show the average data points<sup>6</sup> for each subject group for inward and outward movements, respectively, as well as the modeled adaptation curves. The shaded area represents the 95% confidence interval (CI). The learning coefficients for all groups are listed in Table 4.6, along with Spearman's Coefficient  $r_s$ .

Examining Figure 4.13 and Figure 4.14, both healthy groups showed obvious adaptation for both types of movement, with older adults and younger adults achieving their steady-state performance approximately within the first 20 trials and 5 trials, respectively. This result supports the discussion in Section 4.6.1 that: P17's non-dominant hand trajectory plots showed

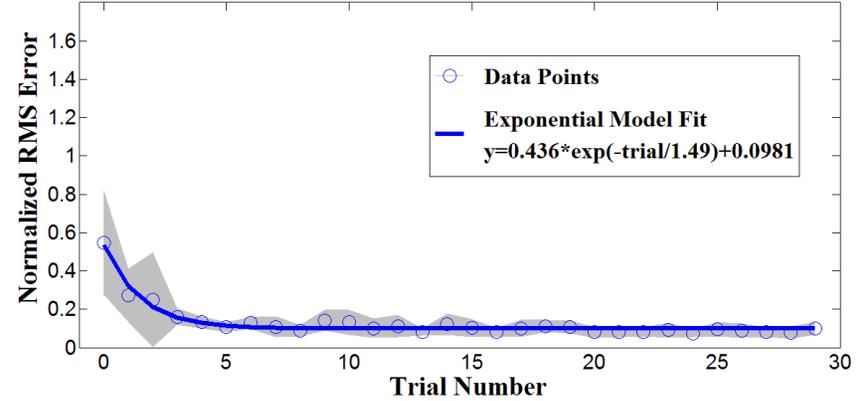
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<sup>6</sup> Since the tracking system error can be up to 15% of the total distance travelled by the controller, it is important to verify that the RMS errors calculated from the data points were a result of subjects' actual hand movement using the worst case scenario. It was found that the minimum *normalized* RMS errors was around 0.15 (normalized by the RRL). Since the RRL for stroke and healthy subjects is within a range of 10-12cm and 21-34cm, respectively, the *non-normalized* RMS error is within a range of 1.5 cm-1.8cm for stroke subjects and 3.2-5.1cm for healthy subjects. By definition, the non-normalized RMS error was calculated from the horizontal deviation between the ideal path and the subject's hand path. Since the maximum horizontal distance that a subject was required to move was 8cm for stroke subjects and 15cm for healthy subjects, the maximum error due to the tracking system accuracy was 1.2cm for stroke subjects and 2.25cm for healthy subject – both smaller than the calculated RMS error. This short calculation demonstrated that the calculated RMS errors were a result of subjects' actual hand movement.

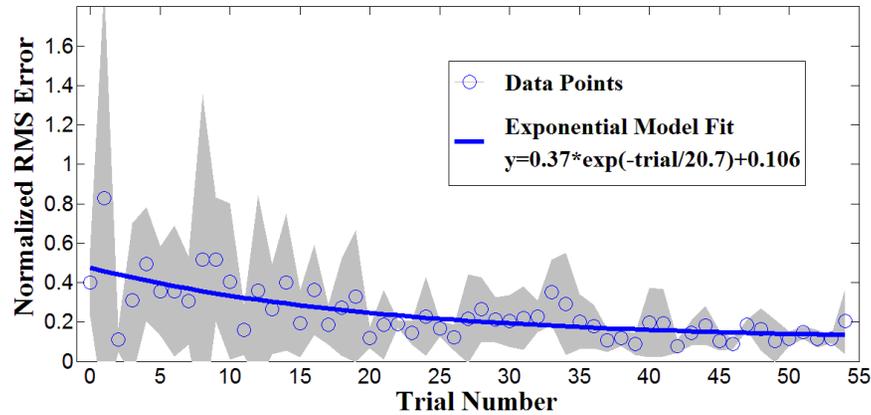
**Adaptation Curve for Older Adults  
Inward Movement**



**Adaptation Curve for Younger Adults  
Inward Movement**

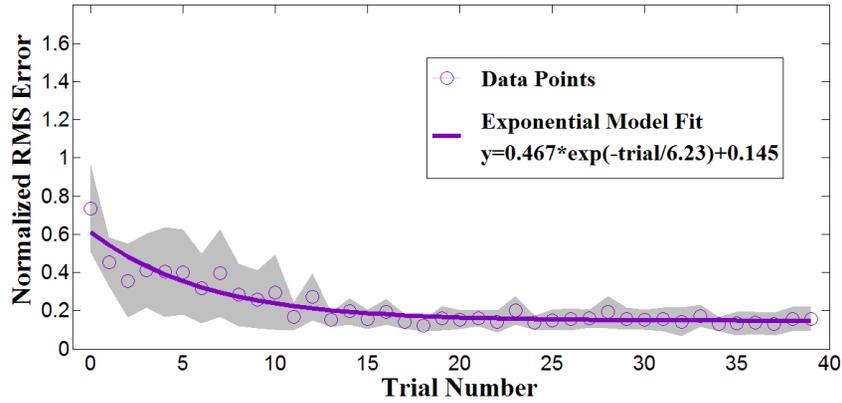


**Adaptation Curve for Stroke Subjects  
Inward Movement**

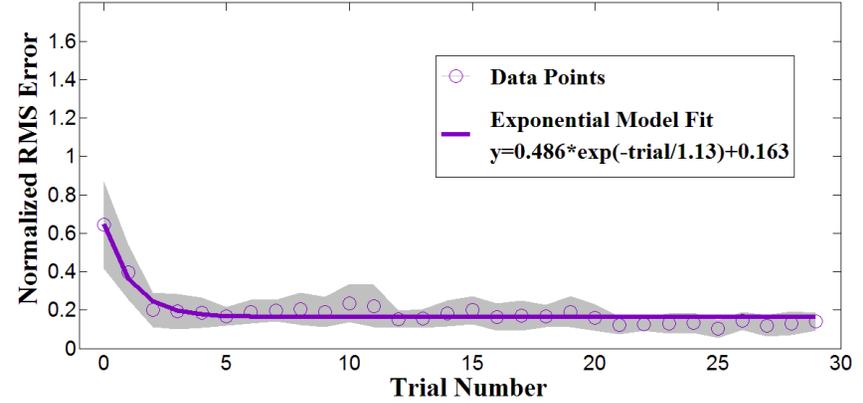


**Figure 4.13: Adaptation curves for all three subject groups performing inward movements. In each plot, the shaded area represents 95% confidence interval. The range of the vertical axis for all charts is the same to allow easy comparison.**

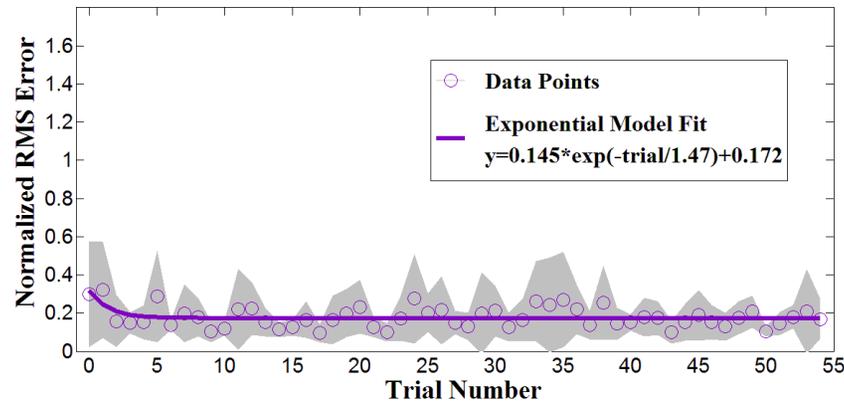
**Adaptation Curve for Older Adults  
Outward Movement**



**Adaptation Curve for Younger Adults  
Outward Movement**



**Adaptation Curve for Stroke Subjects  
Outward Movement**



**Figure 4.14: Adaptation curves for all three subject groups performing outward movements. In each plot, the shaded area represents 95% confidence interval. The range of the vertical axis for all charts is the same to allow easy comparison.**

**Table 4.6: Overall learning coefficients  $a$ ,  $b$ , and  $c$  for the two types of movement for all subject groups. The Spearman's coefficient  $r_s$  and corresponding  $p$ -values are also included in the table to show how correlated the normalized RMS error is to the number of trials. The symbol \* indicates a significant correlation with  $p < 0.05$ . Definitions: OA = older adults; YA = younger adults; SS = stroke subjects.**

<u>Learning Coefficients</u>	<u>Inward Motion/Correction</u>			<u>Outward Motion/Correction</u>		
	<u>OA</u>	<u>YA</u>	<u>SS</u>	<u>OA</u>	<u>YA</u>	<u>SS</u>
$a$	0.494	0.436	0.370	0.467	0.486	0.145
$b$	1.76	1.49	20.7	6.23	1.13	1.47
$c$	0.165	0.098	0.106	0.145	0.163	0.172
<u>Correlation Coefficient</u>	<u>OA</u>	<u>YA</u>	<u>SS</u>	<u>OA</u>	<u>YA</u>	<u>SS</u>
$r_s$	-0.738	-0.773	-0.697	-0.746	-0.816	-0.052
$p$ -value	$p < 0.001^*$	$p < 0.001^*$	$p < 0.001^*$	$p < 0.001^*$	$p < 0.001^*$	$p = 0.706$

fast adaptation because his average trajectory in early-adaptation was already close to the ideal task path. Given the high correlation values of  $r_s$  and significantly decaying trend in normalized RMS error, vibrotactile feedback could be a promising strategy to employ in training asymmetric bilateral motions for the healthy population.

Stroke subjects who performed inward correction showed a slow adaptation (Figure 4.13), but stroke subjects who practiced outward correction did not (Figure 4.14). This finding coincides with the Spearman's Rank-Order Correlation test which revealed significant negative-correlation for the former group but not for the latter group. Thus, although stroke subjects who performed inward correction demonstrated some effect of vibration training, stroke subjects who performed outward correction showed minimum training effect. Using normalized RMS error as an example, the minimum training effect observed in the latter group might be due to the high variance in the data and the small range of data values (~0.1 to ~0.3).

The range of the 95% CI was an indication of the variance between-subjects. The range of the 95% CI for all healthy subjects reduced over trials. In other words, healthy subjects exhibited higher between-subject variations in the initial few movements but were able to achieve a similar trajectory performance after a few trials. The 95% CI for stroke subjects showed more variance than the ones for healthy subjects performing the same movement. This result was unsurprising because of the large differences between the stroke subjects' motor ability.

The author used the calculated learning coefficients (listed in Table 4.6) to compare the learning characteristics between different subject groups. In examining the effect of age differences, younger adults learned faster compared to older adults, but the amount of learning and the final achieved steady-state performance were not necessarily better than older adults. With older adults approximately age-matched with stroke subjects, comparisons between the two groups provided results in terms of proprioception differences. For this analysis, only coefficients for the inward movements were compared, because the normalized RMS error did not show a significant correlation over trials for stroke subjects performing outward movements. The rate of learning for stroke subjects was much slower than older adults in the inward movement group (20.7 vs. 1.76). Coefficients from older adults showed a higher amount of learning and higher steady-state error. This result might be due to the different study tasks assigned to the groups.

### **Statistical Analysis on Improvements during the Vibration Training Stage**

All healthy subject groups and the stroke subject group who performed inward correction showed decaying trends of the performance metrics for both types of movement. However, it was possible that the differences between the start and end performance were not significant enough to be referred to as improvements. The performance differences were first tested with the Shapiro-Wilk test to see if the data samples were normally distributed. Then, depending on the results of the Shapiro-Wilk test, this analysis used the average performance values of all subjects in the early- and late-adaptation stages to perform a two-tailed paired t-test or its non-parametric version, the Wilcoxon Signed-Rank Test. p-values were adjusted using the Bonferroni correction to 0.003. A Cohen's  $d$  of 0.2, 0.5, and 0.8 indicates a small, medium, and large effect, respectively [103].

Table 4.7 lists the mean and standard deviation of the performance metric for all subject groups. Most of the mean values were higher in the early-adaptation stage than the late-adaptation stage. This result was expected since the users were still discovering the designed task paths, and their attention was more focused on interpreting the vibrotactile cues on their weak arm (higher  $R_{dis}$ ). Higher performance metrics in the early-adaptation stage also indicated that vibrotactile cues were playing their role in altering the trajectories of the subjects' ND/A hand.

**Table 4.8: Means of all performance metrics at the beginning and end of the learning stage for both types of movement and all three subject groups. Standard deviations are indicated in parentheses. Definitions: EA=early-adaptation; LA=late-adaptation; OA=older adults group; YA=younger adults group; SS=stroke subjects group; RD = reaching duration;  $IC_{ND/A}$  = index of curvature;  $R_{dis}$ = distance ratio.**

Performance Metrics	Stage	<u>Outward Movement</u>			<u>Inward Movement</u>		
		OA	YA	SS	OA	YA	SS
Normalized RMS error	EA	0.47 (0.27)	0.32 (0.15)	0.21 (0.10)	0.37 (0.19)	0.27 (0.21)	0.43 (0.32)
	LA	0.14 (0.08)	0.13 (0.07)	0.16 (0.09)	0.13 (0.04)	0.09 (0.03)	0.14 (0.05)
Normalized Max error	EA	0.99 (0.52)	0.75 (0.34)	0.31 (0.20)	0.72 (0.35)	0.57 (0.37)	0.65 (0.44)
	LA	0.32 (0.17)	0.31 (0.19)	0.23 (0.18)	0.28 (0.10)	0.2 (0.08)	0.22 (0.10)
Normalized RD (s/m)	EA	350 (242)	247 (267)	386 (101)	257 (177)	182 (159)	699 (273)
	LA	132 (125)	97 (61)	216 (126)	87 (54)	72 (37)	353 (347)
$IC_{ND/A}$	EA	6.47 (3.8)	5.81 (4.98)	3.76 (1.42)	4.19 (1.68)	3.98 (2.41)	9.02 (4.96)
	LA	2.83 (1.53)	2.63 (1.41)	2.53 (0.91)	2.14 (0.65)	2.11 (0.69)	3.6 (1.48)
$R_{dis}$	EA	2.07 (0.55)	2.08 (0.77)	1.23 (0.35)	1.71 (0.34)	1.8 (0.46)	1.06 (0.59)
	LA	1.61 (0.37)	1.68 (0.61)	1.19 (0.31)	1.53 (0.36)	1.57 (0.25)	1.1 (0.28)

The remaining part of this section presents the statistical results by comparing the early- and late-adaptation performances. Table 4.8 and Table 4.9 list the  $p$ -values and the effect sizes using Cohen’s  $d$  for all performance metrics, all subject groups, and both movement types. The  $p$ -values were adjusted using the Bonferroni correction to 0.003. A Cohen’s  $d$  of 0.2, 0.5, and 0.8 indicates a small, medium, and large effect, respectively [103].

Overall, the performance for both movement types in all healthy subjects showed significant improvements in the two error-related metrics in late-training stage, while only stroke subjects who performed an outward correction demonstrated significant improvements in the reaching duration. This result indicates that: 1) healthy subjects learned the study task path in a short amount of time, confirmed with significant negative correlations over trials and significant improvements in the late-training trials, and 2) there is insufficient training evidence for stroke subjects in error-related improvements over the vibration training stage. However, most of the metrics showed a large effect size, which indicates that the results were likely limited due to the sample size.

**Table 4.9: The  $p$ -values and effect size for outward movements, obtained by comparing the performance metrics in the late-adaptation trials to the early-adaptation trials. Bolded values indicate significant results. Definitions: OA=older adults; YA= younger adults; SS = stroke subjects;  $IC_{ND/A}$  = index of curvature for the non-dominant or affected arm;  $R_{dis}$  = distance ratio.**

Outward Movement						
Performance Metrics	OA		YA		SS	
	$p$ -value	Cohen's $d$	$p$ -value	Cohen's $d$	$p$ -value	Cohen's $d$
Normalized RMS error	<b>p = 0.003</b>	1.31	<b>p &lt; 0.001</b>	1.78	p = 0.174	0.886
Normalized Max error	<b>p = 0.002</b>	1.41	<b>p &lt; 0.001</b>	1.92	p = 0.068	1.28
Normalized Reaching Duration (s/m)	<b>p = 0.010</b>	1.03	p = 0.086	0.609	<b>p = 0.001</b>	5.78
$IC_{ND/A}$	<b>p = 0.011</b>	1.01	<b>p = 0.041</b>	0.726	<b>p = 0.030</b>	1.95
$R_{dis}$	<b>p = 0.005</b>	1.16	<b>p = 0.050</b>	0.716	p = 0.641	0.259

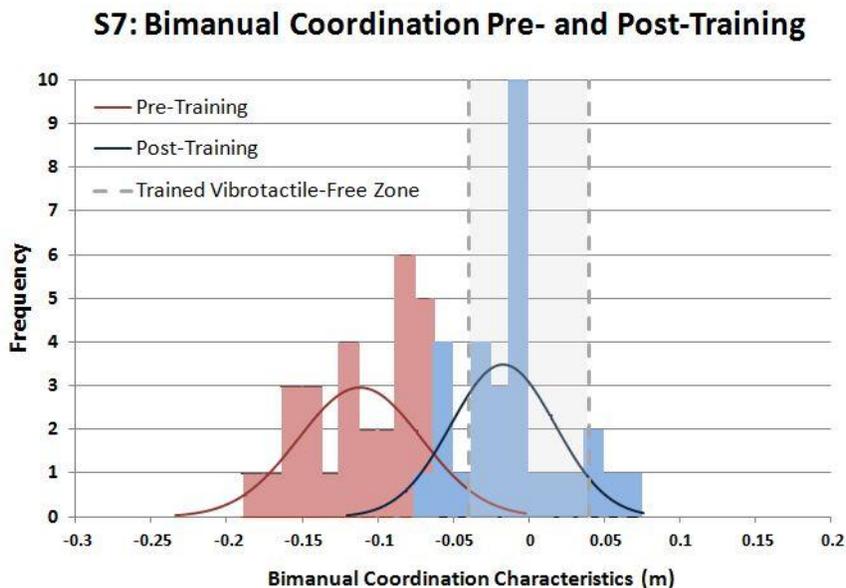
**Table 4.10: The  $p$ -values and effect size for inward movements, obtained by comparing the performance metrics in the late-adaptation trials to the early-adaptation trials. Bolded values indicate significant results. Definitions: OA=older adults; YA= younger adults; SS = stroke subjects;  $IC_{ND/A}$  = index of curvature for the non-dominant or affected arm;  $R_{dis}$  = distance ratio.**

Inward Movement						
Performance Metrics	OA		YA		SS	
	$p$ -value	Cohen's $d$	$p$ -value	Cohen's $d$	$p$ -value	Cohen's $d$
Normalized RMS error	<b>p = 0.002</b>	1.38	<b>p = 0.014</b>	0.957	p = 0.297	0.808
Normalized Max error	<b>p = 0.002</b>	1.39	<b>p = 0.008</b>	1.08	p = 0.290	0.823
Normalized Reaching Duration (s/m)	<b>p = 0.004</b>	1.19	<b>p = 0.033</b>	0.797	p = 0.109	1.55
$IC_{ND/A}$	<b>p = 0.001</b>	1.51	<b>p = 0.019</b>	0.902	p = 0.261	0.895
$R_{dis}$	p = 0.066	0.662	p = 0.118	0.547	p = 0.850	0.124

### 4.6.3 Stroke Subjects: Training Effect on Bilateral Motion Characteristics

This section presents the end-position performance change for stroke subjects post-training. As an example, Figure 4.15 visually shows the bimanual coordination  $char_{bim}$  data in the pre- and post-training stages for one stroke subject (S7), and it also highlights the trained tolerance zone, i.e., the vibrotactile-free zone, for S7. Compared to the pre-training data, the post-training data shifted closer to 0, i.e., an increase in accuracy, and the distribution became narrower, i.e., an improvement in precision. Specifically, S7's bimanual coordination  $char_{bim}$  was found to be

greatly improved from a mean of  $-11$  centimeters with a standard deviation of  $4.06$  to a mean of  $-2$  centimeters with a standard deviation of  $3.44$ . Moreover,  $67\%$  of the post-training performance was within the trained tolerance zone, whereas only  $6.7\%$  of the pre-training performance was within the trained tolerance zone.



**Figure 4.15: The histogram of the bimanual coordination data for S7 pre- and post-training. The corresponding theoretical normal distributions are also shown in the figure. The shaded area indicates the vibrotactile-free zone created for S7. This zone trained S7 to perform symmetric motions with high accuracy (a center value of 0) and 50% improvements in precision (half the range of the 95% prediction interval measured in the pre-training stage).**

Table 4.11 lists the calculated accuracy and precision, normalized using each subject’s RRL, and the corresponding improvements for each subject’s motion characteristics  $char_{bim}$  and  $char_A$ . Since the ideal case was to have both characteristics as 0, the author computed the improvements using the absolute value of the pre-training performance subtracting the absolute value of the post-training performance. In Table 4.11, the values shaded in red refer to a decrease in performance.

For better visualization, the normalized accuracy and precision data are illustrated in Figure 4.16 using a dart board analogy by plotting all data points for  $char_{bim}$  and  $char_A$  on four dart charts. The center for the accuracy charts was the ideal value 0, whereas the center for the precision charts was the mean value of the raw measurement. The four circumferences, from the inner to the outer, respectively, were the 25<sup>th</sup> percentile, 50<sup>th</sup> percentile, 75<sup>th</sup> percentile, and 100<sup>th</sup>

**Table 4.11: Mean values of the normalized accuracy and precision during pre- and post-training and the corresponding improvements. The improvements are defined as the absolute value of the pre-training performance subtracting the absolute value of the post-training performance. Cells highlighted in red indicate a decreased performance. Definitions: Pre: pre-training; Post: post-training; Diff: corresponding improvements.**

Subject	Normalized Accuracy						Normalized Precision					
	<i>char<sub>A</sub></i>			<i>char<sub>bim</sub></i>			<i>char<sub>A</sub></i>			<i>char<sub>bim</sub></i>		
	Pre	Post	Diff	Pre	Post	Diff	Pre	Post	Diff	Pre	Post	Diff
S1	0.60	-0.31	<b>0.30</b>	-0.61	-0.41	<b>0.20</b>	0.33	0.25	<b>0.08</b>	0.32	0.29	<b>0.03</b>
S2	0.03	-0.06	<b>-0.03</b>	0.21	0.14	<b>0.07</b>	0.28	0.19	<b>0.09</b>	0.29	0.23	<b>0.06</b>
S3	-0.01	-0.25	<b>-0.24</b>	0.02	-0.24	<b>-0.22</b>	0.11	0.16	<b>-0.05</b>	0.12	0.15	<b>-0.03</b>
S4	0.22	-0.16	<b>0.07</b>	-0.20	-0.04	<b>0.16</b>	0.17	0.08	<b>0.09</b>	0.16	0.07	<b>0.09</b>
S5	0.18	-0.22	<b>-0.05</b>	0.25	0.22	<b>0.03</b>	0.31	0.16	<b>0.16</b>	0.28	0.17	<b>0.11</b>
S6	-0.51	0.29	<b>0.23</b>	-0.29	-0.19	<b>0.10</b>	0.21	0.09	<b>0.12</b>	0.15	0.11	<b>0.04</b>
S7	-0.03	-0.02	<b>0.01</b>	-1.05	-0.16	<b>0.89</b>	0.09	0.06	<b>0.03</b>	0.31	0.23	<b>0.08</b>
<i>Mean</i>	0.07	-0.11	<b>0.04</b>	-0.24	-0.10	<b>0.18</b>	0.22	0.14	<b>0.07</b>	0.23	0.18	<b>0.05</b>
<i>SD</i>	0.31	0.18	<b>0.17</b>	0.43	0.20	<b>0.32</b>	0.09	0.06	<b>0.06</b>	0.08	0.07	<b>0.04</b>

percentile of the pre-training data. The percentile values for normalized accuracy were calculated using the absolute accuracy to indicate deviation levels from 0. In the figure, each red triangular data point represents the average pre-training characteristics of one subject, while blue circular data points show the post-training characteristics. To interpret the accuracy dart charts: a dataset is *accurate* if data points are close to the center of each chart. Similarly, a dataset is *precise* if the data are close to the chart center in the precision dart charts.

In examining the charts in Figure 4.16, by counting the number of post-training data points within the 50<sup>th</sup> percentile range calculated from the pre-training data, i.e., the range containing 4 data points of the pre-training data, it was possible to roughly observe if there were any improvement existed post-training. The numbers of post-training data within the criterion for *char<sub>bim</sub>* and *char<sub>A</sub>*, respectively, were 6 and 3 for accuracy and 6 and 6 for precision. Therefore, it was most likely that both the accuracy and precision of *char<sub>bim</sub>* and precision of *char<sub>A</sub>* improved post-training.

The performance differences of the two characteristics pre- and post-training were then analyzed statistically using either a two-tailed paired t-test or Wilcoxon Signed-Rank Test, depending on the normality test of the paired data. Table 4.12 lists the associated *p*-values and the calculated Cohen's *d* for each variable.

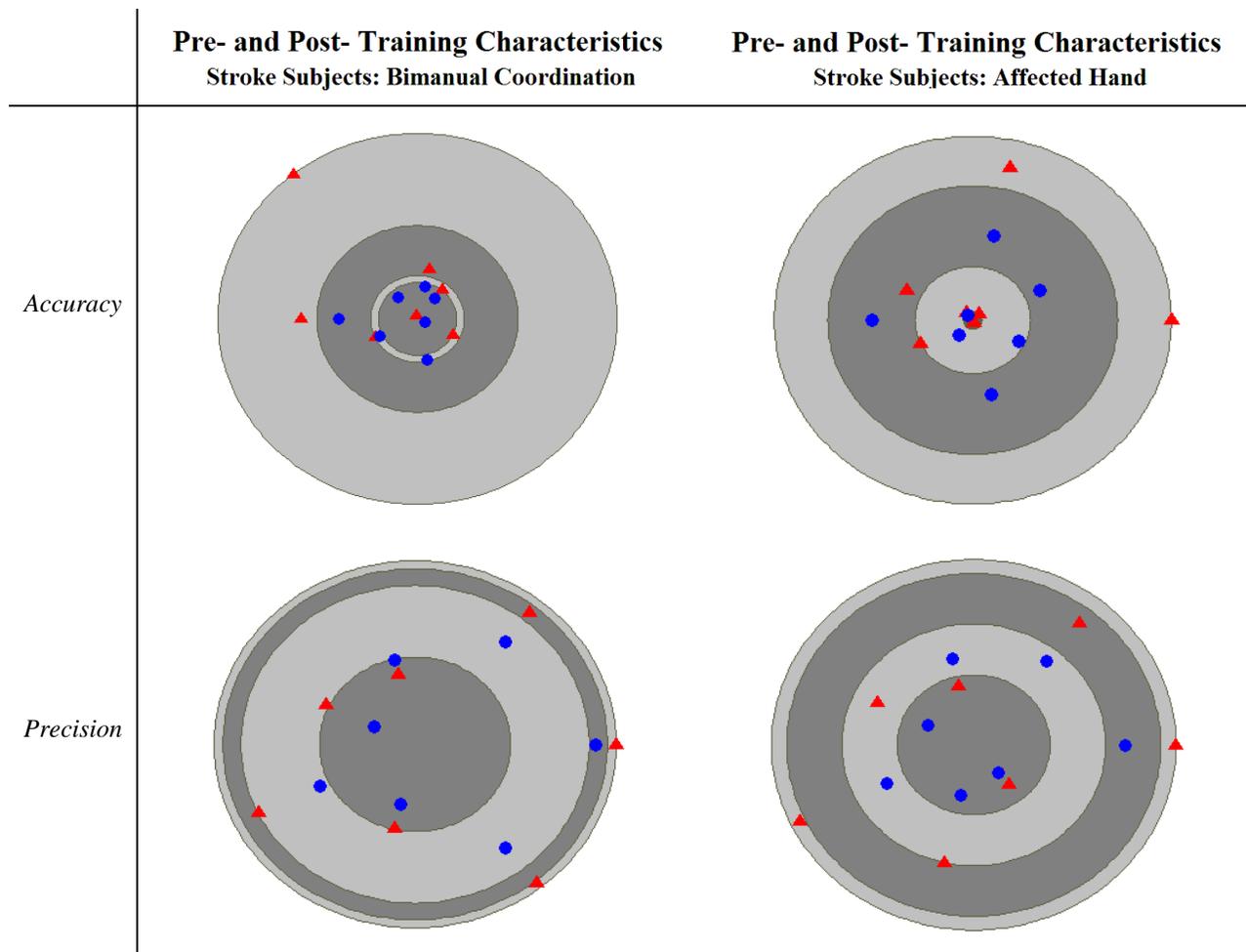


Figure 4.16: Visualization of the pre- and post-training characteristics in terms of accuracy and precision for all stroke subjects. The characteristics are the bimanual coordination  $char_{bin}$  (left) and affected hand characteristics  $char_A$  (right). Red triangular points represent pre-training data, whereas blue circular points indicate post-training data. The four circumferences, from the center to the outer, indicate the 25<sup>th</sup>, 50<sup>th</sup>, 75<sup>th</sup>, and 100<sup>th</sup> percentiles of each pre-training dataset.

Table 4.12: Calculated  $p$ -value and effect size for normalized accuracy and precision of motion characteristics  $char_{bin}$  and  $char_A$ . An asterisk \* indicates the differences pre- and post-training are significant with  $p < 0.05$ .

Stroke Subject <u>Group</u>	Normalized Accuracy				Normalized Precision			
	$char_A$		$char_{bin}$		$char_A$		$char_{bin}$	
	$p$ -value	Cohen's $d$	$p$ -value	Cohen's $d$	$p$ -value	Cohen's $d$	$p$ -value	Cohen's $d$
Inward Correction	0.111	1.59	0.245	0.940	0.397	0.617	0.342	0.714
Outward Correction	0.760	0.167	0.068	0.903	<b>0.026*</b>	2.06	<b>0.020*</b>	2.25

In examining the results in Table 4.12: normalized precision for both characteristics improved (with significantly large effect) for stroke subjects who performed outward corrections, but there were no significant improvements for normalized accuracy. Stroke subjects who performed inward corrections showed no significant improvements.

### Are the Observed Improvements Based on Practice Effect?

The improvements in normalized precision for both characteristics might be results from the training and/or practice effect, i.e., subjects' performance improved after repetitive practice. In order to conclude the observed improvements were the result of vibrotactile training, the author investigated the correlations of the performances in the 30 pre-training trials over time and the performances in the first 30 vibration training trials over time.

Table 4.13 presents the results from the Spearman's Rank-Order Correlation test. The normalized precision values of  $char_{bim}$  and  $char_A$  in the vibration training stage showed significant negative correlations with the trial number for subjects performing outward movements. The pre-training data showed no significant negative correlations for both motion groups, but only a positive correlation in the outward group for  $char_{bim}$ . Those results confirm the finding from the previous section that the improved precision performance for stroke subjects performing outward corrections was the result of vibrotactile training and not from the practice effect.

**Table 4.13: The Spearman's coefficient  $r_s$  and the corresponding  $p$ -value for the motion characteristics of the 30 pre-training trials and the first 30 vibration training trials. An asterisk \* indicates the differences pre- and post-training are significant with  $p < 0.05$ .**

Stroke Subject <b>Group</b>	30 Pre-Training Trials				First 30 Vibration Training Trials			
	$char_A$		$char_{bim}$		$char_A$		$char_{bim}$	
	$r_s$	$p$ -value	$r_s$	$p$ -value	$r_s$	$p$ -value	$r_s$	$p$ -value
Inward Correction	-0.150	0.429	0.004	0.984	-0.248	0.187	-0.138	0.467
Outward Correction	0.269	0.151	0.409	<b>0.025*</b>	-0.366	<b>0.047*</b>	-0.384	<b>0.036*</b>

### 4.6.4 Stroke Subjects: Performance Improvements vs. Clinical Assessments

Correlation analysis revealed that performances improvements were not significantly correlated with the total UE-FM scores or the MAS score for stroke subjects. However, the analysis showed significant positive correlations between the precision of  $char_A$  and the

sensation section of the UE-FM ( $r_s=0.896$ ,  $p<0.01$ ). Precision of  $char_A$  was also positively correlated with the combined score from sensation and coordination section of the UE-FM ( $r_s=0.883$ ,  $p<0.01$ ). Also, this analysis showed that the accuracy of  $char_A$  was significantly negative-correlated with the measured MAS spasticity of the triceps ( $r_s=-0.866$ ,  $p=0.012$ ) and the wrist extensor ( $r_s=-0.808$ ,  $p=0.028$ ).

#### 4.6.5 Post-Test Questionnaire Results

This section presents the results from the post-test questionnaire. Table 4.14 lists the overall answer for Part A of the questionnaire for the two healthy subject groups, reported in modal value. The outcomes were fairly consistent for each question between the two healthy subject groups in either agreeing or disagreeing with the question statement. Both subject groups agreed that: it was easy to control the cursor (A1); it was not difficult for them to reach the target (A2); the vibrotactile cues provided clear guidance for their hand to move to the specified locations (A3); they could feel the vibration on their forearm (A4); the controllers were easy to hold (A5); they did not feel tired after completing the session (A6).

**Table 4.14: Modal answers for the 5-point Likert Scale questions in Part A from both healthy subject groups.**

<u>Subject Groups</u>	<u>A1</u>	<u>A2</u>	<u>A3a</u>	<u>A4</u>	<u>A5</u>	<u>A6</u>
Healthy Older Adults	4	2	4	2	4	2
Healthy Younger Adults	4	2	4	1	5	2

Table 4.15 shows that for stroke subjects, they felt the same as the healthy subject groups for the first two questions (A1 and A2); they strongly agreed that the vibration cues corrected their movement to be more symmetric (A3b); they could feel the vibrotactile cues on their forearm during the reaching task (A4); they strongly felt that the controllers were easy to hold (A5). Their answer was neutral to question A6.

**Table 4.15: Modal answers for the 5-point Likert Scale questions in Part A from the stroke subject group.**

	<u>A1</u>	<u>A2</u>	<u>A3b</u>	<u>A4</u>	<u>A5</u>	<u>A6</u>
Stroke Survivors	4	2	5	5	5	3

Answers to Part B of the questionnaire examined the underlying belief that: “*the device is a good wearable design that can be worn while performing arm movement*”. The analysis

approach was the same as the one used in Study I (Section 3.6.4), i.e., the average score of statements B1-B5 for each subject group was tested against the neutral response using an independent t-test. Figure 4.17 presents the mean data for Part B, and Table 4.16 lists the corresponding *t*-values and *p*-values for the test. The results implied that all three subject groups agreed that the device was a good wearable design and could be worn while performing arm movement. For older adults, younger adults, and stroke subjects, the Cronbach's alpha was 0.869, 0.597, and 0.526, respectively, with only the older adults achieving the commonly used 0.700 standard.

To interpret SUS results, a score above 68 indicates that the usability of the system is above average [98]. The results for all three populations are presented in Figure 4.18, with response from older and younger adults around the above average margin, and high favoured response from stroke subjects.

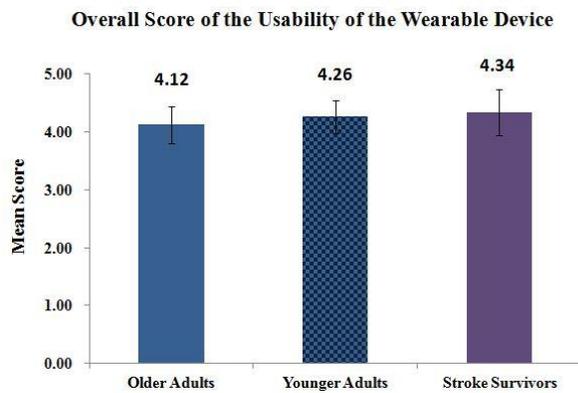


Figure 4.17: Overall scores on the usability of the wearable device.

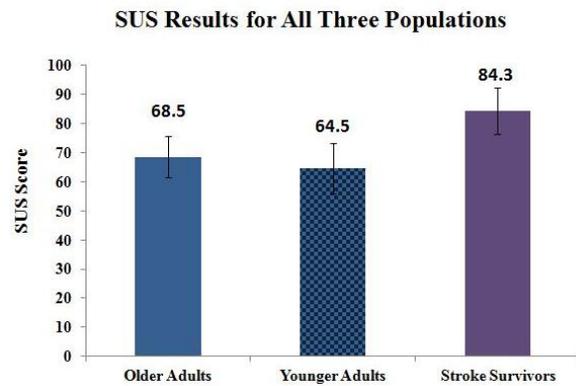


Figure 4.18: Overall SUS scores.

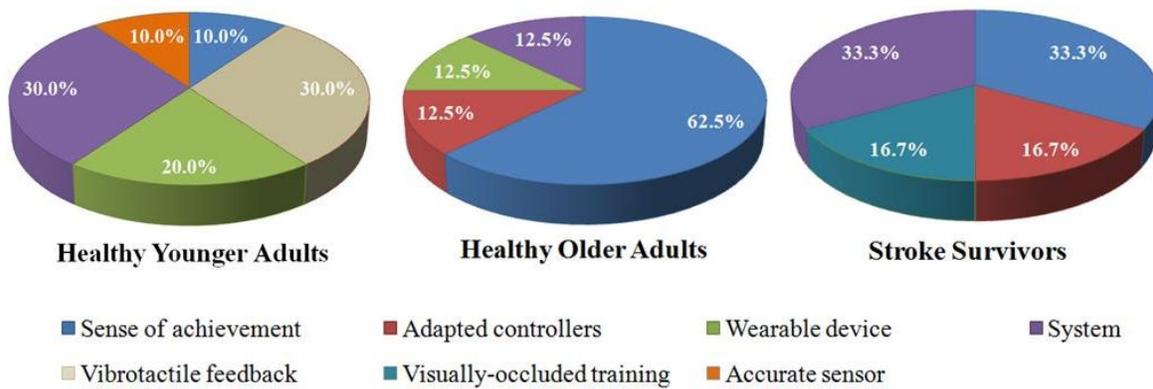
Table 4.16: Calculated *t*-values and corresponding *p*-values on the usability of the wearable device for all three subject groups. An asterisk \* indicates a significant result at  $p=0.05$  level.

<u>Subject Groups</u>	<u>t-value</u>	<u>Significance</u>
Older Adults	6.73	<b>p &lt; 0.001*</b>
Younger Adults	8.80	<b>p &lt; 0.001*</b>
Stroke Survivors	6.60	<b>p &lt; 0.001*</b>

Part D of the questionnaire included open-ended questions for suggestions and comments. Figure 4.19 presents the results on subjects' favorite features of this study. The author calculated the percentages based on the number of people who filled out the questions, which included 10

younger adults, 8 older adults, and 5 stroke subjects. Many younger adults favored the vibration feedback and the wearable device (50%), as well as the whole system (30%). Older adults and stroke subjects liked the sense of achievements obtained from reaching the targets and mastering the game (63.5% and 33.3% for older adults and stroke subjects, respectively), and the system itself (12.5% and 33.3%). Many subjects commented that the system is comfortable, well-integrated, and easy to use.

### Favorite Features of the Study



**Figure 4.19: Questionnaire results on subjects' favourite features of Study II.**

Some subjects provided comments for creating a more enjoyable system. The percentages presented here were also calculated from the number of respondents who filled out the questions. Some examples are: improving the target game to be more engaging and with better graphics (20% from younger adults and 40% from stroke subjects); increasing the vibration intensity (12.5% older adults and 10% younger adults) or varying the vibration intensity and never turned off (10% younger adults). One older adult also suggested that placing vibrators at different arm locations could potentially help in better distinguishing the vibration cues (12.5% older adults).

### **Stroke Subjects: Correlations between Task Performance and Perceived Difficulties or System Usability Score**

Correlation analysis examined the correlations between the improvements of stroke subjects' end-position accuracy and precision versus the answers of A2 and A4 from the post-test questionnaire, and the total SUS score. Specifically, questions A2: *"It was difficult for me to reach the target"*, and A4: *"I can feel the vibration on my forearm during the reaching task"*, addressed the perceived task difficulty, whereas the SUS score reflected the usability of the

whole system. Significant negative correlations exist between: (1) the accuracy improvements of  $char_A$  and SUS score ( $r_s = -0.855$ ,  $p=0.014$ ), (2) the precision improvements of  $char_A$  and the answers to question A2 ( $r_s = -0.842$ ,  $p=0.017$ ), and (3) the precision improvements of  $char_A$  and the answers to question A4 ( $r_s = -0.867$ ,  $p=0.012$ ).

## 4.7 Discussion

The results presented in the previous section assessed the potential of implementing vibrotactile feedback as a means of training bimanual motions for both healthy and post-stroke subjects. The author used different approaches to address the study questions, such as visualization of change in position trajectory, correlation analysis between the performance metrics and trial numbers, and statistical analysis on finding significant improvements.

First, the analysis used four subjects' data as examples to show trajectory progression of their ND/A hand's relative position over time. Overall, the trajectories for healthy subjects gradually changed from a relatively straight baseline to the set task paths over time, whereas the trajectories for stroke subjects progressed from reaching at an angle to straight forward. Those observations show that vibrotactile instructional cues are capable of altering the motion path of ND/A hand's motion in a bilateral reaching motion.

Then, the results showed significant negative correlations between performance metrics and trial number during the vibrotactile training stage for all healthy subjects and stroke subjects who practiced inward correction. However, only healthy subjects showed significant improvements in error-related performance metrics. The modeled adaptation curves fitted for healthy subjects' ND/A hand's data are similar to the ones in current short-term motor learning literature, with an obvious drop of the error-related metrics after a few trials [39], [48]–[50]. This finding indicates that healthy adults are capable of adapting unfamiliar bilateral arm motions with the aid of vibrotactile feedback, and the adaptation happens in a similar manner as to how they adapt unilateral motion using visual, force, and vibrotactile feedback.

As for the stroke subjects who performed inward correction, though there was a decaying trend in their performance metrics, the differences in performance at the beginning and end of the vibration training stage were not significant enough to be referred to as improvements. This result was possibly due to the high variation of the performance metrics in the first few trials,

which also resulted in a much smaller performance change between the early- and late-adaptation stages compared to the ones for healthy adults. Figure 4.13 showed the described trend using the normalized RMS error.

In addition to overall trajectory performance, the author examined the end-position accuracy and precision of stroke subjects. Visualization of normalized accuracy and precision data showed improvements for most of the stroke subjects. However, only stroke subjects who performed outward corrections demonstrated significant improvements on normalized precision of the bimanual coordination  $char_{bim}$  and the affected hand characteristics  $char_A$ . Correlation analysis verified that these improvements were not the result of the practice effect.

In examining all the results for stroke subjects, it remains unknown why the only significant improvements were the end-position precision of  $char_{bim}$  and  $char_A$ . Furthermore, only stroke subjects who performed outward correction showed such improvements. This result suggests that the stroke subjects might have built an internal model of the task path over the course of the vibration training. However, they might not have enough motor control to move to the desired end position with high accuracy or in a straight path, since the analysis revealed no significant improvements in any trajectory-related and error-related performance metric. Nevertheless, most of the trajectory-related performance metrics (Section 4.6.2) and end-position characteristics (Section 4.6.3) for stroke subjects showed medium to large effect sizes. This finding suggests that the non-significant results were possibly limited by the high variance in the paired data and small sample size of this study.

Correlation analysis revealed limited correlations between stroke subjects' end-position improvements and their clinical scores, perceived task difficulties, and system usability. This finding was expected due to the large individual differences among stroke subjects' motor ability. The significant correlations showed that the subjects achieved higher precision improvements of  $char_A$  when they: 1) had higher motor function, 2) thought the reaching task was easier, 3) rated the system lower, or 4) had less confidence with sensing vibration cues. Points (1) and (2) are reasonable because people with higher function have better control of their affected hand, and the motor learning literature also shows that task performance is high when the task is easy [104]. Points (3) and (4) may initially seem unexpected; however, one possible explanation is that the subjects put more attention on their affected arm when they were less confident in sensing the

vibration, leading to a lower confidence of the usability of the system, but a higher improvement in motor performance.

In addition, the high user ratings on the usability of the system and wearable device indicate a promising use of this type of training systems for either casual training or at-home stroke rehabilitation. A few commonly proposed improvements were on: 1) the graphical design of the target game, 2) the intensity of the vibration motors, and 3) the vibrator locations.

#### **4.7.1 Study Limitations**

In addition to the hardware limitations mentioned in Section 3.7.1, the key limitation of this study is the restricted stroke subject pool as a result from the nature of the designed study task. Specifically, this study could only recruit medium- to high-functioning stroke subjects with minimum trunk compensation and ability to sense vibrations on their affected arm. Those criteria resulted in a small sample size for this study. With a small sample size, it is difficult to generalize either the significant or insignificant results to the whole population. Also, the high variability among individual stroke subjects' motor ability also added difficulties in proving the effect from vibrotactile training.

### **4.8 Summary**

This chapter detailed a study which investigated the effect of utilizing vibrotactile feedback in bilateral motion training in both the healthy and stroke populations. This study used an integrated system that allowed system users to play a target game using motion trackers, while receiving correction vibration feedback of their movements from a wearable device. The vibration feedback aimed to train healthy subjects to perform an asymmetric bilateral reaching motion and stroke subjects to perform a symmetric bilateral reaching motion, both with improved precision. The system recorded position data throughout each study session for all 27 subjects, with 10 healthy younger adults, 10 healthy older adults, and 7 stroke survivors.

The findings in this chapter demonstrate that healthy subjects are capable of utilizing vibrotactile feedback in guiding their non-dominant hand without visuals on their hand movements. However, the same analysis shows insufficient evidence of vibration training for improving trajectory-related and error-related performances in stroke subjects. Though there was no significant improvements throughout the entire motion trajectory for stroke subjects, stroke

subjects who performed outward correction showed significant precision improvements post-training for both the bimanual coordination and affected arm characteristics. This result suggests that stroke subjects might have built an internal model of the task path over the course of the vibration training, but might not have enough motor control to move to the desired end position with high accuracy nor in a straight path.

The effect of vibration training on stroke subjects is limited compared to evident changes in healthy subjects' performance. The insufficient evidence for stroke subjects is possibly due to a small sample size and a high variability of individuals' motor functions. However, even with a small sample size, this study managed to show: 1) significant precision improvements in end position, and 2) medium to large effect sizes in most performance improvements. This finding indicates promising applications of vibration feedback mechanisms in stroke rehabilitation and provides impetus for further investigations into such systems.

## Chapter 5

# Conclusions and Future Work

This thesis presented the development and assessment of an upper-arm virtual trainer that utilizes haptic channels for real-time motion guidance. The motivating question was whether a virtual trainer that uses vibrotactile cues can provide an alternate or complementary substitution for human trainers for both stroke and healthy trainees.

In particular, this work attempted to address the following research questions: 1) do people possess an intuitive, consistent motion response to vibrotactile cues? (Section 5.1); 2) do people prefer one motion response (*attractive* or *repulsive* response) over the other? (Section 5.1.1); 3) can a *line* vibration stimulus facilitate a higher consistency in motion response and a faster reaction time compared to a single-point *point* vibration? (Section 5.1.2); and 4) can vibrotactile cues aid able-bodied and stroke trainees in learning/relearning bilateral reaching motions (Section 5.2)?

Results from Study I (Chapter 3) answered the first three research questions and provided a few principles in helping subjects to interpret directional vibrotactile cues in Study II. The results of Study I contribute to a better understanding of how able-bodied adults naturally react to vibrotactile cues. This knowledge is important in minimizing the effect of interpretation of vibrotactile cues on subjects' training performance over time in short-term adaptation studies (Study II). Study II then investigated the fourth research question by evaluating subjects' motor performance in a bimanual reaching training session using an integrated gaming system (Chapter 4). The results from Study II contribute to the motor adaptation literature on the effect of using real-time vibration feedback in bilateral reaching motion training.

Section 5.1 and Section 5.2 summarize the findings corresponding to each of the two studies' research questions. Section 5.3 provides recommendations for future work that can help in further verifying and expanding the knowledge gathered in this thesis work.

## 5.1 Do People Possess an Intuitive, Consistent Motion Response to Vibrotactile Cues?

The findings detailed in Chapter 3 showed that about half of the subjects do not possess an intuitive, *consistent* motion response to vibrotactile stimuli; rather, they showed a *semi-consistent* or an *inconsistent* response. In other words, half of the subjects reacted to vibrotactile cues using more than one motion response. In particular, those subjects either showed no significant differences between the valid responses (*attractive* and *repulsive*), or those subjects possessed a dominant valid response, i.e., one of the valid responses had a significantly higher percentages than the other, but with no differences between the N/A and the dominant valid response. The inconsistency in those subjects' motion responses persisted even when the subjects perceived that vibrotactile cues were clear in direction guidance. This finding implies that some people intuitively react to vibrotactile cues in a consistent way, while others do not. Thus, for studies that intend to use vibrotactile cues in motion training, it is essential to observe each subject's intuitive motion response to vibration cues and reinforce the observed response, e.g., design a training session to ensure motion consistency throughout the study.

### 5.1.1 Do People Prefer One Type of Motion Response Over the Other?

As mentioned in Section 5.1, subjects showed different levels of consistency in motion responses to vibration cues. This section only discusses the results from subjects who showed *consistent* response (47.6%) and *semi-consistent* response (42.9%). Among the subjects who showed *consistent* motion response, even though more subjects favoured moving towards the vibrotactile stimuli, there were no significant differences found between the two types of responses (28.6% showed *attractive* response and 19.1% showed *repulsive* response). However, subjects who showed *semi-consistent* response significantly preferred an *attractive* response (38.1%) over a *repulsive* response (4.76%). These percentages imply that there is a trend where subjects preferred to respond to vibrotactile cues using an *attractive* response, but this trend cannot be generalized to the majority of the people. This finding indicates that there is a high variation between subjects' perception of vibrotactile stimuli in the context of motion guidance. Hence, rather than designing a system that can only accommodate one type of motion response,

the best systems are the ones that account for individual differences and provide vibrotactile cues to users based on their motion response. This result is consistent with the findings in Section 5.1.

### **5.1.2 Do the Line Vibration Stimuli Facilitate a Higher Consistency in Motion Response and a Faster Reaction Time in Comparison to the Point Vibration Stimuli?**

Study I examined subjects' consistency in motion response and reaction time using two types of vibration stimuli: *line* and *point*. The results showed no significant difference in the consistency level in motion response and the reaction time between the two types of vibrotactile stimuli. However, the data from the *point* vibration trials showed a higher consistency in motion response and a faster reaction time compared to the ones from the *line* vibration trials. In addition to subjects' performances, the post-test questionnaire results showed that subjects favoured the *point* vibrations slightly more than the *line* vibrations (not statistically significant).

## **5.2 Can Vibrotactile Cues Aid Able-Bodied and Stroke Trainees in Learning/Relearning Bilateral Reaching Motions?**

Based on all of the results from Study I, the author developed an integrated system that provides single-point vibration cues to users based on their motion response. Chapter 4 detailed the design and evaluation of an integrated system to answer the study question: *Can vibrotactile cues aid able-bodied and stroke trainees in learning/relearning bilateral reaching motions?* The author designed Study II such that the vibration cues were to guide healthy subjects' non-dominant arm and stroke subjects' affected arm either towards the body midline (inward) or away from the body midline (outward) while performing a bilateral forward reaching task. The analysis for examining the effect of vibration training included visualization of position change of the non-dominant or affected hand, correlation analysis on the performance metrics and trial number, and statistical analysis on quantifying late-training or post-training improvements.

For healthy subjects, vibrotactile instructional cues, in the absence of visual and auditory cues, are capable of altering the motion path of their non-dominant hand. Specifically, the position trajectories of healthy subjects' non-dominant hand gradually changed from a relatively straight forward line to the set task paths over time. Moreover, all five defined performance

metrics – RMS error, maximum deviation, reaching duration, index of curvature, and distance ratio – showed significant correlations with the trial number. Except the results from younger adults who performed inward movement, the two error-related performance metrics (RMS error and maximum deviation) showed significant improvements in late-training trials compared to the early-training trials. Those results indicate that healthy subjects are capable of learning a motion task purely based on vibrotactile feedback as guidance cues.

For stroke survivors, performance improvements due to the vibration training were not as evident as the ones for healthy subjects. Although the position trajectories of the stroke subjects' affected hand progressed from reaching at an angle to relatively straight forward, only stroke subjects who performed inward correction showed significant negative correlations over trials. However, for these subjects, the performance differences between the early- and late-training trials were not significant enough to be called improvements. By examining the post-training end-position accuracy and precision for both the bimanual coordination and the affected hand, only stroke subjects who performed outward corrections showed significant improvements in precision for both characteristics. The non-significant results were possibly due to the small sample size and the large between-subjects variations.

There are three plausible explanations *E1-E3* for finding significant improvements in only the end-position precision but not accuracy nor trajectory-related performance:

- E1.** stroke subjects might not have enough motor control to move to the desired end position with high accuracy nor in a straight path,
- E2.** this study recruited a small number of stroke subjects, which increased the difficulty in proving significance, and
- E3.** there was a pre-set condition that required subjects to have their hands within a certain bimanual tolerance at the final target in order to complete each trial.

Both reasons *E1* and *E2* are self-explanatory. Reason *E3* raised the interesting question of whether end-position improvements are influenced by a mixed effect of the pre-set condition and vibrotactile guidance rather than an outcome of vibrotactile guidance alone.

### 5.3 Recommendations & Future Work

This thesis provides insights for researchers who wish to use vibrotactile cues in motor learning and retraining. Since the findings in this study are limited for stroke survivors, this section lists a few ideas for future work to verify and expand the knowledge from this thesis work. The first half of this section discusses some recommended works corresponding to explanations *E2* and *E3*, and the last part of this section focuses on future work related to the utilization of vibrotactile cues.

The recommendation for *E2* is general and straightforward. One approach is to increase the sample size to better characterize any improvements from vibrotactile motion training. Another approach is to narrow the subject pool to recruit stroke subjects who have similar motor functions on a clinical scale, e.g., subjects who score 30-50 on UE-FM, where this approach can reduce individual differences. These suggestions are especially important for stroke population since there are large individual differences among stroke subjects.

A potential research direction to address *E3* is to examine the effect of any *forced* conditions on motor adaptation performance, for example, the pre-set condition in this study that constrained the subjects to have their hands within a certain error tolerance in order to complete each trial. Forced conditions include stopping/pausing the game when there is motion correction required and implementing force feedback that would physically alter the subjects' motion.

The study design in examining the effect of forced conditions on motor learning can be tricky. To illustrate, stopping/pausing the game might increase the frustration level of users. Also, using force feedback to directly move subjects' affected arm is not ideal since passive movements may not aid motor recovery [22]. One possible design is to use forced conditions to create different levels of difficulties. For example, the study can start with forced conditions that only applied at the end position. Then, after seeing improvements at the end position, the system can change the forced conditions to apply to the last 1/5 of the reaching movement, and so on.

As mentioned in Chapter 2, tactile cues are a common feedback technique used by rehabilitation therapists for cueing movements. For design simplicity, this work did not incorporate the therapeutic usage of tactile cues nor muscle tendon vibration. For research that examines multi-joint motions and subjects who are familiar with therapists' tactile cueing

instructions, a system that directly replicates therapists' tactile cueing instructions may be beneficial and easier to learn compared to the one in this study.

Also related to vibrotactile cues, some work can be done to investigate if different vibration patterns result in different outcome measures. Sample variations of vibration cues include varying-intensity vibrations and pulsed vibrations. Some commonly used cues for guidance are vibrations with error-dependent intensity, i.e., vibration intensity increases with increase of error, and vice versa [105], [106]. If researchers wish to investigate different vibration patterns in the context of dynamic motion training, motors with a large range of vibration intensity, such as voice coil vibrators, are recommended. Moreover, since intensive vibrotactile cues cause more sensory fatigue compared to auditory or visual cues, it is important to determine the maximum duration of each vibration training session to ensure the effectiveness of the training. Changing the constant-intensity vibrations used in this study to, for example, pulsed or error-dependent vibrations, might be able to lower the rate of sensory fatigue.

Finally, since this work showed promising results for able-bodied and stroke subjects in a short training session, the next step is to examine the effects of vibration-training using studies with longer durations. This type of study is especially valuable for stroke survivors to investigate if a vibration training regime can be beneficial in regaining motor function.

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# Appendix A

## Advertisements, Screening, and Consent Forms

### Contents

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## A.1 Study I Advertisements and Consent Forms

This section includes the advertising materials and consent form for healthy subjects. The contents of online or poster advertisement to recruit healthy subjects is presented in Figure A.1. The consent form for this study is presented from Figure A.2 to Figure A.6.



Department of Mechanical Engineering, UBC  
Collaborative Advanced Robotics and Intelligent Systems (CARIS) Lab  
ICICS 049, 2366 Main Mall, Vancouver, B.C. V6T 1Z4  
<omit>  
<omit>

### Vibrotactile Guidance of Arm Movement

**Principal Investigator:** Dr. Machiel Van der Loos, Dept. of Mechanical Engineering, <omit>, <omit>  
Dr. Elizabeth Croft, Dept. of Mechanical Engineering, <omit>, <omit>

**Co-Investigator:** Tina Hung, Master Candidate, Dept. of Mechanical Engineering, <omit>, <omit>

The Collaborative Advanced Robotics and Intelligent Systems (CARIS) Laboratory is conducting a study on guiding users' arm movements using vibrotactile cues. This study aims to provide a potential solution - having vibrotactile feedback for motion guidance in gaming - for promoting better motor learning of the non-dominant arm. The study will run for a maximum of 40 minutes. There is no compensation.

A wearable device that provides vibrotactile feedback will be used in this study. In this experiment, you will be asked to put on an armband and sleeve device that provides vibrotactile feedback at different locations on your arm, and you will be asked to do arm movements according to the vibration patterns that you feel on your arm. All the electronics are isolated from your skin with a stretchable, stocking-like material made from polyamide and polyester. You will be given a questionnaire to fill out after each stimulus and a post-test questionnaire regarding your experience.



Participants need to be 19 years or older (or a UBC student of 17 or older) and able to communicate in English. For more information regarding this study or to volunteer as a participant, please contact:

Tina Hung, <omit>  
<omit>

**Figure A.1: Contents of online or poster advertisement to recruit Study I subjects.**



**Department of Mechanical Engineering, UBC**  
Collaborative Advanced Robotics and Intelligent Systems (CARIS) Lab  
6250 Applied Science Lane,  
Vancouver, B.C V6T 1Z4  
<omit>

## **Informed Consent Form**

### **Vibrotactile Guidance of Arm Movement**

#### **Principal Investigator**

Name: Hendrik F. Machiel (Mike) Van der Loos  
Position title: Associate Professor, UBC Department of Mechanical Engineering  
Mailing address: <omit>  
Phone: <omit> Email: <omit>

#### **Co-Investigators**

Name: Elizabeth Croft  
Position title: Professor, UBC Department of Mechanical Engineering  
Mailing Address: <omit>  
Phone: <omit> Email: <omit>

Name: Chai-Ting (Tina) Hung  
Position title: MASC Candidate, UBC Department of Mechanical Engineering  
Mailing Address: <omit>  
Phone: <omit> Email: <omit>

Name: Bulmaro Valdes  
Position title: PhD Candidate, UBC Department of Biomedical Engineering  
Mailing Address: <omit>  
Phone: <omit> Email: <omit>

Name: Navid Shirzad  
Position title: PhD Candidate, UBC Department of Biomedical Engineering  
Mailing Address: <omit>  
Phone: <omit> Email: <omit>

#### **Contact Person:**

Please contact Hendrik F. Machiel (Mike) Van der Loos (office <omit>, cell <omit>, email <omit>) or Chai-Ting (Tina) Hung (cell <omit>, email <omit>) in the event of any unusual occurrences or difficulties related to this research.

#### **Funding Agency**

The Peter Wall Solutions Initiative (PWSI) of the Peter Wall Endowment at UBC and Natural Sciences and Engineering Research Council are funding this study.

**Figure A.2: Consent form for Study I subjects (page 1 of 5).**

**Introduction**

We invite you to take part in a research study being conducted by Mike Van der Loos, who is an associate professor at the University of British Columbia, and the co-investigators. Your participation in this study is voluntary and you may withdraw from the study at any time. The study is described below. This description tells you about the risks, inconvenience, or discomfort that you might experience. Participating in the study will likely not benefit you directly, but we might get useful results that can improve current rehabilitation therapy for stroke survivors. You should discuss any questions you have about this study with Dr. Van der Loos or the other investigators present.

**Purpose of the Study**

The purpose of this study is to investigate the effect of utilizing vibrotactile cues in a home-based stroke rehabilitation system that corrects stroke survivors' movements. In current practice, stroke survivors need to perform repetitive motions to maintain or regain their motor functions, which is tedious and frustrating. The proposed therapy system combines video-gaming and physical therapy to increase user engagement and positive upper-limb motor recovery. For this rehabilitation system, users are required to perform bimanual motions in order to force functional movements of the weaker arm; vibrotactile cues are used for matching the movements of the upper limbs.

The goal for this research is to study motor learning in healthy subjects in gaming. Specifically, this study measures motor learning performance of healthy subjects using a motion tracking system. With similar test conditions, it is expected that motor learning performance of healthy subjects can subsequently be used as an indicator for stroke survivors' motor learning performance. For example, the non-dominant and dominant sides of healthy subjects can be mapped to the affected and non-affected sides of stroke survivors, respectively.

**Study Design**

In this phase of the study, we want to investigate the patterns of vibration cues that give people the most intuitive and accurate motion guidance. We will ask you to put on a sleeve and armband design that is able to provide vibrotactile feedback. Different vibration cues will be provided to you via the sleeve and armband device. You will be asked to answer written questions after each stimulus. We will also ask you to fill out a post-study questionnaire related to the wearable device. Using your feedback from this study, we will improve the design of the wearable device.

**Who can participate in this study?**

We are seeking healthy adults (19 years or older, or a UBC student of 17 or older), who have basic knowledge of computers.

**Figure A.3: Consent form for Study I subjects (page 2 of 5).**

**Who is conducting the research?**

The study is being conducted by Dr. Van der Loos and the co-investigators listed on the title page of this form.

**What will you be asked to do?**

You will be asked to read and sign this consent form. If you choose to consent, you will be considered a participant in the study. You will be asked to attend one study session, conducted by Dr. Van der Loos or one of the co-investigators. It will be about one hour in duration. **The study will be videorecorded, a note taker will document important events as they occur.** For more details about the confidentiality and use of the collected data, please refer to the Confidentiality and Anonymity section of this consent form.

As a participant, you will be asked to put on a wearable device that provides vibrotactile feedback and fill out questionnaires.

**Will there be any negative consequences for you by participating in this study?**

Physical or mental fatigue could occur after trying out the system. If at any time you do not want to continue, you are under no obligation to do so. Dr. Van der Loos or one of the other researchers will also be available to answer your questions after the session.

**What are the benefits to your participation in this study?**

There will be no financial benefits to your participation, but all the researchers will appreciate your help in the development of a new upper extremity therapy system that could potentially help stroke survivors.

**Confidentiality and Anonymity**

Your confidentiality will be respected. No information or records that disclose your identity will be published without your consent, nor will any information or records that disclose your identity be removed or released without your consent unless required by law. You will be assigned a unique study number as a subject in this study. Only this number will be used on any research-related information collected about you during the course of this study, so that your identity [i.e., your name or any other information that could identify you] as a subject in this study will be kept confidential.

Information that contains your identity will remain only with the Principal Investigator and/or designate. The list that matches your name to the unique study number that is used on your research-related information will not be removed or released without your consent unless required by law.

Your rights to privacy are legally protected by federal and provincial laws that require safeguards to insure that your privacy is respected and also give you the

**Figure A.4: Consent form for Study I subjects (page 3 of 5).**

right of access to the information about you that has been provided to the sponsor and, if need be, an opportunity to correct any errors in this information.

According to the UBC Policy on Scholarly Integrity, the notes and the videotaped recordings from the sessions will be used for the purposes of analysis and then destroyed after 5 years after the end of this study. All collected data will be kept in a secure, locked room at UBC for five years after the end of this study. We will blur identifying features in video and photographs presented in publications. Access to the photographs and video will be restricted to the investigators. We will use the collected data only in relation to this particular study. Manuscripts based on the findings will be submitted to scientific journals for publication. In the event that quotes from a discussion are used, there will be no information included that could identify the speaker or the client, and you will not be identifiable in any report.

#### **What Happens if Something Goes Wrong?**

Signing this consent form in no way limits your legal rights against the sponsor, investigators, or anyone else, and you do not release the participating institutions from their legal and professional responsibilities.

#### **What if you still have some questions?**

Please feel free to contact Dr. Van der Loos or any co-investigators at the phone or e-mail addresses listed on the title page of this document if you have questions about this study.

#### **Do you have to participate?**

Your participation is completely on a volunteer basis. There are no penalties if you do not wish to participate. There is no financial reward for participating. If you do volunteer, you have the right to withdraw at any time, for any reason, without penalty. Similarly, the researchers have the right to terminate this research project at any time.

#### **Problems or Concerns**

If you have any concerns about your rights as a research subject or your experience while participating in this study, contact the Research Subject Information Line in the University of British Columbia Office of Research Services at email: [RSIL@ors.ubc.ca](mailto:RSIL@ors.ubc.ca), telephone: 604-822-8598 or toll free telephone number: 1-877-822-8598.

**Figure A.5: Consent form for Study I subjects (page 4 of 5).**

**Informed Consent Form: Vibrotactile Guidance of Arm Movement**

I have read the document entitled: **“Informed Consent Form: Vibrotactile Guidance of Arm Movement”** and understand its content. I understand that my participation in this study is strictly voluntary and that I may withdraw at any time, for any reason, without penalty. I understand that there is no monetary reward for participating in this study. I have been given the opportunity to discuss the study and my questions have been answered to my satisfaction. I understand that I will not be identified by name in any written or verbal report that results from this study. I also understand that I will receive a copy of the study’s Information Sheet and this Consent Form.

In agreeing to participate in this study, I understand that I am consenting to participate in a study that investigates using vibrotactile cues for motion guidance led by Dr. Van der Loos and co-investigators, and acknowledge that this includes that sessions will be video recorded.

Participant Signature: \_\_\_\_\_

Participant Printed Name: \_\_\_\_\_

Date: \_\_\_\_\_

In addition and separately, I agree to allow my comments to be quoted in reports or publications. If a quote were used, there would be nothing in the quote that could identify me or any of my clients.

Participant Signature: \_\_\_\_\_

Participant Printed Name: \_\_\_\_\_

Date: \_\_\_\_\_

\_\_\_\_\_  
Printed Name,  
Principal Investigator

\_\_\_\_\_  
Signature,  
Principal Investigator

\_\_\_\_\_  
Date

**Figure A.6: Consent form for Study I subjects (page 5 of 5).**

## **A.2 Study II Advertisements, Screening, & Consent Forms**

This section includes the advertising materials, list of screening questions, and consent forms for both the healthy and stroke subjects. The contents of online or poster advertisement to recruit healthy subjects and stroke survivors are presented in Figure A.7 and Figure A.8, respectively. The author also slightly modified the contents from healthy subjects' recruitment flyer to generate different versions of the advertisement that specifically look for older adults (45 years old and older) and female participants. Different versions of the advertisement were all approved by UBC Clinical Research Ethics Board but not included in this appendix.

The screening questions to assess the eligibility of the volunteers are presented in Figure A.9 for healthy subjects and Figure A.10 and Figure A.11 for stroke subjects. The consent form for healthy subjects is presented from Figure A.12 to Figure A.20, and the consent form for stroke subjects is shown from Figure A.21 to Figure A.30.



Department of Mechanical Engineering, UBC  
Robotics for Rehabilitation Exercise and Assessment in Collaborative Healthcare (RREACH) Lab  
Collaborative Advanced Robotics and Intelligent Systems (CARIS) Lab

# Come try out our new wearable human-computer interaction system!

## *Seeking volunteers: **Healthy Adults***

The RREACH and CARIS lab are seeking for **healthy volunteers who are 19 years old or older** to participate in a study on correcting users' bimanual reaching forward motion using vibrotactile (vibration) cues. You will be asked to answer some screening questions over the phone beforehand to see if you are eligible for this study.

### *Some study information:*

- **Study Location:** ICICS 049, 2366 Main Mall, UBC Point Grey Campus
- **Study Duration:** 1-1.5 hours
- **Study Compensation:** Transportation expense + a small thank-you gift

In this study, you will be asked to perform sets of bimanual reaching motion and interact with a computer using a motion tracking system and a wearable device. All the electronics on the wearable device are isolated from your skin with a stretchable material made from polyamide and polyester.



For more information or to volunteer as a participant, please contact:

**Tina Hung**  
<omit>

*Principal Investigator: Dr. Mike Van der Loos, Dept. of Mechanical Engineering*

**Figure A.7: Contents of online or poster advertisement to recruit healthy adults.**



Department of Mechanical Engineering, UBC  
Robotics for Rehabilitation Exercise and Assessment in Collaborative Healthcare (RREACH) Lab  
Collaborative Advanced Robotics and Intelligent Systems (CARIS) Lab

# Come try out our new wearable computer rehabilitation system!

## *Seeking volunteers: **Stroke Participants***

The RREACH and CARIS lab are conducting a study on correcting users' bimanual reaching forward behavior using vibrotactile (vibration) cues. We are looking for participants who are **recovering from a stroke** and **weakness on one side of the body as a result of stroke**. You will be asked to answer some screening questions over the phone beforehand to see if you are eligible for this study.

*Some study information:*

- **Study Location:** ICICS 049, 2366 Main Mall, UBC Point Grey Campus
- **Study Duration:** 1.5-2 hours
- **Study Compensation:** Transportation expense + a small thank-you gift

In this study, you will be asked to perform sets of bimanual reaching motion and interact with a computer using a motion tracking system and a wearable device. All the electronics on the wearable device are isolated from your skin with a stretchable material made from polyamide and polyester.



For more information or to volunteer as a participant, please contact:

**Tina Hung**  
<omit>

*Principal Investigator: Dr. Mike Van der Loos, Dept. of Mechanical Engineering*

**Figure A.8: Contents of online or poster advertisement to recruit stroke subjects.**

Healthy Participants: Screening Questions

Subject # \_\_\_\_\_

**Inclusion criteria (please circle Yes or No for each question if applicable):**

- 1) Your age: \_\_\_\_\_. Are you at least 19 years old? Yes (Jump to 2) No (Not Eligible)
- 2) Have you ever had a cerebral (brain) stroke? Yes (Not Eligible; might be eligible as stroke participant) No (Jump to 3)
- 3) Do you use a wheelchair? Yes (Jump to 5) No (Jump to 6)
- 4) If "No", do you have the ability to maintain a sitting position in a standard chair without arm rests, independently or with minimal supervision, for 1 hour? Yes (Jump to 6) No (Not Eligible)
- 5) If "Yes", can you transfer from your wheelchair to a chair without arm rests and stay seated independently or with minimal supervision, for 1 hour? Yes (Jump to 6) No (Not Eligible)
- 6) Do you use any type of brace or orthotic in your arms? Yes (Jump to 7) No (Jump to 8)
- 7) If "Yes", what type? \_\_\_\_\_
- 8) Are you able to stretch both of your arms fully in the air at your waist level? Yes (Jump to 9) No (Not Eligible)
- 9) Please measure the circumferences at the midsection of your upper arm (you can use a flexible string or strap to go around your upper arm and then flatten the string/strap and use a ruler for getting the measurement).  
Mid-upper arm circumference: \_\_\_\_\_ cm
  - (a) Is the measurement larger than 31 cm? Yes (Not Eligible) No (Jump to (b))
  - (b) Is the measurement smaller than 21 cm? Yes (Not Eligible) No (Next Question)

**Exclusion criteria (Any "Yes" makes the participant not suitable for this study):**

- 10) Have you had any surgery in your hands or arms in the past 6 months?  
Yes (Not Eligible) No (Next Question)
- 11) Do you suffer from shoulder subluxation (partial dislocation)? Yes (Not Eligible) No (Next Question)
- 12) Do you suffer from shoulder pain? Yes (Not Eligible) No (Next Question)
- 13) Do you have any other orthopedic or neurological conditions that affect your arm?  
Yes (Not Eligible) No (Next Question)
- 14) Do you have any uncorrected visual impairment? Yes (Not Eligible) No (**candidate is eligible**)

**Other:**

- 15) What transportation method would you use to get to campus? \_\_\_\_\_
- 16) Approx. home address (to calculate transportation costs) \_\_\_\_\_
- 17) Scheduling for test \_\_\_\_\_
- 18) Send Consent form to \_\_\_\_\_

**Figure A.9: Screening questions for healthy subjects.**

**Stroke Participants: Screening Questions**

**Subject #\_\_\_\_\_**

**Inclusion criteria (please circle Yes or No for each question if applicable):**

- 1) Your age: \_\_\_\_\_. Are you at least 19 years old? Yes (Next Question) No (Not Eligible)
- 2) Have you had only one stroke? Yes (Jump to 4) No (Next Question)
- 3) Please tell me the location of where each stroke was occurred at: \_\_\_\_\_
- 4) Do you suffer from hemiplegia (weakness on one side of your body)? Yes (Next Question) No (Not Eligible)
- 5) Was hemiplegia caused by a cerebral (brain) stroke? Yes (Next Question) No (Not Eligible)
- 6) Time since stroke: \_\_\_\_\_. Is it >6 months? Yes (Next Question) No (Not Eligible)
- 7) Weak side of your body? Left Right
- 8) Do you use a wheelchair? Yes (Jump to 9) No (Jump to 8)
- 9) If "No", do you have the ability to maintain a sitting position in a standard chair without arm rests, independently or with minimal supervision, for 1 hour? Yes (Jump to 10) No (Not Eligible)
- 10) If "Yes", can you transfer from your wheelchair to a chair without arm rests and stay seated independently or with minimal supervision, for 1 hour? Yes (Jump to 10) No (Not Eligible)
- 11) Do you use any type of brace or orthotic in your arms? Yes (Next Question) No (Jump to 12)
- 12) If "Yes", what type? \_\_\_\_\_
- 13) While sitting down with your back straight, are you able to move your weak hand forward at your waist level in the air to the middle length of your thigh without any help from the trunk or the strong hand? Are you able to perform this movement for at least 5 times? Yes (Next Question) No (Not Eligible)
- 14) Are you able to stretch your unaffected arm in the air fully around your waist level? Yes (Next Question) No (Not Eligible)
- 15) Please measure the circumferences at the middle length of your upper arm (can use a flexible string or strap to go around your upper arm and then flatten the string or strap to use a ruler for getting the measurement).  
Mid-upper arm circumference: \_\_\_\_\_ cm
  - (a) Is the measurement larger than 31 cm? Yes (Not Eligible) No (Jump to (b))
  - (b) Is the measurement smaller than 21 cm? Yes (Not Eligible) No (Next Question)

**Exclusion criteria (Any "Yes" makes the participant not suitable for this study):**

- 16) Have you had any surgery in your hands or arms in the past 6 months?  
Yes (Not Eligible) No (Next Question)
- 17) Do you suffer from shoulder subluxation (partial dislocation)? Yes (Not Eligible) No (Next Question)
- 18) Do you suffer from shoulder pain? Yes (Not Eligible) No (Next Question)
- 19) Do you have any other orthopedic or neurological conditions that affect your arm?  
Yes (Not Eligible) No (Next Question)

**Figure A.10: Screening questions for stroke subjects (page 1 of 2).**

- 1) Do you have any uncorrected visual impairment?    Yes (Not Eligible)    No (***candidate is eligible***)

**Other:**

- 2) What transportation method would you use to get to campus? \_\_\_\_\_
- 3) Approx. home address (to calculate transportation costs) \_\_\_\_\_
- 4) Scheduling for test \_\_\_\_\_
- 5) Send Consent form to \_\_\_\_\_
- 6) Have you ever participated in one or both of the two studies (FEATHERS or RIS project) in our lab?  
Yes (Next Question)            No
- 7) After you give consent to this study, can we use the clinical assessment scores from the FEATHERS and/or RIS project? For example:  
Fugl-Meyer score for upper extremity (FEATHERS & RIS): \_\_\_\_\_  
Modified Ashworth Scale (RIS): \_\_\_\_\_

**Figure A.11: Screening questions for stroke subjects (page 2 of 2).**



**Department of Mechanical Engineering, UBC**  
Robotics for Rehabilitation Exercise and Assessment in Collaborative Healthcare (RREACH) Lab  
Collaborative Advanced Robotics and Intelligent Systems (CARIS) Lab  
2054-6250 Applied Science Lane,  
Vancouver, B.C V6T 1Z4  
<omit>  
Website: <http://rreach.mech.ubc.ca/> and <http://caris.mech.ubc.ca>

## **Informed Consent Form: Adults**

### **VIBE-Guide Phase II: Vibrotactile Cues in Bimanual Reaching Motion**

#### **Principal Investigator**

Name: Hendrik F. Machiel (Mike) Van der Loos  
Position title: Associate Professor  
Organization: UBC Department of Mechanical Engineering  
Mailing address: 2054-6250 Applied Science Lane  
Phone: <omit> Email: <omit>

#### **Co-Applicants**

Name: Elizabeth Croft  
Position title: Professor, UBC Department of Mechanical Engineering  
Mailing Address: 2054-6250 Applied Science Lane, Vancouver.  
Phone: <omit> Email: <omit>

Name: Chai-Ting (Tina) Hung  
Position title: MAsc Candidate, UBC Department of Mechanical Engineering  
Mailing Address: 2054-6250 Applied Science Lane, Vancouver.  
Phone: <omit> Email: <omit>

#### **Contact Person:**

Please contact Chai-Ting (Tina) Hung (cell <omit>, email <omit>) or Hendrik F. Machiel (Mike) Van der Loos (office <omit>, cell <omit>, email <omit>) in the event of any unusual occurrences or difficulties related to this research.

#### **Funding Agency**

The Peter Wall Solutions Initiative (PWSI) of the Peter Wall Endowment at UBC and Natural Sciences and Engineering Research Council are funding this study.

**Figure A.12: Consent form for healthy older adults and younger adults (page 1 or 9).**

## **Introduction**

We invite you to take part in a research study being conducted by Mike Van der Loos, who is a professor at the University of British Columbia, and his colleagues. Your participation in this study is voluntary and you may withdraw from the study at any time. The study is described below. This description tells you about the risks, inconvenience, or discomfort which you might experience. Participating in the study will likely not benefit you directly, but we might learn things that will benefit others. You should discuss any questions you have about this study with Dr. Van der Loos or the other investigators present.

## **Your participation is voluntary**

Your participation is voluntary. You have the right to refuse to participate in this study. If you decide to participate, you may still choose to withdraw from the study at any time without any negative consequences to the medical care, education, or other services to which you are entitled or are presently receiving.

If you wish to participate in this study, you will be asked to sign this form. Please take time to read the following information carefully and to discuss it with your family and friends before you decide.

## **Purpose and summary of the study**

The purpose of this study is to investigate if vibrotactile (vibration) cues can be used to train healthy adults and people with stroke to reach both hands forward at the same time with system-specific horizontal spacing between both hands, respectively.

For this study, we propose to use a motion tracking system (PS3 Move Eye camera and Move Controllers) to obtain information about the way the participants' hands move in space when they reach forward with both hands. A wearable sleeve and armband device will be worn on healthy adults' non-dominant side and provide vibration feedback to instruct the participant to perform a bimanual reaching movement with system-specific horizontal spacing between both hands.

## **Study design**

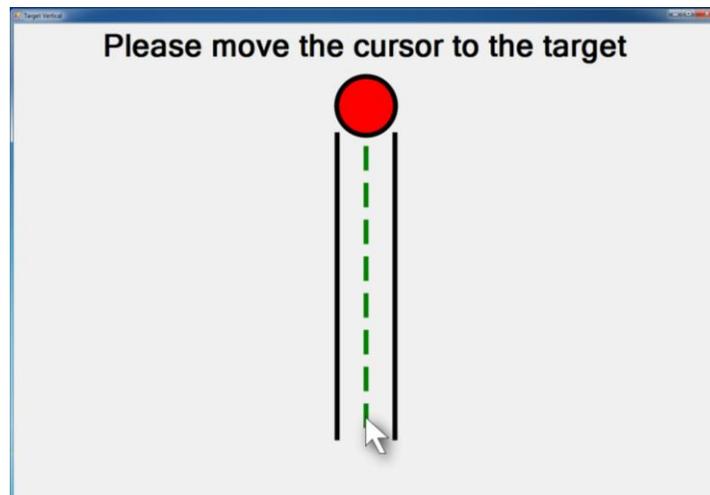
In this study, we will ask you to wear a wearable sleeve and armband device on your non-dominant arm and perform sets of forward reaching movements while holding two controllers in your hands (Figure 1). The controllers are used in combination with a camera to track your hand positions in space. The wearable sleeve and armband device will provide vibration cues around your forearm to instruct you in performing system-specific reaching motion with both hands. A cover will be used in parts of the experiment so that you will not see your hands during the reaching movement.

**Figure A.13: Consent form for healthy older adults and younger adults (page 2 of 9).**



**Figure 1: Picture of the wearable device and the controllers**

On a computer screen, we will display a cursor, two boarder lines, and a target (similar to Figure 2). You will start with an initial position with hands placed close to your body with shoulder width distance apart. The cursor will start on the mid-bottom of the screen. Then, you will have to move the cursor upward by moving both hands at the same time in the forward direction. You will try to keep the cursor within the black boarder lines to keep your movement straightly forward. You will need to hit the target on the screen and correct your hand location before moving on to the next target. Then, you will need to come back to the initial position to start the next target.



**Figure 2: Target Game Screenshot**

During the session, you will be seated in an office chair without armrests. There will be rest period in between sets of forward reaching movements. If at any time you feel tired you will be able to take breaks between targets.

Also, in this study, we will collect basic demographic data (age, gender, diagnosis), and at the end of the session, a questionnaire will be provided to get your valuable feedback in terms of the ease of use and functionality of the system.

**Figure A.14: Consent form for healthy older adults and younger adults (page 3 of 9).**

### **Who can participate in this study?**

We are seeking healthy adults who are willing to test this interactive system.

You may be able to participate in this study if:

- i. You are at least 19 years old (or a UBC student of 17 or older).
- ii. You have the ability to communicate in English.
- iii. You have never had a stroke or significant brain injury.
- iv. You are healthy without any movement disorder.
- v. You are able to maintain a sitting position in a chair without arm rests, independently or with minimal supervision, for 1 hour.
- vi. You are able to stretch both of your arms fully at your waist height.
- vii. The circumference at the middle length of your upper arm is between 21cm-31cm (due to limitation of the wearable device).

### **Who should not participate in this study?**

You will not be eligible to participate in this study if you have::

- i. Disability that would prevent you from completing the study tasks.
- ii. Surgery in the arms and hands in the past 6 months
- iii. Shoulder pain or instability (partial dislocation or subluxation)
- iv. Orthopedic or neurological conditions affecting arm movement
- v. Uncorrected visual impairment

### **How many participants will take part in this study?**

We are aiming to recruit a total of 15 hemiplegic stroke participants and 20 healthy adults to participate in this phase of the study. 10 out of the 20 healthy adults will be approximately age-matched to stroke participants.

### **Who is conducting the research?**

The study is being conducted by Dr. Van der Loos and colleagues listed on the title page of this form. The research is sponsored by UBC Peter Wall Solutions Initiative and Natural Sciences and Engineering Research Council of Canada (NSERC).

### **What will this study cost me?**

This study will be no cost to you. All research-related medical care and treatment and any related tests that you will receive during your participation in this study will be provided at no cost to you.

### **What will you be asked to do?**

You will be asked to read and sign this consent form. If you choose to consent, you will be considered a participant in the study. You will be asked to attend one session, conducted by Dr. Van der Loos or one of his colleagues, and assisted by a research assistant, and a physical therapist. It will be about 1 to 1.5 hours in duration. The study will be videotaped, a note taker will document important events as they occur, and the motion tracking data will be recorded. This is a requirement of the study. For more details about the confidentiality and use of the collected data, please refer to the Confidentiality section of this consent form.

**Figure A.15: Consent form for healthy older adults and younger adults (page 4 of 9).**

**Will there be any negative consequences for you by participating in this study?**

Physical or mental fatigue could occur while using the system. If at any time you do not want to continue, you are under no obligation to do so. Dr. Van der Loos or one of the co-investigators, the therapist, or the research assistant will also be available to answer your questions after the session.

**What are the benefits to your participation in this study?**

You may benefit from the knowledge that using vibration cues to train certain bimanual motion is currently being investigated. And that vibration cues could be used to train healthy adults in hand motion as well as potentially be used by stroke survivors as a mean for improving home-based upper extremity rehabilitation. You may feel satisfied to know that you have contributed to the development of evidence-based practice in rehabilitation for stroke.

In addition, you will be compensated for your travel expenses based on transportation method and the distance between your home and the UBC campus. We will have this reimbursement ready for you when you come in for the study. However, if you prefer, you can bring your travel receipts when you come for the study, and we will send you a reimbursement for the exact amount in the mail afterwards. In addition to travel compensation, you will also receive \$10 cash as a thank you gift for participating.

**What happens if I decide to withdraw my consent to participate?**

You may withdraw from this study at any time without giving reasons. If you choose to enter the study and then decide to withdraw at a later time, you have the right to request the withdrawal of your information collected during the study. This request will be respected to the extent possible. Please note however that there may be exceptions where the data will not be able to be withdrawn for example where the data is no longer identifiable (meaning it cannot be linked in any way back to your identity) or where the data has been merged with other data. If you would like to request the withdrawal of your data, please let the research team know. If your participation in this study includes enrolling in any optional studies, or long term follow-up, you will be asked whether you wish to withdraw from these as well.

**After the study is finished**

With your permission, you may be contacted in the future regarding your participation in other studies or phases of this project. At that time you can refuse to participate and your name will be removed from future correspondence.

If you would be interested in receiving more information about these future studies, please check the appropriate box at the end of this form.

If you are interested in the results of the study, you can contact the researchers and they will provide you with information about the results from this study.

**Figure A.16: Consent form for healthy older adults and younger adults (page 5 of 9).**

## **Confidentiality**

Dr. Van der Loos or one of his colleagues, a research assistant, and a physical therapist will be present in the room.

According to the UBC Policy on Scholarly Integrity, the notes, motion tracking data, and the videotaped recordings from the sessions will be used for the purposes of analysis and then destroyed after 5 years after publication. All collected data will be kept in a secure, locked room at UBC for five years after the end of this study. We will blur identifying features in video and photographs presented in publications. Access to the photographs and video will be restricted to the investigators. We will use the collected data only in relation to this particular study. Also, manuscripts based on the findings will be submitted to scientific journals for publication. In the event that quotes from a discussion are used, there will be no information included that could identify the speaker or the client, and you will not be identifiable in any report.

Your confidentiality will be respected. However, research records and health or other source records identifying you may be inspected in the presence of the Investigator or his or her designate by representatives of UBC Clinical Research Ethics Board for the purpose of monitoring the research. No information or records that disclose your identity will be published without your consent, nor will any information or records that disclose your identity be removed or released without your consent unless required by law.

You will be assigned a unique study number as a subject in this study. This number will not include any personal information that could identify you (e.g., it will not include your Personal Health Number, SIN, or your initials, etc.). Only this number will be used on any research-related information collected about you during the course of this study, so that your identity [i.e. your name or any other information that could identify you] as a subject in this study will be kept confidential. Information that contains your identity will remain only with the Principal Investigator and/or designate. The list that matches your name to the unique study number that is used on your research-related information will not be removed or released without your consent unless required by law.

Your rights to privacy are legally protected by federal and provincial laws that require safeguards to insure that your privacy is respected and also give you the right of access to the information about you that has been provided to the sponsor and, if need be, an opportunity to correct any errors in this information. Further details about these laws are available on request to the researchers.

### **What if you still have some questions?**

If you have any questions or desire further information about this study before or during participation, you can contact Tina Hung at <omit>, or the study principal investigator, Machiel (Mike) Van der Loos at <omit>.

**Figure A.17: Consent form for healthy older adults and younger adults (page 6 of 9).**

**What happens if something goes wrong?**

By signing this form, you do not give up any of your legal rights and you do not release the study doctor, participating institutions, or anyone else from their legal and professional duties. If you become ill or physically injured as a result of participation in this study, medical treatment will be provided at no additional cost to you. The costs of your medical treatment will be paid by your provincial medical plan.

**Do you have to participate?**

Your participation is completely on a volunteer basis. There are no penalties if you do not wish to participate. If you do volunteer, you have the right to withdraw at any time, for any reason, without penalty. Similarly, the researchers have the right to terminate this research project at any time.

If you do not wish to participate, you do not have to provide any reason for the decision nor will you lose the benefit of any medical care to which you are entitled or presently receiving.

**Problems or concerns**

If you have any concerns or complaints about your rights as a research participant and/or your experiences while participating in this study, contact the Research Participant Complaint Line in the University of British Columbia Office of Research Ethics by e-mail at [RSIL@ors.ubc.ca](mailto:RSIL@ors.ubc.ca) or by phone at 604-822-8598 (Toll Free: 1-877-822-8598).

**Figure A.18: Consent form for healthy older adults and younger adults (page 7 of 9).**

**VIBE-Guide Phase II: Vibrotactile Cues in Bimanual Reaching Motion  
Informed Consent Form: Adults**

My signature on this consent form means:

- I have read and understood the information in this consent form.
- I have had enough time to think about the information provided.
- I have been able to ask for advice if needed.
- I have been able to ask questions and have had satisfactory responses to my questions.
- I understand that all of the information collected will be kept confidential and that the results will only be used for scientific purposes.
- I understand that my participation in this study is voluntary.
- I understand that I am completely free at any time to refuse to participate or to withdraw from this study at any time, and that this will not change the quality of care that I receive.
- I understand that I am not waiving any of my legal rights as a result of signing this consent form.
- I understand that there is no guarantee that this study will provide any benefits to me.
- I will receive a signed copy of this consent form for my own records.

**Participant Signature:** \_\_\_\_\_

**Participant Name:** \_\_\_\_\_

**Date:** \_\_\_\_\_

**Signature of Person Obtaining Consent:** \_\_\_\_\_

**Printed Name of Person Obtaining Consent:** \_\_\_\_\_

**Date:** \_\_\_\_\_

**Figure A.19: Consent form for healthy older adults and younger adults (page 8 of 9).**

**VIBE-Guide Phase II: Vibrotactile Cues in Bimanual Reaching Motion  
Informed Consent Form (Cont'd): Adults**

In addition and separately, I agree to allow my comments to be quoted in reports or publications. If a quote were used, there would be nothing in the quote that could identify me.

**Participant Signature:** \_\_\_\_\_

**Participant Name:** \_\_\_\_\_

**Date:** \_\_\_\_\_

**OPTIONAL INFORMATION:**

i) For future studies:

**Yes, please contact me for participating in future studies.**

**Phone/email:**

\_\_\_\_\_

**Figure A.20: Consent form for healthy older adults and younger adults (page 9 of 9).**



**Department of Mechanical Engineering, UBC**

Robotics for Rehabilitation Exercise and Assessment in Collaborative Healthcare (RREACH) Lab  
Collaborative Advanced Robotics and Intelligent Systems (CARIS) Lab  
2054-6250 Applied Science Lane,  
Vancouver, B.C V6T 1Z4

<omit>

Website: <http://rreach.mech.ubc.ca/> and <http://caris.mech.ubc.ca>

## **Informed Consent Form: Stroke Survivors**

### **VIBE-Guide Phase II: Vibrotactile Cues in Bimanual Reaching Motion**

#### **Principal Investigator**

Name: Hendrik F. Machiel (Mike) Van der Loos

Position title: Associate Professor

Organization: UBC Department of Mechanical Engineering

Mailing address: 2054-6250 Applied Science Lane

Phone: <omit> Email: <omit>

#### **Co-Applicants**

Name: Elizabeth Croft

Position title: Professor, UBC Department of Mechanical Engineering

Mailing Address: 2054-6250 Applied Science Lane, Vancouver.

Phone: <omit> Email: <omit>

Name: Chai-Ting (Tina) Hung

Position title: MASc Candidate, UBC Department of Mechanical Engineering

Mailing Address: 2054-6250 Applied Science Lane, Vancouver.

Phone: <omit> Email: <omit>

#### **Contact Person:**

Please contact Chai-Ting (Tina) Hung (cell <omit>, email <omit>) or Hendrik F. Machiel (Mike) Van der Loos (office <omit>, cell <omit>, email <omit>) in the event of any unusual occurrences or difficulties related to this research.

#### **Funding Agency**

The Peter Wall Solutions Initiative (PWSI) of the Peter Wall Endowment at UBC and Natural Sciences and Engineering Research Council are funding this study.

**Figure A.21: Consent form for stroke participants (page 1 of 10).**

## **Introduction**

We invite you to take part in a research study being conducted by Mike Van der Loos, who is an associate professor at the University of British Columbia, and the co-investigators. Your participation in this study is voluntary and you may withdraw from the study at any time. The study is described below. This description tells you about the risks, inconvenience, or discomfort that you might experience. Participating in the study will likely not benefit you directly, but we might get useful results that can improve current rehabilitation therapy for stroke survivors. You should discuss any questions you have about this study with Dr. Van der Loos or the other investigators present.

## **Your participation is voluntary**

Your participation is voluntary. You have the right to refuse to participate in this study. If you decide to participate, you may still choose to withdraw from the study at any time without any negative consequences to the medical care, education, or other services to which you are entitled or are presently receiving.

You should be aware that there is a difference for both you and your doctor between being a patient and being a research participant. As a patient all medical procedures and treatments are carried out for your benefit only according to standard accepted practice. As a research participant you and your doctor also must take into account the requirements for the research study. These may include procedures and treatments that are not part of standard practice or are not yet proven. This consent form describes the diagnostic and treatment procedures that are being carried out for research purposes. Please review the consent document carefully when deciding whether or not you wish to be part of the research and sign this consent only if you accept being a research participant.

If you wish to participate in this study, you will be asked to sign this form. Please take time to read the following information carefully and to discuss it with your family, friends, and doctor before you decide.

## **Purpose and summary of the study**

The purpose of this study is to investigate if vibrotactile (vibration) cues can be used to train healthy adults and people with stroke to reach both hands forward at the same time with system-specific horizontal spacing between both hands, respectively.

For this study, we propose to use a motion tracking system (PS3 Move Eye camera and Move Controllers) to obtain information about the way the participants' hands move in space when they reach forward with both hands. A wearable sleeve and armband device will be worn on stroke participants' affected side and provide vibration feedback to instruct the participant to perform a bimanual reaching movement with system-specific horizontal spacing between both hands.

**Figure A.22: Consent form for stroke participants (page 2 of 10).**

## Study design

In this study, we will ask you to wear a wearable sleeve and armband device on your affected arm and perform sets of forward reaching movements while holding two controllers in your hands (Figure 1). The controllers are used in combination with a camera to track your hand positions in space. The wearable sleeve and armband device will provide vibration cues around your forearm to instruct you in performing system-specific reaching motion with both hands. A cover will be used in parts of the experiment so that you will not see your hands during the reaching movement.



Figure 1: Picture of the wearable device and the controllers

On a computer screen, we will display a cursor, two boarder lines, and a target (similar to Figure 2). You will start with an initial position with hands placed close to your body with shoulder width distance apart. The cursor will start on the mid-bottom of the screen. Then, you will have to move the cursor upward by moving both hands at the same time in the forward direction. You will try to keep the cursor within the black boarder lines to keep your movement straightly forward. You will need to hit the target on the screen and correct your hand location before moving on to the next target. Then, you will need to come back to the initial position to start the next target.

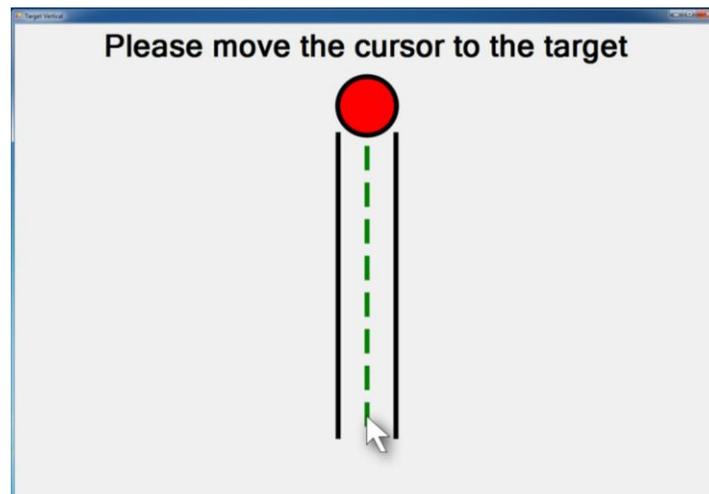


Figure 2: Target Game Screenshot

Figure A.23: Consent form for stroke participants (page 3 of 10).

During the session, you will be seated in an office chair without armrests. There will be rest period in between sets of forward reaching movements. If at any time you feel tired you will be able to take breaks between targets.

Also, in this study, we will collect basic demographic data (age, gender, diagnosis). In addition, a physical therapist will perform clinical assessments using the Fugl-Meyer Upper Extremity and the Modified Ashworth Scales to measure your upper limb impairment and spasticity. Your active range of motion of your arm will also be measured. During this assessment, he/she will require you to move your upper limb in different directions and orientations. At the end of the session, a questionnaire will be provided to get your valuable feedback in terms of the ease of use and functionality of the system.

### **Who can participate in this study?**

We are seeking adult stroke survivors who are willing to test this interactive system.

You may be able to participate in this study if:

- i. You are at least 19 years old and able to give consent.
- ii. You have the ability to communicate in English.
- iii. You have weakness on one of side of your body (hemiplegic) as a result of brain (cerebral) stroke.
- iv. Stroke occurred at least 6 months before this study.
- v. You are able to maintain a sitting position in a chair without arm rests, independently or with minimal supervision, for 1 hour.
- vi. You are able to move your affected hand forward at your waist level in the air to the middle length of your thigh without any help from the trunk or the strong hand for at least 5 times.
- vii. You are able to stretch your unaffected arm fully at your waist level.
- viii. The circumference at the middle length of your upper arm is between 21cm-31cm (due to limitation of the wearable device).

### **Who should not participate in this study?**

You will not be eligible to participate in this study if you have:

- i. Disability that would prevent you from completing the study tasks.
- ii. Surgery in the arms and hands in the past 6 months
- iii. Shoulder pain or instability (partial dislocation or subluxation)
- iv. Orthopedic or neurological conditions affecting arm movement
- v. Uncorrected visual impairment

### **How many participants will take part in this study?**

We are aiming to recruit a total of 15 hemiplegic stroke participants and 20 healthy adults to participate in this phase of the study. 10 out of the 20 healthy adults will be approximately age-matched to stroke participants.

**Figure A.24: Consent form for stroke participants (page 4 of 10).**

**Who is conducting the research?**

The study is being conducted by Dr. Van der Loos and colleagues listed on the title page of this form. The research is sponsored by UBC Peter Wall Solutions Initiative and Natural Sciences and Engineering Research Council of Canada (NSERC).

**What will this study cost me?**

This study will be no cost to you. All research-related medical care and treatment and any related tests that you will receive during your participation in this study will be provided at no cost to you.

**What will you be asked to do?**

You will be asked to read and sign this consent form. If you choose to consent, you will be considered a participant in the study. You will be asked to attend one session, conducted by Dr. Van der Loos or one of his colleagues, and assisted by a research assistant, and a physical therapist. It will be about 2 to 2.5 hours in duration. The study will be videotaped, a note taker will document important events as they occur, and the motion tracking data will be recorded. This is a requirement of the study. For more details about the confidentiality and use of the collected data, please refer to the Confidentiality section of this consent form.

**Will there be any negative consequences for you by participating in this study?**

Physical or mental fatigue could occur while using the system. If at any time you do not want to continue, you are under no obligation to do so. Dr. Van der Loos or one of the co-investigators, the therapist, or the research assistant will also be available to answer your questions after the session.

**What are the benefits to your participation in this study?**

You may benefit from the knowledge that a new upper extremity therapy is being developed that could potentially be used by stroke survivors, and you may feel satisfied to know that you have contributed to the development of evidence-based practice in rehabilitation for stroke.

In addition, you will be compensated for your travel expenses based on transportation method and the distance between your home and the UBC campus. We will have this reimbursement ready for you when you come in for the study. However, if you prefer, you can bring your travel receipts when you come for the study, and we will send you a reimbursement for the exact amount in the mail afterwards. In addition to travel compensation, you will also receive a \$10 cash incentive as a thank you gift for participating.

**What happens if I decide to withdraw my consent to participate?**

You may withdraw from this study at any time without giving reasons. If you choose to enter the study and then decide to withdraw at a later time, you have the right to

**Figure A.25: Consent form for stroke participants (page 5 of 10).**

exceptions where the data will not be able to be withdrawn for example where the data is no longer identifiable (meaning it cannot be linked in any way back to your identity) or where the data has been merged with other data. If you would like to request the withdrawal of your data, please let the research team know. If your participation in this study includes enrolling in any optional studies, or long term follow-up, you will be asked whether you wish to withdraw from these as well.

### **Assessment scores from past studies**

If you have participated and provided consent in the FEATHERS project and/or Reaching in Stroke project, your assessment scores (i.e., Fugl-Meyer Upper Limb Assessment score and Modified Ashworth Scale) from those previous studies may be passed on to this study upon your consent. Please check the appropriate box at the end of this form. Your privacy will be protected using our participant numbering system.

### **After the study is finished**

With your permission, you may be contacted in the future regarding your participation in other studies or phases of this project. At that time you can refuse to participate and your name will be removed from future correspondence.

If you would be interested in receiving more information about these future studies, please check the appropriate box at the end of this form.

If you are interested in the results of the study, you can contact the researchers and they will provide you with information about the results from this study.

### **Confidentiality**

Dr. Van der Loos or one of his colleagues, a research assistant, and a physical therapist will be present in the room.

According to the UBC Policy on Scholarly Integrity, the notes, motion tracking data, and the videotaped recordings from the sessions will be used for the purposes of analysis and then destroyed after 5 years after publication. All collected data will be kept in a secure, locked room at UBC for five years after the end of this study. We will blur identifying features in video and photographs presented in publications. Access to the photographs and video will be restricted to the investigators. We will use the collected data only in relation to this particular study. Also, manuscripts based on the findings will be submitted to scientific journals for publication. In the event that quotes from a discussion are used, there will be no information included that could identify the speaker or the client, and you will not be identifiable in any report.

Your confidentiality will be respected. However, research records and health or other source records identifying you may be inspected in the presence of the investigator or his or her designated representatives on UBC Clinical Research Ethics Board for the purpose of monitoring the research. No information or records

**Figure A.26: Consent form for stroke participants (page 6 of 10).**

that disclose your identity will be published without your consent, nor will any information or records that disclose your identity be removed or released without your consent unless required by law.

You will be assigned a unique study number as a subject in this study. This number will not include any personal information that could identify you (e.g., it will not include your Personal Health Number, SIN, or your initials, etc.). Only this number will be used on any research-related information collected about you during the course of this study, so that your identity [i.e. your name or any other information that could identify you] as a subject in this study will be kept confidential. Information that contains your identity will remain only with the Principal Investigator and/or designated representatives. The list that matches your name to the unique study number that is used on your research-related information will not be removed or released without your consent unless required by law.

Your rights to privacy are legally protected by federal and provincial laws that require safeguards to insure that your privacy is respected and also give you the right of access to the information about you that has been provided to the sponsor and, if need be, an opportunity to correct any errors in this information. Further details about these laws are available on request to the researchers.

#### **What if you still have questions?**

If you have any questions or desire further information about this study before or during participation, you can contact Tina Hung at <omit>, or the study principal investigator, Machiel (Mike) Van der Loos at <omit>.

#### **What happens if something goes wrong?**

By signing this form, you do not give up any of your legal rights and you do not release the study doctor, participating institutions, or anyone else from their legal and professional duties. If you become ill or physically injured as a result of participation in this study, medical treatment will be provided at no additional cost to you. The costs of your medical treatment will be paid by your provincial medical plan.

#### **Do you have to participate?**

Your participation is completely on a volunteer basis. There are no penalties if you do not wish to participate. If you do volunteer, you have the right to withdraw at any time, for any reason, without penalty. Similarly, the researchers have the right to terminate this research project at any time.

If you do not wish to participate, you do not have to provide any reason for the decision nor will you lose the benefit of any medical care to which you are entitled or presently receiving.

**Figure A.27: Consent form for stroke participants (page 7 of 10).**

**Problems or concerns**

If you have any concerns or complaints about your rights as a research participant and/or your experiences while participating in this study, contact the Research Participant Complaint Line in the University of British Columbia Office of Research Ethics by e-mail at [RSIL@ors.ubc.ca](mailto:RSIL@ors.ubc.ca) or by phone at 604-822-8598 (Toll Free: 1-877-822-8598).

**Figure A.28: Consent form for stroke participants (page 8 of 10).**

VIBE-Guide Phase II: Vibrotactile Cues in Bimanual Reaching Motion  
**Informed Consent Form: Stroke Survivors**

My signature on this consent form means:

- I have read and understood the information in this consent form.
- I have had enough time to think about the information provided.
- I have been able to ask for advice if needed.
- I have been able to ask questions and have had satisfactory responses to my questions.
- I understand that all of the information collected will be kept confidential and that the results will only be used for scientific purposes.
- I understand that my participation in this study is voluntary.
- I understand that I am completely free at any time to refuse to participate or to withdraw from this study at any time, and that this will not change the quality of care that I receive.
- I understand that I am not waiving any of my legal rights as a result of signing this consent form.
- I understand that there is no guarantee that this study will provide any benefits to me.
- I will receive a signed copy of this consent form for my own records.

**Participant Signature:** \_\_\_\_\_

**Participant Name:** \_\_\_\_\_

**Date:** \_\_\_\_\_

**Witness Signature:** \_\_\_\_\_

**Witness Name:** \_\_\_\_\_

**Date:** \_\_\_\_\_

**Signature of Person Obtaining Consent:** \_\_\_\_\_

**Name of Person Obtaining Consent:** \_\_\_\_\_

**Date:** \_\_\_\_\_

**Figure A.29: Consent form for stroke participants (page 9 of 10).**

**VIBE-Guide Phase II: Vibrotactile Cues in Bimanual Reaching Motion  
Informed Consent Form (Cont'd): Stroke Survivors**

In addition and separately, I agree to allow my comments to be quoted in reports or publications. If a quote were used, there would be nothing in the quote that could identify me.

**Participant Signature:** \_\_\_\_\_

**Participant Name:** \_\_\_\_\_

**Date:** \_\_\_\_\_

**OPTIONAL INFORMATION:**

i) If I had participated in the FEATHERS study and/or Reaching in Stroke (RIS) study before and had my assessment scores collected using the Fugl-Meyer Upper Limb Scale and/or Modified Ashworth Scale, I allow the researcher in this study to collect the score information from the researchers participated in the FEATHERS and/or RIS study.

**Participant Signature:** \_\_\_\_\_

**Participant Name:** \_\_\_\_\_

**Date:** \_\_\_\_\_

ii) For future studies:

**Yes, please contact me for participating in future studies.**

**Phone/email:**

\_\_\_\_\_

**Figure A.30: Consent form for stroke participants (page 10 of 10).**

# Appendix B

## Data Collection Forms

### Contents

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## B.1 Study I Demographics Questionnaire

This section includes the demographics questionnaire used in Study I for the subjects in Figure B.1.

### Demographic Questionnaire

1. What is your gender?

- Male
- Female

2. What is your age?

- 17-25
- 26-35
- 36-45
- 46-55
- 56-64
- 65+

3. Do you have any experience in using computers?

- Yes
- No

4. Do you have any experience with game consoles (i.e., PlayStation Move, Nintendo Wii, Microsoft Kinect, etc.)?

- Yes
- No

5. Do you have any experience with technologies that provide vibrotactile feedback (i.e., cellphones, Nintendo Wii, PlayStation Move, etc.)?

- Yes
- No

6. Do you have any experience with wearable technologies (i.e., GoPro camera)?

- Yes
- No

Figure B.1: Demographics form for Study I subjects.

## B.2 Study I Post-Test Questionnaire

For Study I, the post-test questionnaire includes two main categories: (A) perception and preference vibration cues based on type of vibration stimuli and (B) wearable device design. For the questions that include a five-point Likert scale in section (A) and (B), subjects were instructed to circle the number that best represents how strongly they feel about each statement. The post-test questionnaire is presented from Figure B.2 to Figure B.3.

### **Study I Post-Questionnaire: Vibrotactile Guidance of Arm Movement**

Please provide feedback on your experience with this study.

#### **A. Vibration Cues**

For the following statements, please circle the number that best represents how strongly you feel about each statement.

##### Types of Vibrations:

- **Point Vibration:** when there was only one vibrotactile stimulus applied at the elbow.
- **Line Vibration:** when there were two vibrotactile stimuli simultaneously applied at the wrist and elbow.

##### **A1. You know which direction to move based on the vibration type.**

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
<b>Point Vibration</b>	1	2	3	4	5
<b>Line Vibration</b>	1	2	3	4	5

##### **A2. You are confident that you are moving in the correct direction.**

	Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
<b>Point Vibration</b>	1	2	3	4	5
<b>Line Vibration</b>	1	2	3	4	5

##### **A3. Which type of vibration would you prefer to use for motion guidance?**

Type	Point Vibration	Line Vibration

Figure B.2: Post-test questionnaire for Study I subjects (page 1 of 2).

## **B. Device Design**

For the following statements, please circle the number that best represents how strongly you feel about each statement.

***B1. The device constrained your movement.***

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

***B2. The device is light-weighted and compact.***

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

***B3. The device material is comfortable.***

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

***B4. You feel unsafe wearing the device.***

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

***B5. It is simple to put on the device.***

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

***B6. You would use this device for arm movement motion guidance.***

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

***B7. Are there improvements that can be made to this wearable device?***

***B8. Do you have any concerns about this wearable device?***

***B9. Are there any other suggestions?***

**Thank you very much for your participation!**

Figure B.3: Post-test questionnaire for Study I subjects (page 2 of 2).

### B.3 Study II Demographics Questionnaire

This section includes the demographics questionnaire used in Study II for healthy subjects (Figure B.4) and stroke subjects (Figure B.5 and Figure B.6). For the demographics form for stroke subjects, larger fonts and spacing were designed to improve the readability of the forms.

#### Demographics Questionnaire: Healthy Participants

#### Effects of Vibrotactile Cues in Bimanual Reaching Motion

1. **Sex:**  Male  Female
2. **Age:** \_\_\_\_\_
3. **Dominant hand:**  Left  Right
4. **Do you have any experience in using computers?**  Yes  No
5. **Do you play computer games or video games?**  Yes  No
6. **Do you have any experience with game consoles (i.e., PlayStation Move, Nintendo Wii, Microsoft Kinect, etc.)?**  Yes  No
7. **How many times in total have you played games using any of the game consoles?**
  - 0 times
  - 1- 5 times
  - 6-10 times
  - 10-20 times
  - 20+ times
8. **Do you have any experience with technologies that provide vibrotactile feedback (i.e., cellphones, Nintendo Wii, PlayStation Move, etc.)?**  Yes  No
9. **Do you have any experience with wearable technologies (i.e., electronic watch, heart rate monitor, GoPro camera, etc.)?**  Yes  No

Figure B.4: Demographics form for healthy subjects.



1. **Do you play computer games or video games?**  
 Yes       No
  
2. **Do you have any experience with game consoles (i.e., PlayStation Move, Nintendo Wii, Microsoft Kinect, etc.)?**  
 Yes       No
  
3. **How many times in total have you played games using any of the game consoles?**  
 0 times  
 1- 5 times  
 6-10 times  
 10-20 times  
 20+ times
  
4. **Do you have any experience with technologies that provide vibrotactile feedback (i.e., cellphones, Nintendo Wii, PlayStation Move, etc.)?**  
 Yes       No
  
5. **Do you have any experience with wearable technologies (i.e., electronic watch, heart rate monitor, GoPro camera, etc.)?**  
 Yes       No
  
6. **Fugl-Meyer Score:** \_\_\_\_\_
  
7. **Modified Ashworth Scale:** \_\_\_\_\_
  
8. **Active Range of Motion Measurements:** \_\_\_\_\_

---

Figure B.6: Demographics form for stroke subjects (page 2 of 2).

## **B.4 Study II Post-Test Questionnaire**

For Study II, the post-test questionnaire includes four main categories: (A) reaching tasks, (B) wearable device design, (C) System Usability Scale, and (D) system design. All questions in section (A), (B), and (C) include a five-point Likert scale below each question for subjects to circle. Subjects were instructed to circle the number that best represents how strongly they feel about each statement.

For healthy and stroke subjects, questions in category (A) were slightly different due to the different study tasks, whereas questions in category (B) to (D) were the same. Thus, Figure B.7 presents the questions for healthy subjects regarding the reaching task, whereas Figure B.8 lists the questions for stroke subjects. Questions for the wearable device design, System Usability Scale, and open-ended questions regarding the system design are presented from Figure B.9 to Figure B.11.

## Effects of Vibrotactile Cues in Bimanual Reaching Motion

We would like your feedback on your experience with this study.

### **A. Reaching Task**

For the following statements, please circle the number that best represents how strongly you feel about each statement.

**A1. It was easy to control the cursor.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**A2. It was difficult for me to reach the target.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**A3. The vibration cues provided clear guidance for my hand to move to the specified locations.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**A4. I cannot feel the vibration on my forearm during the reaching task.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**A5. The controllers were easy to hold on to.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**A6. I felt tired after completing the session.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**(Please continue to the next page)**

Figure B.7: Questions regarding the reaching task for healthy subjects (page 1 of 4).

Post-Test Questionnaire: Stroke Participants

## Effects of Vibrotactile Cues in Bimanual Reaching Motion

We would like your feedback on your experience with this study.

### A. Reaching Task

For the following statements, please circle the number that best represents how strongly you feel about each statement.

**A1. It was easy to control the cursor.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**A2. It was difficult for me to reach the target.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**A3. The vibration cues corrected my movement to be more symmetric.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**A4. I can feel the vibration on my forearm during the reaching task without any problem.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**A5. I felt tired after completing the session.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**A6. The controllers were easy to hold on to.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

Figure B.8: Questions regarding the reaching task for stroke subjects (page 1 of 4).

## **B. Wearable Device Design**

For the following statements, please circle the number that best represents how strongly you feel about each statement.

### **B1. The wearable device constrained your movement.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

### **B2. The wearable device is light-weighted and compact.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

### **B3. The wearable device material is comfortable.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

### **B4. You feel unsafe wearing the device.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

### **B5. It is simple to put on the wearable device.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**(Please continue to the next page)**

**Figure B.9: Questions regarding the wearable device (page 2 of 4).**

**C. System Usability Scale (SUS)** © Digital Equipment Corporation, 1986.

In the following statements, “system” refers to the target game, wearable device, and controllers. Please circle the number that best represents how strongly you feel about each statement.

**C1. I think that I would like to use this system frequently.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**C2. I found the system unnecessarily complex.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**C3. I thought the system was easy to use.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**C4. I think that I would need the support of a technical person to be able to use this system.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**C5. I found the various functions in this system were well integrated.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**C6. I thought there was too much inconsistency in this system.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**C7. I would imagine that most people would learn to use this system very quickly.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**C8. I found the system very cumbersome to use.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

Figure B.10: Questions regarding the first eight questions of the System Usability Scale test (page 3 of 4).

**C9. I felt very confident using the system.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

**C10. I needed to learn a lot of things before I could get going with this system.**

Strongly disagree	Disagree	Neutral	Agree	Strongly Agree
1	2	3	4	5

## **D. System Design**

**D1. Are there any improvements that can be made to this system (i.e., target game, wearable device, and controllers)?**

**D2. What is your favorite feature of this system?**

**D3. What is your least favorite feature of this system?**

**D4. Are there any other suggestions?**

**Thank you for your participation!**

**Figure B.11: Questions regarding the remaining System Usability Scale test and open-ended questions on system design (page 4 of 4).**

# Appendix C

## Residual Analysis for Determining Cutoff Frequency

Residual analysis is one of the techniques to determine a suitable cutoff frequency for filters. For Study II, the author performed a residual analysis on all X-, Y-, and Z-position data for each subject's data file. In particular, the residual analysis includes the following steps:

- (1) apply a user-specified filter using different cutoff frequencies on the raw movement data,
- (2) calculate the residuals (defined as the standard deviation of the discrepancies between the original data and the filtered data, divided by number of observation) corresponding to the different cutoff frequencies, and
- (3) plot the residuals with respect to the cutoff frequencies to generate a residual plot.

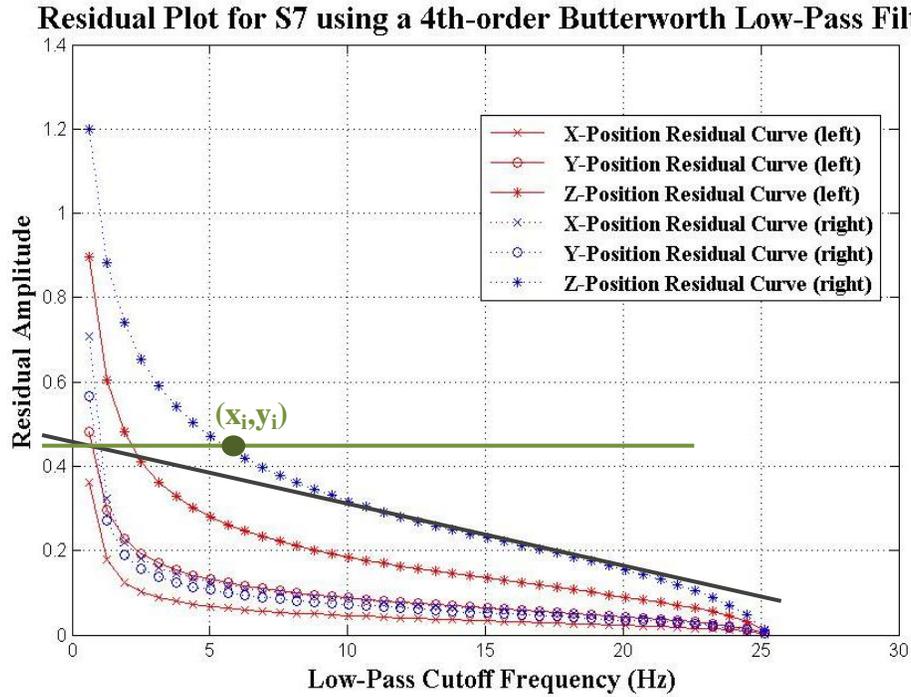
A sample residual plot for one stroke subject (S7) is shown in Figure C.1. The six residual curves were computed from the 3D position data of the subject's left and right hand. A sharper turn of the residual curve at a low cutoff frequency indicates that the movement data contain a narrower range of low frequency components compared to a residual curve with a smoother turn. To determine the cutoff frequency for human movement from a residual analysis, the rule of thumb is to retain most of the movement's low frequency components while removing noises at higher frequencies. Thus, the curve with the smoothest turn in Figure C.1, i.e., blue curve with asterisk marker, was used to determine the cutoff frequency for S7.

Using the residual plot of S7 (Figure C.1) as an example, the procedures to determine the cutoff frequency are:

- (1) draw a straight line which matched to most of the data points on the blue curve with asterisk marker (the Z-position residual curve of S7's right hand), i.e., the dark gray line in Figure C.1,

- (2) extend the straight line from (1) to find the y-intercept  $y_i$ , and
- (3) draw a horizontal line which passes by point  $(0, y_i)$  and intercept with the Z-position residual curve of S7's right hand at  $(x_i, y_i)$ , i.e., the green line in Figure C.1.

The value  $x_i$  is the desired cutoff frequency. In this case,  $x_i$  for S7 was around 6.2 Hz.



**Figure C.1: Residual plot for one of the stroke subjects (S7) who participated in Study II.**

# Appendix D

## Performance Metrics Correlations

This appendix lists the correlation test results in examining the correlations between the five performance metrics, defined in Section 4.5.2, and number of repetitions. Negative correlations were expected for all performance metrics to show performance improvements over trial. Table D.1 presents the Spearman's coefficient  $r_s$  and the corresponding  $p$ -values calculated from the test results.

**Table D.1: The  $p$ -values and correlation coefficient  $r_s$  obtained from the Spearman's Rank-Order Correlation Test. An asterisk \* indicates a significance of  $p < 0.05$ , whereas two asterisks \*\* refers to a significance of  $p < 0.001$ . Definitions: OA=older adults; YA= younger adults; SS = stroke subjects;  $IC_{ND/A}$  = index of curvature for the non-dominant/affected arm;  $R_{dis}$  = distance ratio.**

Performance Metrics	Outward Movement						Inward Movement					
	OA		YA		SS		OA		YA		SS	
	$r_s$	$p$ -value	$r_s$	$p$ -value	$r_s$	$p$ -value	$r_s$	$p$ -value	$r_s$	$p$ -value	$r_s$	$p$ -value
Normalized RMS error	-.722	<0.001**	-.568	0.001**	-0.250	0.068	-.851	<0.001**	-.747	<0.001**	-.514	<0.001**
Normalized Max error	-.746	<0.001**	-.816	<0.001**	-0.052	0.706	-.738	<0.001**	-.773	<0.001**	-.697	<0.001**
Normalized Reaching Duration (s/m)	-.701	<0.001**	-.850	<0.001**	-0.112	0.420	-.763	<0.001**	-.751	<0.001**	-.692	<0.001**
$IC_{ND/A}$	-.688	<0.001**	-.592	0.001**	-0.070	0.613	-.827	<0.001**	-.602	<0.001**	-.546	<0.001**
$R_{dis}$	-.701	<0.001**	-.657	<0.001**	0.024	0.864	-.408	0.009*	-.410	0.025*	-.332	0.014*