ABSTRACT

Validating Creativity: Use of the HTC Vive in Post-Stroke Upper Limb Rehabilitation

Amber Schulze

Director: Jonathan Rylander, Ph.D.

Physical therapists often creatively use virtual reality (VR) gaming systems in rehabilitation for patients with neurological deficits. However, therapists need to be aware of what games are applicable to their patient population, as well as how the virtual environment affects patients' perception of their motion. This study investigated how the game Google Tilt Brush, a 3D painting environment offered on the HTC Vive, could be applied in post-stroke upper limb rehabilitation, and explored limitations of the system through measuring reach distance of healthy subjects. Nine healthy subjects were recruited and asked to perform various reaching and drawing tasks while data on their movement was gathered using a Vicon motion capture system. The data showed that while in simple reaching tasks individual subjects may alter their reach distance by up to 3 cm in the virtual environment, across all subjects there is not a statistically significant change. Moreover, in more complicated drawing tasks, participants could reliably reach to particular points, but most participants missed the exact target by several centimeters. Overall, it seems that the HTC Vive and Google Tilt Brush can be utilized in post-stroke upper limb rehabilitation if therapists monitor patients to ensure they are accomplishing the desired movement.

APPROVED BY DIRECTOR OF THE HONORS THESIS:

Dr. Jonathan Rylander, Mechanical Engineering

APPROVED BY HONORS PROGRAM:

Dr. Elizabeth Corey, Director

DATE: ______________________

VALIDATING CREATIVITY:

USE OF THE HTC VIVE IN POST-STROKE UPPER LIMB REHABILITATION

A Thesis Submitted to the Faculty of

Baylor University

In Partial Fulfillment of the requirements for the

Honors Program

By

Amber Schulze

Waco, Texas

May 2019

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

This thesis is thanks to the support and encouragement of many people. It most certainly would not have happened without the direction of Dr. Jonathan Rylander and his consistent dedication to and excitement about the project. Jenny Tavares offered immense support in assisting with data collection, answering questions, and offering kindness. Tyler Jost also contributed greatly with his ideas and support.

I would also like to acknowledge all of the friends standing behind me in this project. Gennie, thank you for being a statistics consultant. A thank you also goes out to Sarah, Christine, Emma, and the others who offered their support and encouragement. I also could not have accomplished this thesis without the support of the numerous people who volunteered as subjects.

Lastly I would like to acknowledge the support of my family. I am not sure I could have completed this thesis without the support of Andrew and my parents.

DEDICATION

To my mom. Thank you for your constant encouragement and belief in me.

CHAPTER ONE

Introduction

The prevalence and outcomes of stroke require that it be addressed by creative rehabilitation solutions. In developed countries, stroke is the third most common cause of death, behind heart attacks and all cancers.[1] Globally, it is the second most common cause of death, with an estimated 5.8 million deaths annually due to stroke.[2] However, this is just a small piece of the global impact of stroke. There are actually approximately 17 million occurrences of stroke each year, and it is estimated that only one third of strokes result in death.[3] In fact, two thirds of patients that suffer a stroke survive with disability; half of these patients will experience major disabilities.[4] Thus, stroke is the leading cause of adult disability, and in the United States alone there are approximately 7 million people living with disability due to a stroke.[5]

While there are currently many therapeutic modalities to treat the impairments that may be caused by a stroke, one tool that has been used more and more is virtual reality gaming systems.[6] These gaming systems may offer many of the benefits of conventional

---

[1] Lindley, *Stroke*.

[2] Lindley.

[3] Lindley.

[4] Lindley.

[5] Nichols-Larsen and Kegelmeyer, "Stroke."

[6] Levin, Weiss, and Keshner, "Emergence of Virtual Reality as a Tool for Upper Limb Rehabilitation."

therapies while adding the motivation of an engaging game.[7] These technologies now range from games projected on a screen, to hand sensing technologies, to games utilizing a head-mounted display (HMD) system.[8] Some of these games may offer unique benefits and incorporate not only important aspects of conventional therapy and the novelty of a game, but also bring in unique opportunities for patient feedback and customization.[9] This thesis will explore one such system and game, Google Tilt Brush, played on the HTC Vive, and discuss how it may be applied to post-stroke upper limb rehabilitation.

How Strokes Occur

The nature of stroke leads to a broad spectrum of medical outcomes. Strokes occur when blood flow is interrupted to a particular portion of the brain.[10] This could be due to a blockage of a blood vessel (ischemia) or to a rupture of the blood vessel (hemorrhage).[11] Ischemic strokes may be caused by a clot that formed elsewhere, known as an embolism, or due to the formation of a thrombus, which is a build-up of plaque in the artery.[12] A diagram of the process of developing an ischemic stroke is shown in Figure 1. Hemorrhagic strokes may be further classified by whether they occurred within the cerebral vessels (intracerebral hemorrhage) or in the pia lining of the brain (subarachnoid

---

[7] Levin, Weiss, and Keshner.

[8] Levin, Weiss, and Keshner.

[9] Levin, Weiss, and Keshner.

[10] Nichols-Larsen and Kegelmeyer, “Stroke.”

[11] Nichols-Larsen and Kegelmeyer.

[12] Nichols-Larsen and Kegelmeyer.

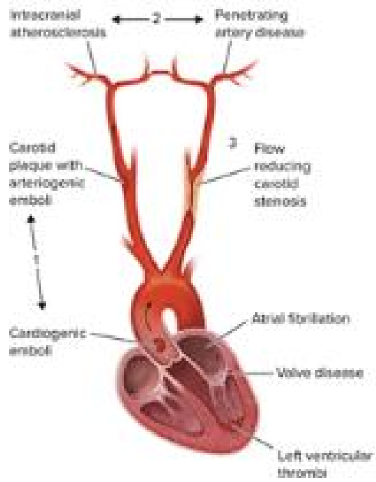


Figure 1: Development of an ischemic stroke. Left- embolus from heart enters cerebral circulation and is caught in atherosclerotic artery. Right- stenosis of carotid artery reduces cerebral blood flow and results in ischemia within arteria of cerebrum. [13]

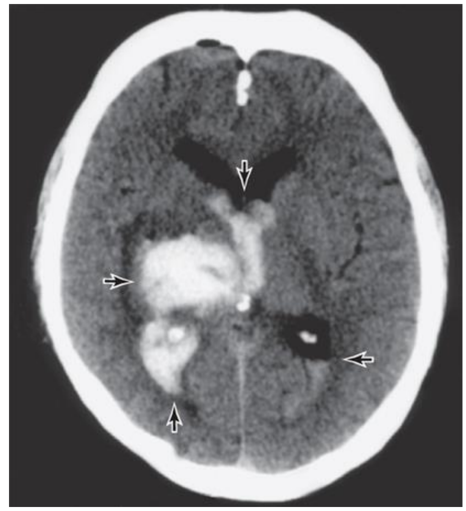


Figure 2: CT of a hemorrhagic stroke. Blood is seen as the white, high density signal.[14]

hemorrhage).[15] Figure 2 shows a CT scan of an intracerebral stroke.

Factors that Affect Impairment

The type of stroke and duration both affect the consequences of the stroke. Hemorrhagic strokes are more likely to lead to death than ischemic strokes.[16] Within ischemic strokes, the type of vessel blocked will affect the severity of the stroke; lacunar strokes, which are ischemic strokes in small vessels, may go undiagnosed, as they will interrupt blood flow to a small portion of the brain.[17] Ischemic strokes in larger vessels will

[13] Nichols-Larsen and Kegelmeyer.

[14] Hammer, *Pathophysiology of Disease*.

[15] Nichols-Larsen and Kegelmeyer, "Stroke."

[16] Nichols-Larsen and Kegelmeyer.

[17] Nichols-Larsen and Kegelmeyer.

interrupt blood flow to a larger portion of the brain and lead to more consequences.[18] Strokes that persist for a longer period of time will cause more brain damage, whereas transient ischemic attacks (TIAs) last for only a brief period and the stroke symptoms resolve in under 24 hours. [19]

The location of the stroke will greatly impact its outcomes. The arterial supply to the brain is quite complex, as shown in Figure 3. The brain is served by both pairs of internal carotid arteries and vertebral arteries.[20] Near the cerebellum the vertebral arteries join to form the basilar artery and send off several projections including the anterior inferior cerebral, superior cerebral, and pontine arteries, which service areas such as the cerebellum and pons.[21] The internal carotid also sends off the posterior cerebral artery, which supplies the occipital lobe, thalamus, hippocampus, and midbrain.[22] The posterior and anterior communicating arteries join the blood supply from the basilar artery with that from the interior carotid artery to form the Circle of Willis, from which the middle and anterior cerebral arteries branch off. The middle cerebral artery supplies parts of the frontal, temporal, and parietal lobe, while the anterior cerebral artery supplies the anterior and superior portions of the frontal and parietal lobe.[23] Figure 4 depicts the locations of several major areas of the brain, in order to clarify the areas each artery serves.

---

[18] Nichols-Larsen and Kegelmeyer.

[19] Nichols-Larsen and Kegelmeyer.

[20] Nichols-Larsen and Kegelmeyer.

[21] Nichols-Larsen and Kegelmeyer.

[22] Nichols-Larsen and Kegelmeyer.

[23] Nichols-Larsen and Kegelmeyer.

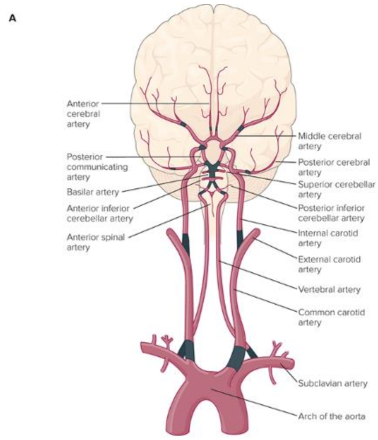


Figure 3: Diagram of the cerebral circulation[24]

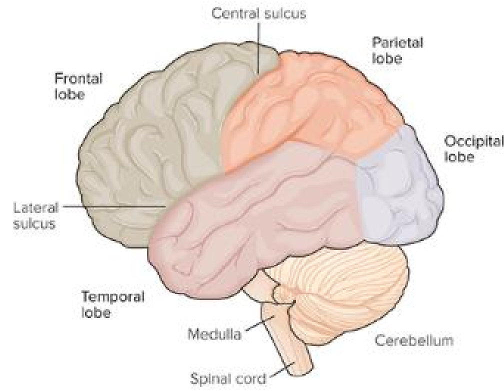


Figure 4: Diagram of the brain, highlighting the major areas of the brain[25]

The symptoms of a stroke reflect the location because the symptoms are determined by the regions of the brain that are damaged.[26] For instance, approximately 51% of strokes occur in the middle cerebral artery, thus affecting the premotor and motor cortexes, Broca's area, Wernicke's area, and the parietal lobe.[27] This leads to the commonly seen stroke symptions such as hemiparesis, due to damage in the primary motor cortex, sensory loss from damage in the parietal lobe, and expressive and receptive aphasia due to damage in Wernicke's and Broca's areas respectively.[28] Difficulty in planning motor activities, or apraxia, is another common symptom which occurs due to damage to the premotor cortex.[29] This is just one general example of the relationship between location

[24] Nichols-Larsen and Kegelmeyer.

[25] Nichols-Larsen and Kegelmeyer.

[26] Nichols-Larsen and Kegelmeyer.

[27] Nichols-Larsen and Kegelmeyer.

[28] Nichols-Larsen and Kegelmeyer.

[29] Nichols-Larsen and Kegelmeyer.

and symptoms. There are many other areas of the brain that could be impacted by a stroke and the exact location and length of the stroke will impact the exact nature and severity of impairments.

Aside from general brain region, there is also much research to show that the cerebral hemisphere in which the stroke occurs will determine not only which side of the body suffers greater motor and sensory deficits, but also affects the nature of those deficits.[30, 31, 32] Most deficits will be on the opposite, or contralateral side of the body as the brain damage; however, patients may also experience ipsilateral, or same side, deficits.[33] Furthermore, research has found that the hemisphere of the brain in which the stroke occurred affects the nature of the motor and sensory deficits that occur due to the stroke.[34] If the stroke occurs on the left side of the brain, the patient is likely to experience difficulty in controlling direction and making smooth, coordinated movements. Strokes occurring on the right side of the brain typically lead to difficulties in controlling final position of the arm and hand.[35]

---

[30] Mani et al., "Contralesional Motor Deficits after Unilateral Stroke Reflect Hemisphere-Specific Control Mechanisms."

[31] Kamper et al., "Alterations in Reaching after Stroke and Their Relation to Movement Direction and Impairment Severity."

[32] Kantak, Jax, and Wittenberg, "Bimanual Coordination."

[33] Nichols-Larsen and Kegelmeyer, "Stroke."

[34] Mani et al., "Contralesional Motor Deficits after Unilateral Stroke Reflect Hemisphere-Specific Control Mechanisms."

[35] Mani et al.

Common Results of a Stroke

While patients may experience very different disabilities after a stroke, there are some common deficits, particularly in regard to upper limb function. Many patients experience acute or chronic hemiparesis, or muscle weakness that affects one side of the body.[36] With this, many patients have difficulty achieving their maximum reach distance, no matter the direction, and their active range of motion (AROM) decreases with the severity of the stroke.[37] However, some studies found that stroke patients tend to have the most difficulty reaching high up and across their body, as well as placing their arm in abduction. [38,39] Moreover, stroke patients typically have a slower movement speed in their upper limb and typically use a longer path length to reach a goal, often due to compensatory movements.[40] Many patients suffer from deficits in their proprioception, which contributes to their kinesthetic deficits. [41,42] Various visual deficits are also common.[43]

---

[36] Nichols-Larsen and Kegelmeyer, "Stroke."

[37] Nichols-Larsen and Kegelmeyer.

[38] Kamper et al., "Alterations in Reaching after Stroke and Their Relation to Movement Direction and Impairment Severity."

[39] Sukal, Ellis, and Dewald, "Shoulder Abduction-Induced Reductions in Reaching Work Area Following Hemiparetic Stroke."

[40] Kamper et al., "Alterations in Reaching after Stroke and Their Relation to Movement Direction and Impairment Severity."

[41] Semrau et al., "Robotic Identification of Kinesthetic Deficits After Stroke."

[42] Dukelow et al., "The Independence of Deficits in Position Sense and Visually Guided Reaching Following Stroke."

[43] Sand et al., "Vision Problems in Ischaemic Stroke Patients."

One interesting impairment to note is the lack of isolated muscle control. The muscles of the limbs function in synergistic pairs in flexion or extension.[44] For example, in the upper limb synergy, flexion of the shoulder occurs with elbow and wrist flexion and hand closing. In the same manner, shoulder extension is associated with elbow and wrist extension and hand opening. These flexor and extensor synergies are controlled by brainstem level motor control.[45] In contrast, the isolated muscle control needed to activate single muscles and create a full range of movement is controlled by the motor cortex. Thus, as a patient is recovering from a stroke, they may regain synergistic muscle control but not isolated muscle control.[46]

Treatment of Impairments Due to a Stroke

To address the many deficits patients experience, therapy for stroke patients is personalized but includes several particular aspects. Research has found that post-stroke upper limb rehabilitation should work to prevent learned non-use of the paretic limb while still teaching compensatory techniques to enable individuals to perform activities of daily living (ADLs).[47] Thus, as far as is possible, therapy should encourage the use of the paretic upper limb, and provide opportunities for successful movement. Therapy should be meaningful and tasks goal-oriented, as the goal will dictate the type of movement (reaching

---

[44] Nichols-Larsen and Kegelmeyer, "Stroke."

[45] Nichols-Larsen and Kegelmeyer.

[46] Nichols-Larsen and Kegelmeyer.

[47] Nichols-Larsen and Kegelmeyer.

for a glass versus placing a thumb tack on a board).[48] These tasks will be designed to fit the patient's current abilities and goals. Research has shown that therapy for the upper limb is most beneficial when patients receive feedback on their movement performance, rather than feedback simply on the outcomes of their movement. [49] With this, therapy should allow for intensive practice of activities that are just outside of the abilities of the patient.[50]

Despite the differences in patients, we see that these aspects are worked into various treatment techniques commonly used by physical therapists in the treatment of upper arm deficits. Parry, Lincoln, and Appleyard found that the treatment techniques employed by clinicians can be divided into several categories. There were less active treatments such as preparation/relaxation, passive movements and stretching carried out by the therapist, inhibitory mobilizations, and massage aimed at increasing sensory awareness of the arm. Pain management and care of the arm were often discussed with patients. Therapists also included facilitated movements, active movements, functional movements, and instruction in self-practice activities. Therapists made functional movements goal oriented and related to activities of daily living; these included reaching to touch or grasp an object, simple grasping and releasing tasks, and using the arm in board or ball games.[51]

---

[48] Nichols-Larsen and Kegelmeyer.

[49] Cirstea and Levin, "Improvement of Arm Movement Patterns and Endpoint Control Depends on Type of Feedback During Practice in Stroke Survivors."

[50] Nichols-Larsen and Kegelmeyer, "Stroke."

[51] Parry, Lincoln, and Appleyard, "Physiotherapy for the Arm and Hand after Stroke."

Alongside treatment, assessment of improvement of stroke patients is also important and involves aspects similar to the therapy. Two common forms of assessment are the Wolf Motor Function Test (WMFT) and the Fugl-Meyer Upper Extremity Assessment (FMA-UE). The WMFT covers activities ranging from large shoulder and elbow movements, particularly flexion, abduction, and elbow extension during shoulder abduction. It also looks at patients' ability to reach, grasp, and lift items, as well as exhibit hand coordination. Tasked are scored based on how long it takes the patient to complete the task.[52] The FMA-UE requires many similar tasks, both large, gross motor tasks, and tasks that require fine motor skills. Moreover, it addresses measurement of how strongly patients are locked into the flexor synergy, as well as patients' sensory deficits.[53]

How Virtual Reality May Meet the Needs of Therapy for Impairments Due to Stroke

Virtual Reality (VR) gaming can serve as a unique tool for clinicians in treating stroke patients. It offers ways to integrate conventional therapy with the motivation of a novel game. Therapists have been taking advantage of this for many years, and as a result many technologies have either been appropriated from commercial gaming or developed specifically for therapy.

---

[52] Wolf et al., "Wolf Motor Function Test (WMFT)."

[53] Fugl-Meyer et al., "FUGL-MEYER ASSESSMENT UPPER EXTREMITY (FMA-UE) Assessment of Sensorimotor Function."

What Constitutes "Virtual Reality"?

Virtual reality systems create simulated environments with which the user can interact.[54] However, VR technology is not just the futuristic technology we may initially think of. VR started as interactive environments displayed on 2D computer and TV screens.[55] Some of the first examples we would think of would be the Nintendo Wii and Xbox Kinect systems. Today, that technology has progressed to include more immersive systems, such as the CAVE automatic virtual environment and Head Mounted Displays (HMDs).[56] While VR may include a wide range of technology, the systems do have commonalities. They incorporate both a computer providing sensory input to the user, and the user being able to give input back into the computer.[57] Beyond this however, they create a complex environment that the user can interact with and affect. Generally, these environments include 3D style graphics, even if those graphics are displayed on a 2D screen. The user may interact with the environment in many ways, including through a mouse or movement sensing cameras and controllers.[58]

[54] Wilson, Foreman, and Stanton, "Virtual Reality, Disability and Rehabilitation."

[55] Subramanian and Levin, "Viewing Medium Affects Arm Motor Performance in 3D Virtual Environments."

[56] Gamito et al., "Virtual Exercises to Promote Cognitive Recovery in Stroke Patients."

[57] Gamito et al.

[58] Gamito et al.

Use of Virtual Reality

Historically, VR has not only been used in gaming. It has also been commonly applied in flight simulators [59] and procedural training for surgeons.[60] However, there has been movement towards applications in therapy.

Some of the earliest applications of virtual reality technologies in physical therapy were in rehabilitation of traumatic brain injury patients. These systems were quite varied; however, most incorporated simple patient input compared to what is available today. One earlier system, which is still used today, consisted of a cycle ergometer with a monitor that displayed various scenery that the patient could "ride" through in order improve cognitive function through exercise.[61] Another early system created a virtual kitchen, displayed using head mounted 3D display glasses that the patient interacted with using a computer mouse. The goal of this system was to create a way for patients to practice daily living skills in a less dangerous environment.[62]

From here, as technology progressed, the technologies used in rehabilitation also progressed. Gaming technology advanced to utilizing motion tracking and larger display screens. One early iteration was the VividGroup's Gesture Xtreme VR system, which utilized a large display screen that the user stood in front of. A video camera recorded the

---

[59] Lintern, Roscoe, and Sivier, "Display Principles, Control Dynamics, and Environmental Factors in Pilot Training and Transfer."

[60] Abboudi et al., "Current Status of Validation for Robotic Surgery Simulators – a Systematic Review."

[61] Grealy, Johnson, and Rushton, "Improving Cognitive Function after Brain Injury."

[62] Christiansen et al., "Task Performance in Virtual Environments Used for Cognitive Rehabilitation after Traumatic Brain Injury."

user, whose image was displayed on the screen in the game environment. Thus, the user interacted with the environment through their on-screen avatar. The various games available made this system suited to multiple types of rehabilitation.[63]

Commercially popular games have also proven useful in therapy. The Nintendo Wii and Microsoft Kinect have been two highly popular systems that have been utilized in various types of rehabilitation, particularly orthopedic and neurologic rehabilitation. Both of these systems utilize a large display screen with motion tracking. Many studies utilizing the Wii also incorporated the Wii Fit, which also uses a balance board to gather information on player weight distribution. The Wii and Kinect have been investigated for use in therapy for post-stroke hemi-paralysis, post-stroke balance issues, cerebral palsy, and total knee arthroplasty.[64]

Larger combined systems have also been used in various types of rehabilitation. One study utilized a treadmill with a large, circular display screen to improve mediolateral instability individuals with unilateral transfemoral amputation.[65] Other studies have used a similar system of treadmill and display screen to improve balance in stroke patients.[66]

---

[63] Kizony, Katz, and (Tamar) Weiss, "Adapting an Immersive Virtual Reality System for Rehabilitation."

[64] Laver et al., "Virtual Reality for Stroke Rehabilitation."

[65] Sheehan et al., "Use of Perturbation-Based Gait Training in a Virtual Environment to Address Mediolateral Instability in an Individual with Unilateral Transfemoral Amputation."

[66] Corbetta, Imeri, and Gatti, "Rehabilitation That Incorporates Virtual Reality Is More Effective than Standard Rehabilitation for Improving Walking Speed, Balance and Mobility after Stroke."

Furthermore, a more common virtual reality system, the CAVE has also show possibilities of applications in rehab.[67,68]

Several of the newer technologies for virtual reality that are currently on the market are head mounted display (HMD) systems. These systems, such as the HTC Vive and Oculus Rift immerse the player in the virtual world using a stereoscopic head mounted display to create a 3-D, 360 degree field of view. Motion tracking cameras and hand-held controllers allow the user to interact with virtual world. Initial research has been done on the use of these systems in therapy, particularly in neurological rehabilitation.[69,70,71,72,73]

Uses for VR in physical therapy may be divided into three broad, and often overlapping categories- as an analgesic, in orthopedic rehabilitation, and in rehabilitation for traumatic brain injury patients.

VR may be used as an analgesic by diverting patients' attention from the pain they often experience during therapy. While we often think of things with analgesic properties, pain medication is usually what comes to mind, the power of simple diversion can prove

---

[67] Cruz-Neira et al., "Scientists in Wonderland."

[68] Borrego et al., "Feasibility of a Walking Virtual Reality System for Rehabilitation."

[69] Gamito et al., "Virtual Exercises to Promote Cognitive Recovery in Stroke Patients."

[70] Grealy, Johnson, and Rushton, "Improving Cognitive Function after Brain Injury."

[71] Corbetta, Imeri, and Gatti, "Rehabilitation That Incorporates Virtual Reality Is More Effective than Standard Rehabilitation for Improving Walking Speed, Balance and Mobility after Stroke."

[72] Christiansen et al., "Task Performance in Virtual Environments Used for Cognitive Rehabilitation after Traumatic Brain Injury."

[73] Anglin, Sugiyama, and Liew, "Visuomotor Adaptation in Head-Mounted Virtual Reality versus Conventional Training."

quite useful in alleviating pain experienced during physical therapy. For instance, Schmitt et al. found that although therapy utilizing immersive VR technology did not affect maximum range of motion achieved by patients, patients did report 27-44 percent decreases in pain ratings during the VR therapy as compared to conventional therapy.[74]

VR has also proven useful in orthopedic rehab. One study investigated the effect of exergaming, performing exercises in a gamified setting, using a Wii on pain due to shoulder impingement syndrome as compared to a traditional home exercise program using resistance bands.[75] The Wii group took part in training that included boxing, bowling, and tennis games, at first without resistance, and then progressing to using resistance bands during game play. The games provided exercises parallel to those of the home exercise program. While both groups experienced a significant reduction in pain, the Wii group experienced significantly more pain reduction than the conventional therapy group.

Perhaps one of the most common uses of VR in physical therapy is in the treatment of patients with stroke or traumatic brain injury. McNulty et al. demonstrated the efficacy of utilizing the Wii console for rehabilitation of stroke patients by comparing it to one of the current best practice methods, modified constraint-induced movement therapy (mCIMT). The Wii protocol included specific drills utilizing games such as golf, boxing, baseball, bowling, and tennis. The mCIMT protocol involved patients wearing a

---

[74] Schmitt et al., "A Randomized, Controlled Trial of Immersive Virtual Reality Analgesia, during Physical Therapy for Pediatric Burns."

[75] "Structured Wii Protocol for Rehabilitation of Shoulder Impingement Syndrome: A Pilot Study - ScienceDirect."

mitt on their less affected hand for much of the day, to encourage them to use their more affected hand, along with formal therapy sessions of equivalent duration to the Wii protocol. The study found the Wii protocol to be as effective in their outcomes measures as the mCIMT, with a higher patient preference and engagement.[76]

Virtual Reality for Stroke Patients: Difficulties and Benefits

The novelty of VR gaming is precisely why it is often so useful in physical therapy, particular in therapy for post-stroke patients. As we have seen, it offers both a unique and interesting environment, as well as many interesting ways to creatively adjust and sometimes improve therapy. However, to understand its specific contributions to stroke rehab, it is important to consider the intricacies of stroke and post-stroke rehabilitation, particularly for patients with hemiparesis of the upper limb.

Previous studies have attempted to use VR to meet these needs but have found the technology to be lacking in different areas. Acosta, Dewald, and Dewald compared the achieved reaching distances of patients playing an air hockey game to patients asked to reach to three specific targets designed to encourage flexion and elbow extension. They found that on average, subjects achieved greater reach distances when asked to reach specific targets, even when the arm avatar in the air hockey game was scaled to encourage them to reach further. However, for particular subjects and reaching targets, the converse was true and the subjects achieved significantly greater reach distance using the game. Overall, patients stated that they found the game to be a more engaging system of feedback

[76] McNulty et al., "The Efficacy of Wii-Based Movement Therapy for Upper Limb Rehabilitation in the Chronic Poststroke Period."

and said that they would prefer it for a hypothetical intervention. The authors discussed the need for the game to still include specific targets, particularly in areas that require the patients to break out of the flexion synergy, as well as the ability to scale the game to the patient and slowly increase the difficulty.[77]

Other groups have sought to address the various needs of post-stroke therapy by creating their own virtual environment. Subramanian et al. created a virtual environment to practice pointing movement using a head mounted display, a PC running a Computer Assisted Rehabilitation Environment (CAREN), and motion tracking system, and a CyberGlove. The system displayed two rows of three targets which may be adjusted to fit the patients reach length so that patient did not need to move their trunk in order to reach the targets. The system provided feedback on results by auditory warnings if the patient hit the target. Furthermore, the system would give auditory and visual cues if patients displaced their trunk too far forward. The researchers found that patient accuracy was comparable between the virtual environment and a similar physical environment, with patients finding the virtual environment more enjoyable and motivating.[78]

Several reviews of the needs of virtual reality systems for post-stroke upper limb rehabilitation have been performed. Levin et al. noted several specific improvements and requirement for VR systems to realize their full potential in rehabilitation. Systems must balance between focusing on task outcome and performance. Many commercially available

---

[77] Acosta, Dewald, and Dewald, "Pilot Study to Test Effectiveness of Video Game on Reaching Performance in Stroke."

[78] Subramanian and Levin, "Viewing Medium Affects Arm Motor Performance in 3D Virtual Environments."

games simply focus on task outcome, and give no feedback on the performance task, thereby allowing patients to utilize compensatory motions. However, it is important for games to give explicit instructions on how tasks should be performed and only reinforce proper movement. Furthermore, Levin et al. noted that the virtual environment should include 3D visual cues, such as perspective lines, shading, and drop lines, as well as include accurate tracking and representations of the arm and hand. Games should also be modifiable to patient needs and incorporate motions to various parts of the workspace, particularly the side contralateral to the more affected hand.[79] Proffitt and Lange also reviewed the state of VR use in post-stroke therapy and made recommendations for further research and advancement of the use of VR technology. They noted that VR technology has the capability to be used for assessment as well as providing much higher levels of feedback during treatment. Integrating the motion tracking of the software into a system to provide quantitative motion data could offer a way for clinicians to easily assess patient performance and improvement, and well as give real time qualitative feedback to patients.[80]

HTC Vive and Tilt Brush

The HTC Vive is one of the newest commercially available VR gaming systems. It uses an HMD with an individual screen for each eye to allow for stereoscopic depth perception.[81] The HTC Vive also has two hand-held controllers that the player uses to

[79] Levin, Weiss, and Keshner, "Emergence of Virtual Reality as a Tool for Upper Limb Rehabilitation."

[80] Proffitt and Lange, "Considerations in the Efficacy and Effectiveness of Virtual Reality Interventions for Stroke Rehabilitation."

[81] "VIVE™ | Discover Virtual Reality Beyond Imagination."

interact with the virtual world. These controllers offer haptic feedback in the form of vibration.[82] Two base stations track the movement of the player using infrared light to adjust the player's view accordingly.[83] Players can walk while in game, and a 'chaperone' system will notify them if they are going to leave the boundaries they have set up for themselves.[84]

Figure 5: The components of the HTC Vive. The HMD is seen in center with the two controllers (lower) and base stations (upper) to the sides.

Of the games available on the HTC Vive, the game Tilt Brush by Google was determined to be a particularly good candidate for use in post-stroke upper limb rehabilitation. Tilt Brush is a 3D painting environment where players can draw almost anything they want in any direction.[85] The game offers many brushes[86] and researchers

---

82 "VIVE™ | Discover Virtual Reality Beyond Imagination."

83 Kelly, Cherep, and Siegel, "Perceived Space in the HTC Vive."

84 "VIVE™ | Discover Virtual Reality Beyond Imagination."

85 "Tilt Brush by Google."

86 "Tilt Brush by Google."

found that it was easy for players to quickly start drawing. All players need to do is press the back trigger button, and they are immediately able to draw.

The HTC Vive, and specifically the game Tilt Brush, offer unique solutions to some of these needs as well as other unique abilities. The HTC Vive allows players to interact with and manipulate objects in a more natural way then previous VR systems, but the fact that actions take place in a virtual world can allow for a reduced danger of incidents as well as the ability to change up the task with fewer resources. The VR environment also provides a novel and engaging way for patients to partake in therapy. The game Tilt Brush offers many exciting possibilities for clinicians. Clinicians can design reaching and drawing tasks customized to the patient and easily modify tasks. Patients can not only receive feedback on the outcome of their motion, but by using the brush to track their motion, patients can see their exact motion path and the clinician can instruct the patient on how to modify the motion path. The system allows for intensive practice, realistic goal setting, and the ability to increase the difficulty of the task.

Thus, this study has several goals, based on some of the perceived needs of a VR system for post-stroke upper limb rehabilitation. This study will seek to determine how effectively the game Tilt Brush can be used to elicit motions relevant to post-stroke upper limb therapy and assessment. These motions include reaching in multiple planes, particularly in the plane of abduction, motions both utilizing and going against flexor and extensor synergies, and meaningful motions through multiple planes. This study will also generate data on how healthy individuals interact with the virtual environment to generate an initial set of baselines for in-game range of motion, percentage of reach distance achieved during gameplay, and accuracy of motion, and other relevant variables. With this, the study will specifically focus on how well healthy subjects are able to hit targets and trace lines within the game. This focus derives from the thought that giving subjects targets to achieve will likely be useful for clinicians. However, to do so they need to be confident that the target they hope for their patient to reach will elicit the desired length reach, rather than be distorted by the environment.

CHAPTER 2

Methods

The goal of this study was to determine the usefulness of the HTC Vive virtual reality gaming system in physical therapy. Quantitative data was collected using a Vicon motion capture system. The Baylor Internal Review Board (IRB) reviewed and approved this study. All testing took place the Baylor BioMotion Lab in the Baylor Research and Innovation Collaborative. One researcher performed all of the data collection with the help of assistants.

Motion Capture: Lab Set Up

The lab includes three force plates (Advanced Mechanical Testing, Inc., Watertown, MA), fourteen Vicon Vantage Cameras (Vicon Motion Systems, LTD, Oxford, UK), and two high speed Bonita cameras (Vicon Motion Systems, LTD, Oxford, UK). For the purpose of this study, the lab also included the HTC Vive gaming system, including two infrared motion tracking cameras, two controllers, and a head mounted display.

Motion Capture: Marker Set

This study utilized the Upper Limb Model, which is based off of the Plug-in-Gait marker set and the work of several researchers. [1,2] This model is offered by Vicon as an

[1] Murray, "Determining Upper Limb Kinematics and Dynamics during Everyday Tasks."

[2] Cutti et al., "Soft Tissue Artefact Assessment in Humeral Axial Rotation."

extension of the Plug-in-Gait model to increase accuracy of motion capture and analysis of the motion of the upper limb. This model was chosen because initial data collection and analysis using the Plug-in-Gait model yielded clearly inaccurate results on shoulder angles.

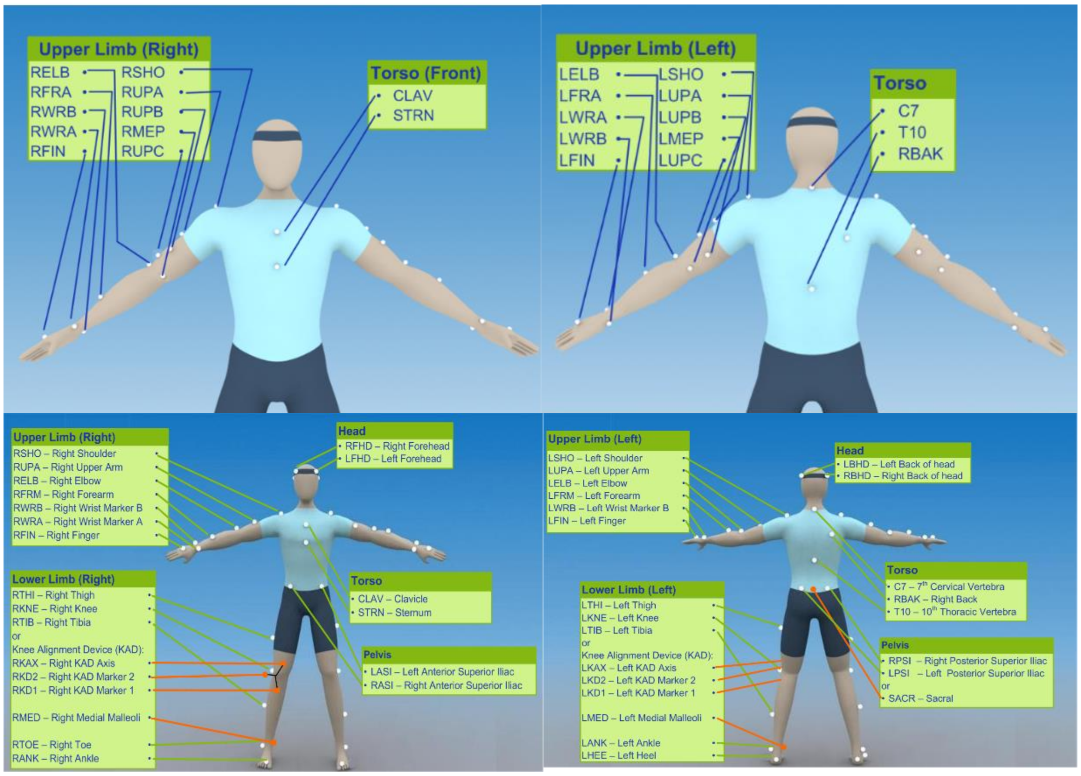


Figure 6: Marker sets. Top left, front view of upper limb maker set. Top Right, back view of upper limb marker set. Bottom left, front view of Plug-in-Gait marker set. Bottom Right, back view of Plug-in-Gait marker set [3,4]

The Upper-Limb Model adds a cluster of markers on each upper arm and a marker on the medial epicondyle of the humerus to the Plug-in-Gait model (Figure 6). This allows for a complete 3D description of the upper limb kinematics and improvement in accuracy of calibration of the joints involving the humerus, the shoulder and elbow joints. The cluster of markers on the upper arm also reduces error due to soft tissues artefact.

---

[3] "Full Body Modeling with Plug-in Gait - Nexus 2.6 Documentation - Vicon Documentation."

[4] "Nexus Model Documentation - Nexus Reference Documentation - Vicon Documentation."

For this study, reflective markers were placed directly upon the skin of the subject using double sided tape. This reduces the amount of error, as while the skin may move over the bony prominences on which many of the markers are located, placing the markers on top of fabric would increase the amount of error, as the fabric would also move relative to the underlying skin and bones.

Participants

Participants were recruited via social media and word of mouth (see appendix for flyer). Participants were required to complete a consent form. Participants were informed of the following inclusion criteria both verbally and through the consent form to ensure that subjects had healthy, normal, shoulder movement:

- Age: 18 – 55
- BMI less than 30
- Not have had any upper extremity injuries

Collection Set Up

Before the arrival of the subject, researchers prepared the lab. They turned on all force plates, cameras, and the Vive. They ensured that are were in working condition and that the signals from the Vicon cameras were not interfering with the Vive tracking system. They also prepared the markers with double-sided tape. Researchers set up the Nexus software used to collect data and created the subject and capture session.

As a part of preparation before each collection, researchers had the software mask any non-marker reflection in the lab, and then researchers calibrated the cameras using a wand with markers at known locations. The known locations of the markers on the wand allow the Vicon system to calculate the relative camera positions and lens distortion error for each camera. The researchers ensured that all calibration errors for each camera were below 0.27 mm for each camera for every collection. After this, the researchers used the wand to calibrate the origin and axes.

Collection

Upon arrival subjects read and signed the consent form and were once again checked for eligibility. Subjects were also asked which hand was dominant. Subjects were then prepared for collection. Subjects wore athletic shorts and tennis shoes. Women wore a sports bra, while men were shirtless for the data collection. The 47 markers were then placed in the locations shown in Figure 6. After the markers were placed, researchers measured the subjects' height, weight, and various arm and legs measurements needed for system calibration.

Figure 15: Subject during data collection

The researchers captured several static trials, where the subject stands unmoving in the anatomical position. These trials are necessary for system calibration. The researchers also captured two range of motion trials, which the software uses to determine the normal range of motion of the body segments.

Subjects than began performing the tasks described in the section below. They completed reaching calibration, free draw, in game reaching tasks, various drawing tasks, and various tracing tasks. Five trials were collected of each reaching task, and simple reaching tasks were performed with both arms. Three trials were collected for drawing tasks, and only the dominant arm was used for drawing tasks. During these tasks, subjects were seated on a sturdy chair adjusted to the appropriate height. Other than during tracing tasks, subjects were asked to erase any drawings in between trials. The researchers monitored subjects' motions and actions both directly and through mirroring the headset display on another monitor.

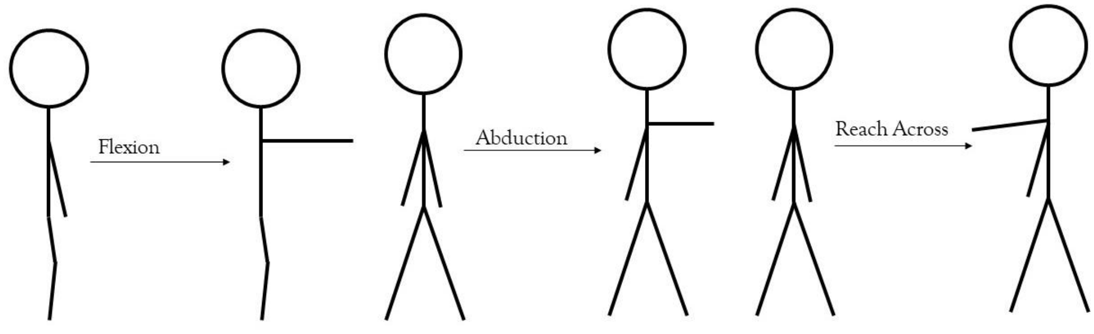
After completion of data collection, the markers were removed and cleaned using alcohol wipes. Subjects were allowed to play with the Vive for a bit long if time allowed, as a way of thanking them for their time.

Study Tasks

In order to determine how effectively Tilt Brush can be used to elicit motions relevant to post-stoke upper limb rehabilitation, drawing tasks were created and motion during these tasks was compared to commonly used rehabilitation tasks. Thus, the study protocol involved controlled instructed reaching motions, and various in game reaching and drawing tasks. Furthermore, tasks involving tracing or reaching to various targets were used to determine how reliably subjects could perceive and reach the depth of a given target.

Reaching Calibration

After completing initial data collection system calibration, subjects were asked to perform several reaching motions while holding the controllers, but without the headset



on. This gave the researcher a control baseline reach distance in several planes. Subjects were asked to flex their shoulder forward to approximately 90 degrees, abduct to 90 degrees, reach directly upwards as far as their anatomy and ability would allow, and reach across their chest as far as they were able while keeping their arm straight. These motions are depicted in Figure 7 for clarity.

Figure 7: Stick figure demonstration of the three main simple reaching calibration motions. These motions were later repeated within the VR game. Reaching upwards was flexion, but to 180 degrees.

Free draw

After completing the reaching calibration, subjects put on the headset and began interacting with the virtual environment. Subjects were first allowed time to draw whatever they wanted. This both gave them time to become familiar and comfortable with the drawing environment and allowed the researcher to collect 15 second trials of uninstructed gameplay.

In Game Reaching

Subjects then repeated three out of the four reaching motions while in the virtual environment. Subjects drew a line while performing these reaching motions; however, they were not allowed to follow their movement visually if the motion was to the side. This offered a basic comparison of reaching within the virtual environment, as subjects were mostly relying upon their proprioception to determine how far they were reaching. It was unexpected that reach distance would be altered much in this case.

Synergy Movements

Subjects performed movements with the upper arm flexor and extensor synergy. Subjects moved their hand from their ipsilateral ear to contralateral knee and back. This is a movement used in the Fugl-Meyer Assessment for the upper extremity, a method for evaluating physical performance of hemiplegic post-stroke patients. [5] This movement is depicted in Figure 8.

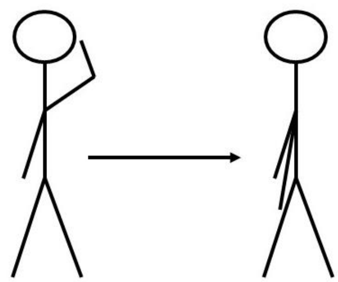


Figure 8: Depiction of synergy motion. Note that subjects were seated when performing this motion.

Line Drawing and Tracing

The researcher first used a straight, flat surface to help the subjects create a straight line forward and away from their body (in the sagittal plane) at stomach height. Subjects also used the straight-line tool within the game to ensure that they made a straight line. The subjects were then asked to trace this line to the best of their ability. This process was repeated, but with a horizontal line (in the transverse plane). This tested subjects' ability to accurately perceive line depth and smoothly trace a given line. The motions for this exercise are depicted in Figure 9, and a 2D view of what one subject drew during these exercises is shown in Figure 10.

[5] Fugl-Meyer et al., "FUGL-MEYER ASSESSMENT UPPER EXTREMITY (FMA-UE) Assessment of Sensorimotor Function."

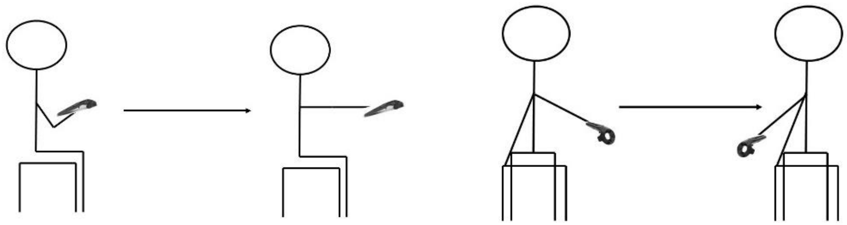


Figure 9: Depiction of the sagittal (left) and transverse (right) drawing and tracing

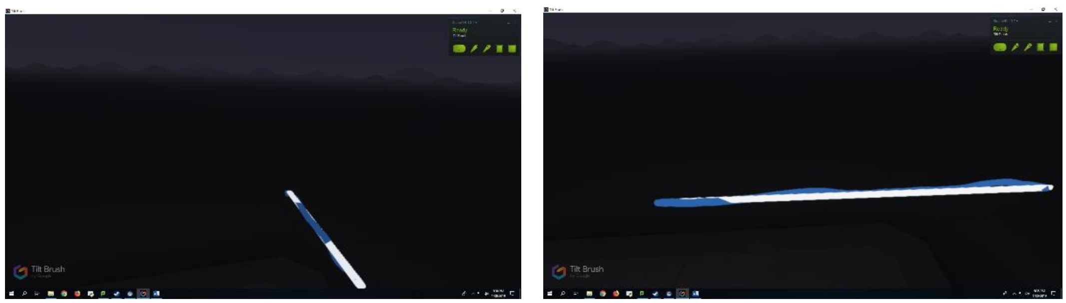


Figure 10: A screenshot of what subject saw in game during the sagittal (left) and transverse (right) tracing exercises.

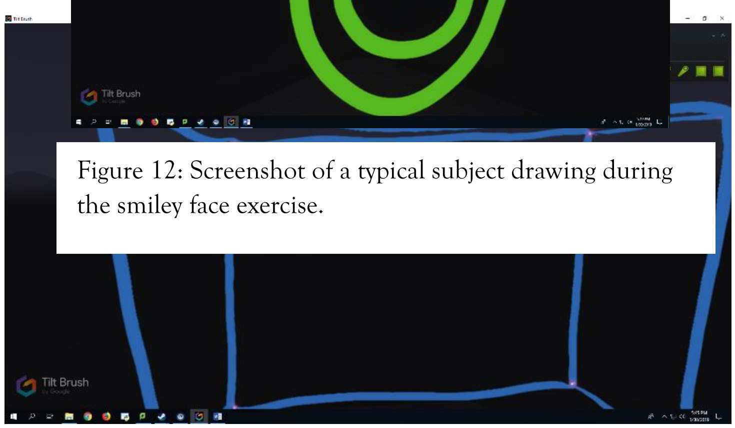
Cube Drawing and Poking

Subjects were asked to draw a cube and given specific instructions on how to do so. They were to first draw a rectangle as far away as they could reach, with the top being at approximately eye level and the bottom being at approximately stomach level. They were to then draw the closer side of the cube, using the same dimensions. They were then to connect the two sides. After drawing and erasing two cubes, subjects were asked to keep their third cube. They were asked to reach out and place a dot in each corner of the cube, returning their arm to resting position after each reach. The goal of this task was both to generate a task that would create arm movements in multiple planes, as well as see how accurately subjects could reach self-created targets. Figure 11 shows a subject view of what one subject drew. Note that part of the lower portion of the box cannot be seen due to the size of the box and proximity to the subjects' face. However, this part of the box could easily be seen in game if the subject looked down slightly. Note also the small bright dots in the corners. These were the dots the subjects placed in each corner.

Figure 11: In game view of box exercise

Smiley Face

Subjects drew a smiley face to the contralateral side of their body right above chest height. This was included to give an example of subjects performing a drawing task in a reaching area that is difficult for many hemiplegic post-stroke patients. [6] A typical subject drawing is shown in Figure 12.



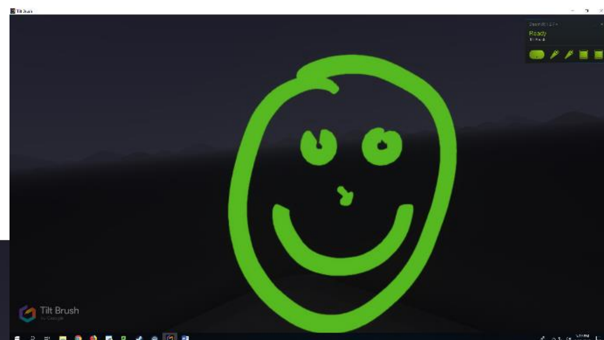


Figure 12: Screenshot of a typical subject drawing during the smiley face exercise.

Abduction Rainbow

[6] Kamper et al., "Alterations in Reaching after Stroke and Their Relation to Movement Direction and Impairment Severity."

Subjects drew a “rainbow” using a specific brush within the game. To draw the rainbow, they started in the flexor synergy position (hand by ipsilateral ear) and extended their forearm. This was also chosen to give an example of how movements that are difficult for post-stroke patients[7] may be performed in gameplay. A subject view from in the game is shown in Figure 13.

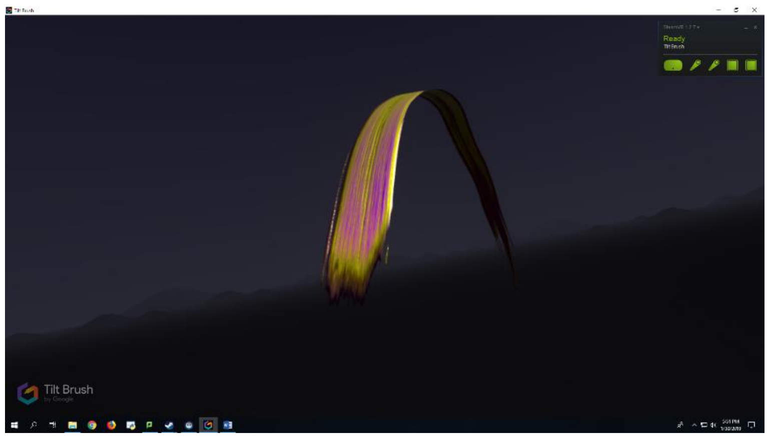


Figure 13: Screen shot of subject’s view when the subject turned to look at the abduction rainbow.

Word Tracing

[7] Sukal, Ellis, and Dewald, “Shoulder Abduction-Induced Reductions in Reaching Work Area Following Hemiparetic Stroke.”

Subjects were asked to trace the word "Life". This was included to collect data on motion characteristics, such as velocity, on healthy subjects performing a task that could possibly be used during therapy. A subject view of this activity is shown in Figure 14.

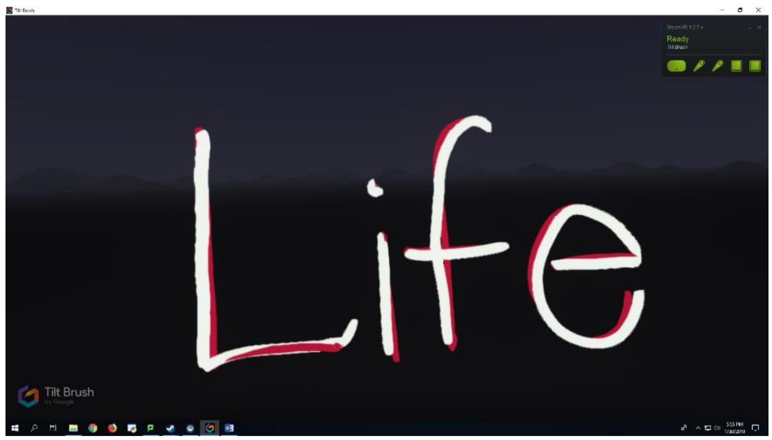


Figure 14: A subject's tracing of the word "Life" as viewed from the subject's perspective.

Data Processing

Data processing included labeling the marker trajectories and gap filling. Gap filling ensures that the marker trajectory data is complete. Gaps occur when a marker is visible to less than two cameras and typically only occur for less than ten frames. Thus, when the sampling rate is 120 frames per second, gaps represent small portions of missing data. There several methods are available to fill gaps. The ideal method is spline interpolation, when the gap is small and the marker position before and after the gap are known. If this method was not available, a pattern or rigid body fill was used. A pattern fill bases the missing marker trajectory off the trajectory of a nearby marker on the same body segment. A rigid body fill may be used when the missing marker trajectory is on a body segment that may be modeled as a rigid body and requires three known marker trajectories off which to base the missing trajectory. Lower body gaps were not filled, as they were not of primary concern for this study.

General Data Analysis

After data was processed, analysis was performed using Nexus, Matlab, and Microsoft Excel software. For the purposes of this thesis, the calibration and VR simple reaching motions, the line tracing, and box drawing and reaching tasks were analyzed. The analysis for the simple reaching motions utilized the method of averaging three subject trials together to create one data point for each subject. The tracing trials looked at all trials for all subjects, and the box trials only utilized one drawing and one reaching trial from each subject.

CHAPTER THREE

Results

A total of ten subjects were recruited for this study. However, technical difficulties occurred during the data collection of one subject. Thus, nine subjects completed the study. Of the nine subjects, 5 were male and four were female. 2 of the subjects, one male and one female were left hand dominant, all others were right hand dominant. All subjects were college students between ages 18 and 25.

Subject reach distance and location were measured under various conditions. Overall, changes were inconsistent between subjects. Although some trends are noted and discussed in the results section that follows, there was high inter-subject variation for most variables. Subjects did tend to see a slight decrease in reach distance with the VR, and minor inaccuracies in tracing and reaching tasks. These changes and inaccuracies, along with the variation between subjects, are presented in the following results section.

Simple Reaching Motion

Subjects performed simple reaching motions both with and without the VR headset both to gather data on maximum reach distance at various reaching angles and determine if wearing the HMD and reaching in the virtual environment affected reach distance. There is evidence to suggest that reaching kinetics, including distance and velocity, may be altered by a virtual environment.[1] It is important for physical therapists to know how patients' motion may tend to be affected by the virtual reality environment so that they can account for this change and plan accordingly. Thus, basic data was gathered on patients performing flexion to 90 degrees, abduction to 90 degrees, and reaching across their torso as far as they were able while maintaining a straight arm. For this study, reach distance was defined at the distance from the marker placed on the acromion to the marker placed on the hand. Since distances were not calculated directly from the shoulder joint center, it is important to note that they decrease slightly as the arm is raised, leading to the need to compared distances at specific angles. It was hypothesized that the reach distances in the virtual environment would be less than the reach distances in a normal environment.

Reach distances with and without the VR headset for both dominant and nondominant hands were compared and it was found that the only significant change occurred with flexion in the dominant hand, with a two-tailed p-value of 0.02. Both flexion and reaching across the torso with the non-dominant experienced a slight difference. None of the other movements experienced a consistent difference. Figure 16 summarizes the average change in reach distance in mm. The statistical results are summarized in Table 1.

[1] Ebrahimi et al., "An Empirical Evaluation of Visuo-Haptic Feedback on Physical Reaching Behaviors During 3D Interaction in Real and Immersive Virtual Environments."

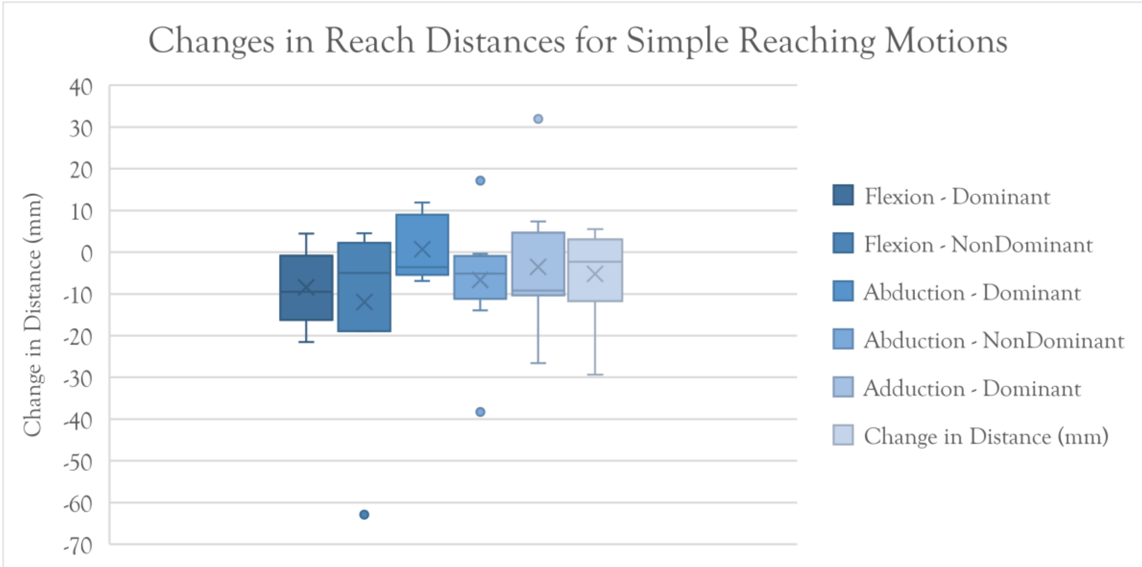


Figure 16: Change in reach distance from normal to with the VR headset.

		Flexion	Abduction	Reaching Across
Dominant	p-value	0.02	0.79	0.53
Non-Dominant	p-value	0.13	0.21	0.19

Table 1: Two tailed p-values of change in reach distance between control and with the VR

However, it is important to note that these conglomerated values, while interesting, don't fully capture the variance that can be seen between subjects. While the full set of graphs depicting the changes of the reach distances may be found in the appendix, it will be helpful to explore a few examples here. Reaching data from subject 14 is depicted in Figure 17 and outlined in Table 2 for clarity. Note that in all three reaching directions, the subject decreased the reach distance, by 9.49 mm with flexion, 6.92 mm in abduction, and

9.49 mm in reaching across the body, and the standard deviation for these measurements ranged from .27 mm to 5.16 mm.

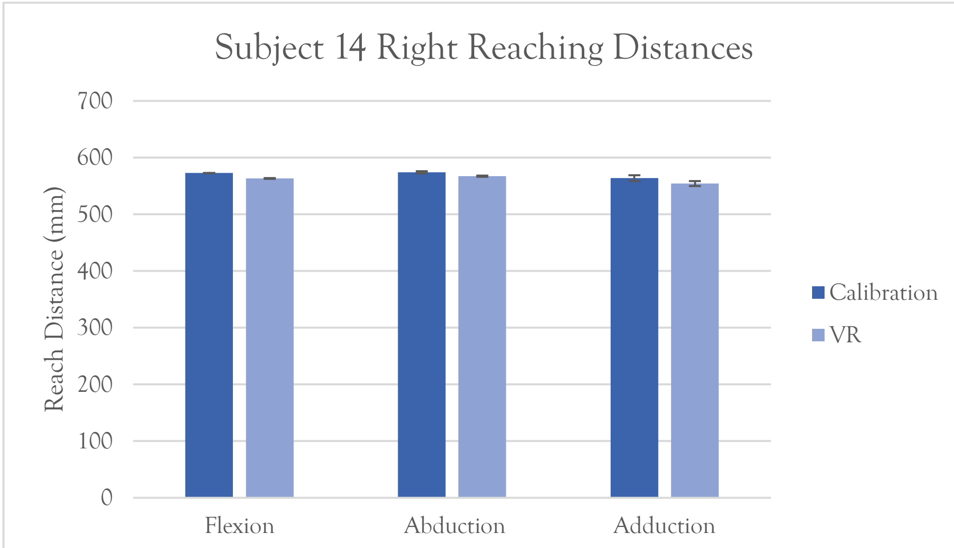


Figure 17: Graph depicting change in reach distance when using the VR headset

Subj 14 Right Reaching Distances		
Names	Means	SD
Flexion Cal	572.72	0.27
Flexion VR	563.23	0.71
Abduction Cal	574.15	1.92
Abduction VR	567.23	1.11
Adduction Cal	563.75	5.16
Adduction VR	554.26	4.38

Table 2: Table listing the data displayed in Figure 3.2, as the changes are small compared to the larger scale. These are the means and standard deviations for the three trials performed for each movement.

The data from subject eleven offers an interesting contrast to subject fourteen. The data from subject eleven is depicted in Figure 18 and Table 3. Contrary to subject 14, subject eleven saw a slight increase in reach distance during flexion and

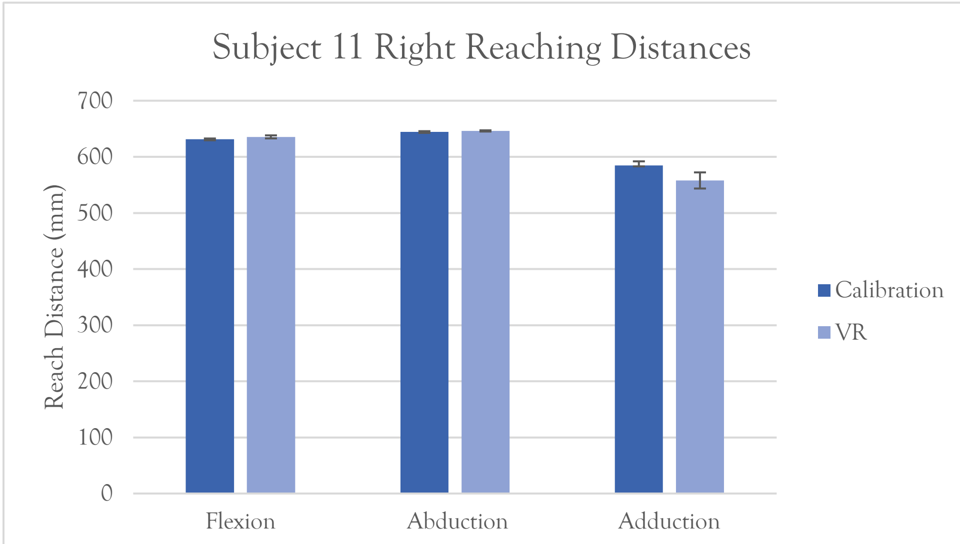


Figure 18: Graph depicting change in reach distance when using VR headset

Subj 11 Right		
Names	Means	SD
Flexion Cal	631.08	1.62
Flexion VR	635.51	2.70
Abduction Cal	644.25	1.49
Abduction VR	646.16	1.08
Adduction Cal	584.45	7.47
Adduction VR	557.86	14.36

Table 3: Table listing the data for subject 11, used in Figure 18

abduction when using the VR headset. These distances increase by 4. 43 mm and 1.91 mm respectively.

While we will not go into full detail of the changes in reach distance for each individual subject, the interested reader may find the charts and tables containing the reach distances for each subject, each arm, and each reaching direction located in the appendix. The reach distances were taken as an average of three trials for each subject under each condition, and the standard deviations presented are the standard deviation for those three trials. The summary data in Figure 16 and Table 1 were derived using the average of three trials for each subject.

Tracing Lines

This analysis sought to examine healthy subject's ability to trace a self-generated line. One possible application of the tools available in Google Tilt Brush would be the physical therapist creating a path for a patient to trace to elicit a specific motion pattern. Given that previous studies have shown that subjects may initially overestimate the distance of a target viewed through augmented reality[2], it is relevant to establish how accurately subjects can perceive and trace a defined path, and know what deficits healthy subjects may exhibit, in order to adjust for these differences with patients. Thus, healthy subjects were asked to draw a straight line using their dominant hand with the help of a flat surface and guidance from the researcher. Subjects where then asked to trace that line. Subjects drew and traced lines both in the sagittal and transverse planes.

Three tracing trials were performed by each subject in each direction. Dynamic time warping (DTW) was used to compare the trajectory of the marker on the hand between the original drawing and tracing trials. Dynamic time warping is an algorithm used to align and measure the difference of two different signals that may vary in speed. The result of the algorithm is a root mean squared error (RMSE) between the two aligned signals. Figure 3.4 displays the distribution of the RMSE after DTW. On average, subjects had an overall error of 30-40 mm in both the sagittal and transverse tracing directions, with the transverse having a slightly higher and more variable error.

---

[2] Swan, Singh, and Ellis, "Matching and Reaching Depth Judgments with Real and Augmented Reality Targets."

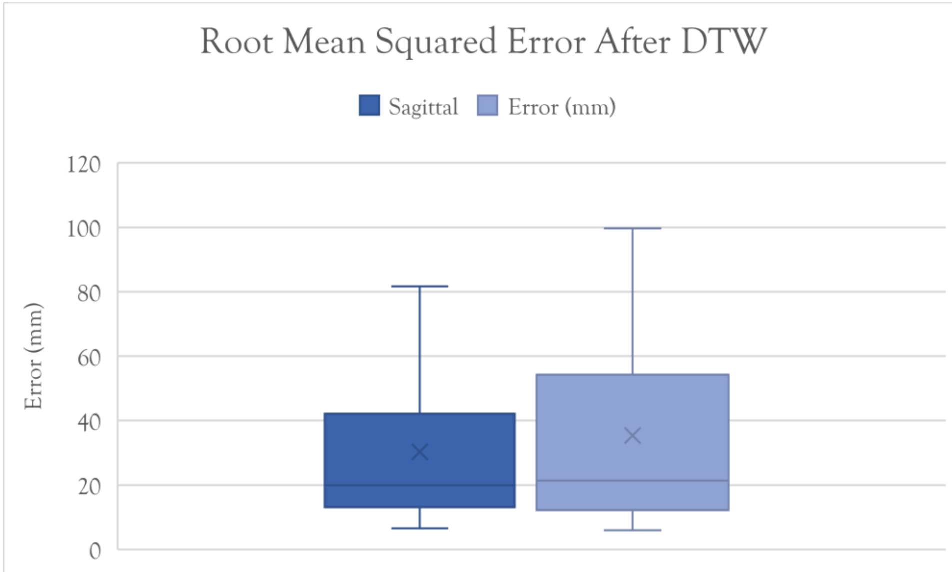


Figure 19: Distribution of the RMSE after DTW was applied to compare the tracing and drawing trials. Tracing lines in both the sagittal and transverse planes were examined.

Once again, however, the aggregated data fails to capture the intricacy of subjects' movement patterns. Thus, exploring a particular example will prove useful. Figures 20, 21, and 22 show different views of one subject's sagittal drawing and tracing trials. The trajectory of the hand marker used to determine the hand location during these trials is projected on a 3D graph, with Figures 20 and 21 showing the XZ and YZ planes respectively, and Figure 22 showing a three-quarters view of the 3D trajectories. The perspective displayed in the graph is also shown using the stick figure drawing to put the graph into the proper perspective.

Note that the graphs do not depict the time component and therefore do not capture changes in subject movement velocity. However, these graphs offer illuminating depictions of how subjects tracing differed from their drawing in 3D space, and in which directions subjects tended to err. In the case of this subject and trial, note that the subject had substantial but inconsistent error in the Z direction, but a relatively constant error in the Y direction. Putting this in the perspective of how the subject was situated relative to

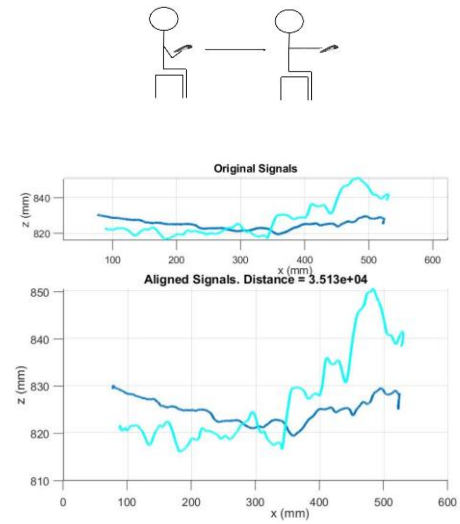


Figure 20: XZ plane view of drawing (darker) and tracing (lighter) trials. The top graph is the original signal, and the bottom graph is the aligned signals after DTW.

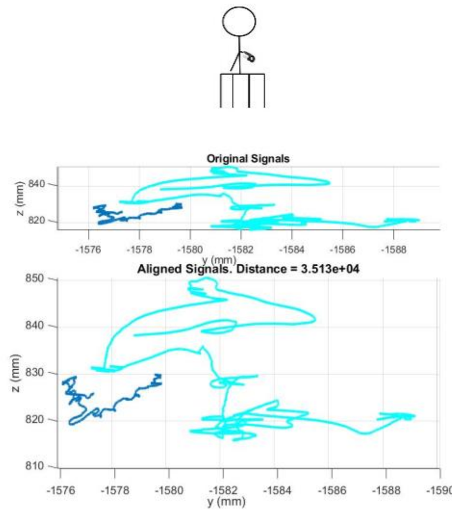


Figure 21: YZ plane view of drawing (darker) and tracing (lighter) trials. The top graph is the original signal, and the bottom graph is the aligned signals after DTW.

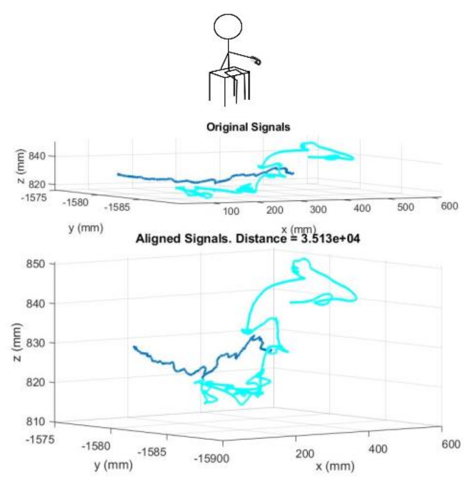


Figure 22: Three-quarters 3D view of drawing (darker) and tracing (lighter) trajectories. Once again the top graph is the original trajectories and the bottom is the aligned graphs after DTW.

the axes, this means that at times the subject's hand was positioned too high or too low relative to the original drawing, but at almost all times the subject failed to reach far enough to the left.

While we cannot investigate all subjects in such a detailed manner in the body of the thesis, three-quarter view 3D graphs are located for all subject's tracing trials in the appendix.

Box Drawing

General data was gathered on subject movement during the box drawing exercises to determine the range of reach distance and range of motion during the box drawing. Data was processed and averaged from three trials for each subject, and then this data was averaged together to generate group averages. Reach distance is reported as a percentage of maximum reach distance, which was taken during the simple reaching motions, and shoulder angles are reported as degrees from neutral, resting position. The data is summarized in Tables 4, 5, and 6.

	Max % of Reach Distance	Min % of Reach Distance	Range
Average	99.90%	52.79%	47.11%
Standard Deviation	5.65%	10.48%	10.83%

Table 4: Average percentages of maximum reach distance during box drawing

	Max Angle (degrees)	Min Angle (degrees)	Range (degrees)
Average	120.75	-24.84	145.59
Standard Deviation	24.02	57.51	56.43

Table 5: Average maximum and minimum angles of flexion during box drawing

	Max Angle (degrees)	Min Angle (degrees)	Range (degrees)
Average	52.56	-24.18	76.72
Standard Deviation	23.92	22.86	16.76

Table 6: Average maximum and minimum angles of abduction during box drawing

Box Reaching

Along with tracing a path, physical therapists may find it useful to have patients reach to a specific point. In order to determine how well healthy subjects were able to do this, subjects were asked to draw a box and then reach out and place a dot in each corner of their drawn box. Each corner location in the original drawing was determined by locating points where the speed of the hand marker was closest to zero and determining which of these points were corners based on the in-motion replay of the trail. This method was used because subjects consistently slowed or stopped their hand motion when they reached a corner or placed a dot in the corner. However, not every point where the hand speed approached zero was a corner. Thus, the researcher determined which decreases in speed were corners using the in-motion replay. The researcher also averaged the XYZ location of the marker at the frame with lowest speed with the XYZ locations of the marker for two frames on either side. During the drawing trial, the location of the corner was taken from the location of the hand at the first time the subjects created the corner. The distance between the corner in the original drawing trial and the reaching trial was then compared. Subject 12 was removed from the calculations because this subject had an error that was much greater than any other subject, and during the collection could be visibly seen to be less careful. Subject 12 had an average error distance of 94.80 mm, whereas the subject with the next highest error had an average error distance of 67.71 mm. Although subject 12 was not included in the main calculations, the effects subject 12 would have had on the results are mentioned.

When looking at overall distance between the original and reaching corners, subjects missed the exact corner by an average of 39.06 mm. This average was across all subjects for all the corners of the square. This average had a wide range, with a minimum distance of 6.78 mm to a maximum distance of 110.65 mm, with the standard deviation being 21.33 mm. When normalized to the subjects' arm length, which was measured from the shoulder to hand marker when the arm was at rest, the average error as a percentage of subjects' reach distance was 6.14%. The error distance as a percentage of reach distance varied from 1.03% to 16.08%, with a standard deviation of 3.32%. This is summarized in Table 7. If subject 12 had been included, the average error distance would have been 45.26 mm, or 7.02% of subjects' reach distance, with a range of 174.85 mm and a standard deviation of 30.17 mm.

	Distance Between Points (mm)	Distance as a Percentage of Reach Distance
Average	39.06	6.14%
Max	103.88	17.11%
Min	6.78	1.03%
Range	103.88	16.08%
Standard Deviation	21.33	3.32%

Table 7: Summary of difference in original corner and reach locations

It is enlightening, however, to examine the difference in the X, Y, and Z directions. Figure 23 shows the error distance in the X, Y, and Z directions independently. Table 8 summarizes the average distances in the X, Y, and Z directions as well as the p-values for the change in each direction. Note that the values calculated in Table 8 are based on averages of both the positive and negative error values, as seen in Figure 23. Table 9 gives the same information but uses absolute values of the error distances.

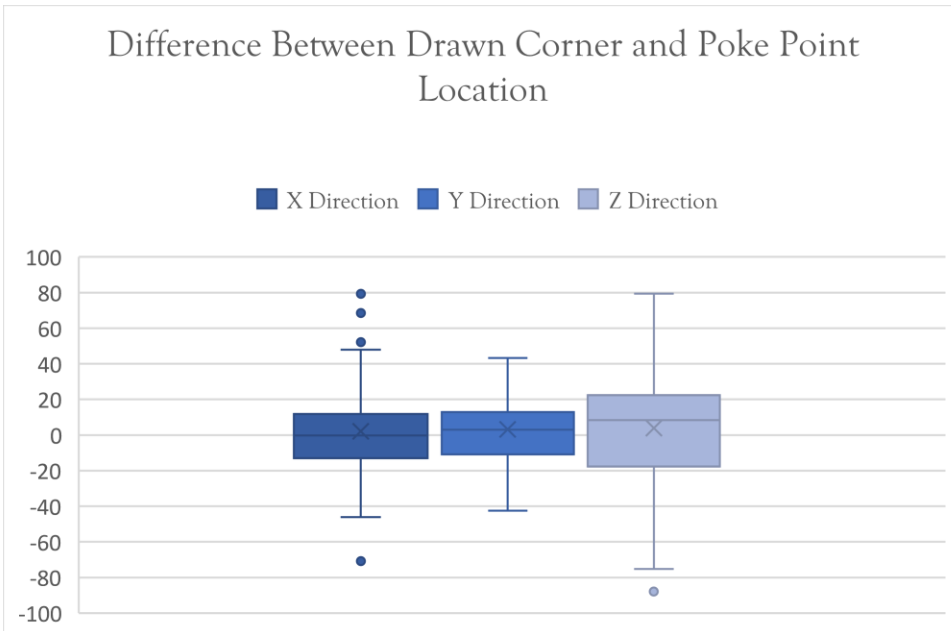


Figure 23: Ranges of error in location in the X, Y, and Z directions

Direction	Average Distance	Standard Deviation	Two-Tailed p-value
X	2.01 mm	27.33 mm	0.56
Y	3.13 mm	18.77 mm	0.19
Z	3.91 mm	29.6 mm	0.29

Table 8: Summarization table for error in corner location using both positive and negative error

Direction	Average Distance	Standard Deviation
X	18.74 mm	19.85 mm
Y	14.88 mm	11.72 mm
Z	23.77 mm	17.81 mm

Table 9: Summarization table for error in corner location using the absolute value of the error.

If subject 12 had been included, the average error distance would have been much higher. The average error distance using both positive and negative values was 5.16 mm, 4.66 mm, and 7.71 mm in the X, Y, and Z directions, respectively.

It is also interesting to note that when drawing the box, subjects will touch a corner at least two times in the process of creating it. Comparing the distance of the error of repeated touches of the corner to the error when reaching to the corner later to place a dot in it provides further perspective on subjects' ability to accurately reach to the corners. The average distance when reaching to place a dot in the corner, as seen above, is 39.06 mm. The average distance from the original location of the corner when completing the corner is 32.01 mm. This change is significant, with a p-value is 0.02. However, there is a large amount of variability in this, with the difference between the two ranging from -56.86 mm to 80.18 mm.

CHAPTER FOUR

Discussion and Conclusions

This study sought to establish how the HTC Vive and the game Google Tilt Brush could be used in rehabilitation that involves reaching movements, such as post-stroke upper limb rehabilitation, and determine what challenges healthy subjects encountered in interacting with the virtual environment. Accomplishing this goal will give physical therapists a basis of knowledge for utilizing this technology with patients. The primary variables of interest were reach distance and hand marker location. Reach distance is a key element of assessing and rehabilitating post-stroke upper limb function.[1] Hand marker location was used to determine subject reach accuracy, which patients who suffer from upper-limb paresis often need to develop.[2] We will begin by discussing the overall study design and methods, continue with discussion of specific results, and conclude with a discussion of the overall results and conclusions to be drawn.

---

[1] Kamper et al., "Alterations in Reaching after Stroke and Their Relation to Movement Direction and Impairment Severity."

[2] Lindley, *Stroke*.

Study Design and Methods

While research is being done on the use of the HTC Vive and similar technology in rehabilitation,[3,4,5,6] the author found that the number of studies currently available were limited. Thus, this study took the opportunity to explore ways in which a typical immersive VR system like HTC Vive could be easily adapted for use in a rehabilitation setting. One of the easiest ways to do so would be to identify relevant commercially available games that physical therapists could utilize with patients.

Although it is not the main focus of this thesis, there was a selection process of choosing which game(s) to investigate. An initial list of possibilities was created and classified based on game type and movements elicited. From these possibilities, types of rehabilitation were also considered. Rehabilitation involving the shoulder was focused on, and possible areas of rehabilitation included post rotator-cuff surgery, shoulder impingement syndrome, and post-stroke upper limb. Rehabilitation for post rotator-cuff surgery was ultimately eliminated due to the need for stricter limits on patient motion and the ultimate need for more strengthening exercises than was effectively offered by the HTC Vive. Post-stroke upper limb rehabilitation was selected because of the precedent of use of

---

[3] Gerig et al., "Missing Depth Cues in Virtual Reality Limit Performance and Quality of Three Dimensional Reaching Movements."

[4] Acosta, Dewald, and Dewald, "Pilot Study to Test Effectiveness of Video Game on Reaching Performance in Stroke."

[5] Levin, Weiss, and Keshner, "Emergence of Virtual Reality as a Tool for Upper Limb Rehabilitation."

[6] Subramanian and Levin, "Viewing Medium Affects Arm Motor Performance in 3D Virtual Environments."

computer and virtual reality gaming as well as the lack of strict limitations on patient movement.

Once post-stroke upper limb rehabilitation was selected for investigation, the game Google Tilt Brush was proposed as an excellent fit for this type of rehabilitation. As stated in Chapter One, Google Tilt Brush offers the possibility for targeted motion, motion at multiple reach distances and angles, feedback on motion path, and the possibility for repeated practice, all important components of post-stroke upper limb rehabilitation.[7,8,9] The game also offers many features that may prove useful to clinicians, such as easy undoing of previously drawn lines, the ability to place dots in one location using the dotted line brush, and some built in 3D shapes. Moreover, Google Tilt Brush offers clinicians the opportunity to easily personalize the therapy to the individual patient. The environment of the game is novel enough to retain the interest of most people, while not so overwhelming or fast paced as to scare away those less familiar or comfortable with VR.

Once Google Tilt Brush was chosen as the game of focus, the researcher developed drawing tasks relevant to post-stroke upper-limb rehabilitation, as described in Chapter Two. Many tasks were developed to encourage reaching in different forms, and the researcher could generate specific tasks, such as starting with one's hand by one's ear and extending one's elbow to draw a rainbow, that countered known deficits in stroke

---

[7] Lindley, *Stroke*.

[8] Kamper et al., "Alterations in Reaching after Stroke and Their Relation to Movement Direction and Impairment Severity."

[9] Sukal, Ellis, and Dewald, "Shoulder Abduction-Induced Reductions in Reaching Work Area Following Hemiparetic Stroke."

patients[10], would allow patients to visualize their motion, and were still interesting to complete. Moreover, tasks such as the box drawing could be used to accomplish multiple goals such as reaching in different directions, targeted reaching, practicing achieving smooth reaching.

Overall, the work used to determine the game and tasks used within the methods of this study offer one suggestion of how the HTC Vive can be applied to a clinical setting. The preliminary work identified that the HTC Vive and the game Google Tilt Brush could offer a novel way to engage patients in physical therapy who suffer from upper-limb deficits due to a stroke. The body of this study then explores whether or not the virtual environment within Google Tilt Brush affects patient reaching and targeting.

Simple Reaching Motions

The results from the simple reaching motions portion of the study can be seen from two different perspectives. From one point of view, we can note that the reach distances changed very little from the control reach distance to when subjects where reaching in the virtual world. Across all reaching directions, most subjects altered their reach distance by less than two centimeters on average. This is roughly 3.1% of the average person's total reach distance. Moreover, only one of these changes, forward flexion of the arm of the dominant hand, was a statistically significant change (p-value of <0.05).

However, we can look at these same results and be intrigued at the fact that they changed by this much. After all, subjects were reaching to their maximum reach distance at the same angle each time. Theoretically, subjects should be able to achieve a very similar

[10] Sukal, Ellis, and Dewald.

reach distance each time, even in the virtual environment. This is where we may consider a few different aspects of the reaching task. Firstly, the fact that for the purposes of this study, reach distance was represented as the distance between the shoulder marker and hand marker, rather than the shoulder joint center and fingertips, introduces a source of error. Since the shoulder marker, rather than the shoulder joint center was used, the calculated reach distance would decrease slightly as the subject's arms were raised. Although this was controlled for by taking the reach distances at 90 degrees for flexion and abduction, this was likely still a source of error.

Another consideration as to why there may be a change, however slight, in reach distance is the fact that subjects may not have been as focused on reaching in the virtual environment. While the simple reaching motions were relatively easy and repetitive, in the novel environment of the VR game, subjects may not have been paying as much attention to ensuring they were fully extending their elbow. This effect would be similar to that noted by Acosta et al. in that to an extent the "game" draws attention away from the therapeutic goals. If this is the case, it will be an important consideration for physical therapists and may be something they need to instruct their patients to work against.

Yet another possible consideration in why the reach distance may have changed in the VR is that subjects could not see their arm and had to rely almost entirely on proprioception to determine the positioning of their arm. Although in the game subjects could see the location of their hands via the location of the controllers projected into the environment, subjects could not see their arms or any stand-in for their arm. While overall subjects could determine their relative arm location and position using proprioception, the lack of visual input may have contributed to their error. Once again, this is a relevant consideration for physical therapists, as the lack of visual cues could either lessen the effectiveness of the therapy and what patients are able to do or offer an opportunity for patients to be forced to practice relying upon their proprioception, since a lack of proprioception is often seen in patients after a stroke.[11]

Tracing

The most interesting element to consider in regards to the tracing trials is the typical direction of error of the tracing trajectories. We can note that for the tracing in both the sagittal and transverse directions, subjects tended to err by drawing higher in the z direction, although there was some variation in this. This trend is likely due to the subjects viewing angle. From their perspective, they blocked out their original drawn line as long as they were in the same location and higher than that line. Beyond this, there was not a way for subjects to determine how far above the line they were unless they leaned sideways to look at the line, which was not allowed during the study. It also seems that some subjects would slowly adjust their hand up and down as they traced as a method of trying to find the height of the line. It may be helpful for physical therapists to know this tendency, although, in this case, the tendency is for patients to do more work by raising their arm higher.

The X and Y directions experienced less consistent error. During the tracing in the sagittal direction, some subjects tended to err by moving their tracing line closer to their

[11] Dukelow et al., "The Independence of Deficits in Position Sense and Visually Guided Reaching Following Stroke."

centerline than their drawn line, while others would draw the trace farther away from their centerline. Similarly, during the tracing in the transverse plane, some subjects tended to place the trace closer to their body, while others placed it further away from their body. Overall, there does not seem to be a consistent error or technique used to determine the X or Y location of the line.

Box Drawing

The box drawing data demonstrates that this exercise, and others like it, can be a way to encourage a large range of subject motion. In this exercise, healthy subjects reached to 99.9% of their maximum reach distance on average. On average subjects went to a minimum of 52.79% of their reach distance. This creates a large workspace that subjects tended to move within. This data is encouraging because it shows that subjects tended to reach to their full distance even when given only verbal instruction and not specific targets. Moreover, subject had an average range of motion of 145.59 degrees of flexion and 76.72 degrees of abduction. Although the range of motion for flexion is higher, this is to be expected, because the box more easily lent itself to reaching upwards to make more of a tall rectangle.

Box Reaching

The overall average distance from the target corner of the box when subjects performed the reaching at various distances was 39.06 mm, which was an average of 6.14% of the reach distance. While it is helpful for physical therapists to know how much they can expect a healthy patient to err when reaching for a target, it is also helpful to look at the range of error. Amongst all reaches there was a range of error of 103.88 mm, which was an average of 16.08% of subjects' reach distance. Given that subjects erred by a maximum of 17.11% of their reach distance, it is evident that even in heathy patients there can be a large range of error. It should be noted that some subjects were much careful and took more time in their reaching than others, as evidenced by the overall time it took them to complete the task. In the context of physical therapy, subjects would likely be much more careful. However, this data sets a general baseline for what can be expected from healthy patients.

Much like the tracing data, when we look at which direction subjects tended to err in, we find that the Z direction, or height of the hand, had the highest average error, with the X direction, the direction in which the hand moved closer to or away from the torso, have the next highest error, and the Y direction having the lowest error. What is interesting, however, is that the Y direction had the change that was closest to statistically significant. This may be due to the fact that while the difference between points was smaller, the locations of the points, on which the paired t-test was based, had a broader range than either the X or Z directions. Although none of the trials saw a significant error, both the Y and Z directions saw a larger difference in error than the X direction. When paired with the results of the tracing exercise, it is interesting to note that both saw a trend towards erring in the Z direction.

Lastly, when we compare the error distance of the in-drawing repeated corner touches to the corner touches in a separate trial, we find that although the difference between the errors is only 7 mm, with the in-drawing repeats being closer, the p-value is quite low- only 0.019. The low difference in distance is to be expected, since the in-drawing repeated touches occurred when the subject draw lines in the X direction, to and from their body, in order to connect the two square faces. This type of movement is similar to the reaching out to touch the corners that occurred in later trials. However, the fact that the change is significant is a bit surprising and may be due to the low amount of variance in the data.

Overall Discussion and Conclusions

This study sought to create a basis of knowledge on how the HTC Vive could be used within a physical therapy setting and characterize motion characteristics of healthy subjects' interaction with the virtual environment. The game Google Tilt Brush offers many tools for the physical therapist to utilize in rehabilitation for patients with post-stroke upper limb paresis. It allows for the therapist to easily set goals tailored to the patient, either by manipulating the patient's arm to help them draw a target or path that they can then aim for, or by drawing a desired motion or target for them. The game creates the possibility of giving patients visual feedback on their motion path.

Although there are some trends that the therapist should be aware of, the overall picture is that subjects can reach relatively reliably and accurately. This is consistent with the findings of an earlier study published in 2018, which found that HMDs provided depth perception that was sufficient enough to allow healthy young adults to perform natural reaching movements.[12] The findings are further corroborated by a 2017 study that

[12] Gerig et al., "Missing Depth Cues in Virtual Reality Limit Performance and Quality of Three Dimensional Reaching Movements."

concluded the HTC Vive decreased, but did not entirely eliminate, under-perception of distance.[13] While there were certainly repeated inaccuracies of reaching, many of these were not consistent enough to prove to be statistically significant. One consideration physical therapists can keep in mind is that the patients may tend to not reach as far in game as they would out of game, but that this change is likely to be no more than 2 cm. Moreover, physical therapists can keep in mind that subjects may reach higher than actually necessary and remember to give verbal guidance if this is a concern.

[13] Kelly, Cherep, and Siegel, "Perceived Space in the HTC Vive."

CHAPTER 5

Limitations, Future Work, and Significance

Limitations

The current study has several limitations. The first is a lack of larger subject numbers and diversity. Nine subjects, all of which were 18-25 years old completed the study. Given the high variability of the data, a larger of subjects could have helped show clearer trends in the data. Moreover, obtaining a broader range of subjects would also be beneficial, as while the current subject population provides a good sample of young, healthy adults who are likely interested in VR gaming, this population is not the best sample of people who would be likely to experience a stroke. Given that increasing age is a risk factor for stroke, a more accurate healthy population sample would include a larger percentage of people who are older in age. Moreover, the fact that increased age may affect subjects' reaching kinetics[1] makes it even more important to include older adults in the subject population.

The study also experienced some technical difficulties that may have affected the data. Since both the Vicon Vantage cameras and the HTC Vive towers utilize infrared light to perform their tracking[2,3], it seems that the two infrared signals tended to interfere with

[1] Lee et al., "The Effects of Age, Gender, and Hand on Force Control Capabilities of Healthy Adults."

[2] Niehorster, Li, and Lappe, "The Accuracy and Precision of Position and Orientation Tracking in the HTC Vive Virtual Reality System for Scientific Research."

[3] VICON, "Vantage Motion Capture Camera."

each other. At times, this would cause the controller to appear to randomly and rapidly shift in the subjects' view, sometimes by several feet. When this occurred, it made it very difficult for the subject to perform the drawing exercises. The researchers would attempt to adjust the strobe or frame rate of the Vicon cameras or restart the HTC Vive trackers, and this would often cause the issue to resolve. However, with one subject the researchers could not resolve the issue and the trial had to be terminated. Moreover, several subjects had a much higher gap frequency than others, and it is possible that this was due to the competition between the two infrared signals. Although this generally did not directly affect the necessary data, the number of gaps that needed to be filled could have made the data less accurate.

Another limitation was the fact that when shoulder angles approach and surpass 90 degrees, the calculations of the shoulder angles will experience gimbal lock. Gimbal lock occurs due to uncertainty in the Euler Angle calculations that arises when any of the three angles is equal to 90 degrees. This leads to inaccuracies in the calculated shoulder angles.[4] Although the Upper Limb Model was used to reduce these inaccuracies[5], the issue cannot be entirely avoided, and the researcher noted what appeared to be minor inconsistencies in calculated shoulder angle. Although shoulder angles were not a large part of this study, they were used to determine the reach distance at 90 degrees flexion and abduction, and at maximum angle of reaching across the body. Thus, if the angle was slightly off, these values may have been impacted.

---

[4] "Nexus Model Documentation - Nexus Reference Documentation - Vicon Documentation."

[5] "Nexus Model Documentation - Nexus Reference Documentation - Vicon Documentation."

Another limitation of the study was that we did not have a physical therapist observe subject movement to insure consistency and proper motion. Although a physical therapist was consulted on the study design and methods, this physical therapist was not involved on a day to day basis. Furthermore, while the researcher provided detailed instructions to subjects on how to perform the motions, this was not specifically reviewed by a physical therapist, and the researcher was not specifically trained to recognize possible errors in subject motion or technique.

The fact that we were determining the drawing location based on a marker placed on the hand was another limitation of this study. Although the hand marker serves as a good descriptor of hand location, it does not necessarily capture where the drawing tip of the controller was. Thus, while the subject may have perceived that he or she was drawing an accurate line, the subject may have shifted their hand position relative to the controller, making it seem like he or she was not tracing accurately, when from the subject's perspective, the tracing was accurate.

One specific limitation of the study occurred during the box drawing and reaching exercises. The accuracy of these results was limited by the fact that the researcher did not know exactly when and where the subject placed the dot in each corner. Although the location could be approximated using hand speed, there was not a way to connect the user input in the HTC Vive with any sort of reference marker in trial as captured by the cameras. Thus, the exact frame used to determine the hand location at the placing of the dot may be slightly off. However, because the hand was not moving very much at these points, the error is likely to be minimal.

One limitation of the use of VR in post-stroke therapy in general, and a limitation within this study, is due to the fact that visual deficits are commonly seen in stroke patients.[6] Although these deficits will likely affect patients in any environment, it will be important to know if the commonly occurring visual deficits affect how patients interact with the VR environment.

Future Works

Further Analysis

The available data from this study could undergo much more analysis and several more variables could be examined. Of pertinence would be determining range of reach distance and range of motion for all drawing exercises to provide a possible way of classifying exercises. Further analysis could be done on the box exercise to look at multiple variables. Hand speed in various directions could be examined to develop baselines for healthy subjects. Reaching technique could also be determined through looking at velocity peaks. These analyses would provide healthy subject baselines within the VR environment on several variables relevant to stroke, as seen in Chapter One of this thesis.[7,8,9]

---

[6] Sand et al., "Vision Problems in Ischaemic Stroke Patients."

[7] Kamper et al., "Alterations in Reaching after Stroke and Their Relation to Movement Direction and Impairment Severity."

[8] Sukal, Ellis, and Dewald, "Shoulder Abduction-Induced Reductions in Reaching Work Area Following Hemiparetic Stroke."

[9] Cirstea and Levin, "Improvement of Arm Movement Patterns and Endpoint Control Depends on Type of Feedback During Practice in Stroke Survivors."

EMG Data

Another possible future work is collecting EMG data. Due to time limitations, it was decided that EMG would not be included in this study. However, EMG data would have helped create a richer picture of how subjects responded to the VR game. Moreover, data on muscle activation is a variable that physical therapists would likely value having, as stroke often involves changes in muscle activation, and part of rehabilitation is working on creating more normal patterns of muscle activation.[10]

Comparing Exercises

Further research on comparing the drawing exercises developed in this study to current methodologies for the rehabilitation of the paretic upper-limb is also necessary. Aside from demonstrating the ability to obtain similar reach distances and range of motion as conventional therapy by using the VR game, this research could also seek to compare the repeatability of motions in both contexts. This could originally be done with healthy patients, but the ultimate goal would be to study the effect of the VR game-based therapy in patients receiving rehabilitation for a paretic upper limb and compare its outcomes to those of conventional therapy.

Game Development

Aside from simply studying the use of commercially available games, another possible future work is the development a game tailored to post-stoke upper limb rehabilitation. Ideally, this game would take the useful the elements of Google Tilt Brush,

---

[10] Nichols-Larsen and Kegelmeyer, "Stroke."

such as the ability to tailor the exercises to the patient and the ability for almost instant feedback on movement performance[11], and pair them with control measures to help ensure that patients perform the desired movement correctly.

One feature that may be helpful is the use of sound or visual changes to inform patients of when they are within a set radius of a target. For reaching exercises this could mean that the patient hears a ding and the target flashes green when they reach close enough to the target. In exercises where the patient is tracing a given path, the path could change color bases on how close the patient is to the desired path. Similarly, control features could be developed such that it is easier to switch between a solid line and a more transparent line, so that patients could draw using a more transparent path in order to still be able to see the path they are trying to trace underneath.

Another feature that may be helpful in developing a game would be to utilize currently available trackers that are compatible with the system to create a virtual arm in the game. Since one current limitation for the use of the system in rehabilitation is the lack of a visual sense of where the players arm is,[12] providing this visual feedback would be a definite advantage. There are currently trackers that work with the HTC Vive that can be placed anywhere on the body and be tracked by the base stations. These trackers could thus be incorporated in game design and utilized to create a virtual arm.

Ultimately, game development could also incorporate longer-term feedback features such as generating a report of the patient's abilities and tracking patient progress. The

---

[11] Cirstea and Levin, "Improvement of Arm Movement Patterns and Endpoint Control Depends on Type of Feedback During Practice in Stroke Survivors."

[12] Acosta, Dewald, and Dewald, "Pilot Study to Test Effectiveness of Video Game on Reaching Performance in Stroke."

possibility of using the HTC Vive to provide quantitative measurements could be explored and could add a great deal to patient rehabilitation.

Physical Therapy Takeaways

Overall, the HTC Vive and similar VR gaming systems offer unique possibilities for physical therapists. Games such as Google Tilt Brush can be easily applied to a physical therapy context with little modification. The game can certainly be used to elicit patients' full range of motion, particularly if the therapist is targeted in what the patient draws. Although physical therapists should be aware of the fact that patients may tend to not reach quite as far as well as reach higher than necessary while in the VR, these systems can serve as a useful tool for physical therapists to engage patients in therapy.

Final Conclusions and Significance

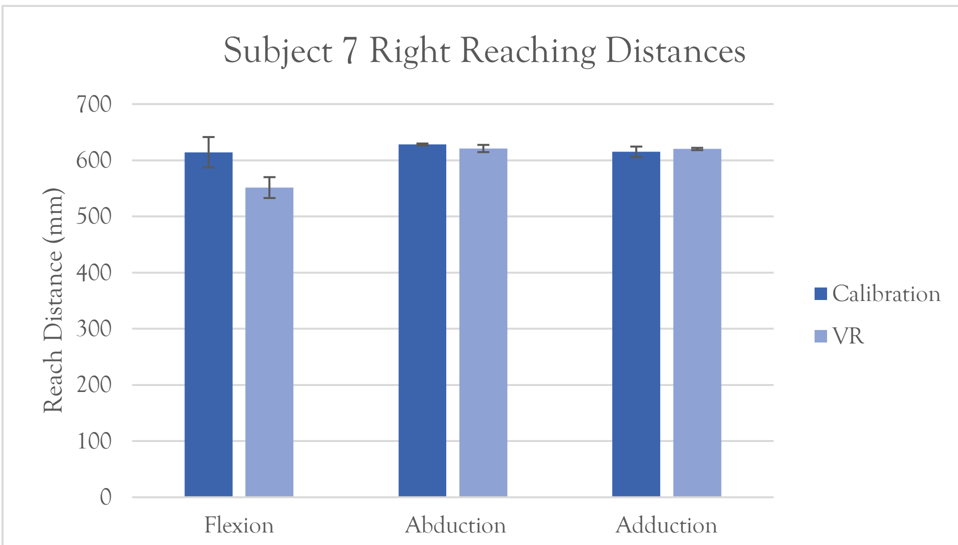
This study provides an idea of how the HTC Vive can be used in post-stroke upper limb rehabilitation. It shows that the game Google Tilt Brush could be a viable option for inclusion in a rehabilitation plan. While a physical therapist would certainly need to monitor and guide the patient to ensure the patient performs the desired motions, the therapist can expect the patient to move relatively naturally while interacting with the virtual environment. Although the patient may experience some tendencies to not reach as far away from his or her body or to reach higher than necessary, these are things that the physical therapist can monitor. Overall, the HTC Vive offers many possibilities to physical therapists that can be further developed in the future.

APPENDICES

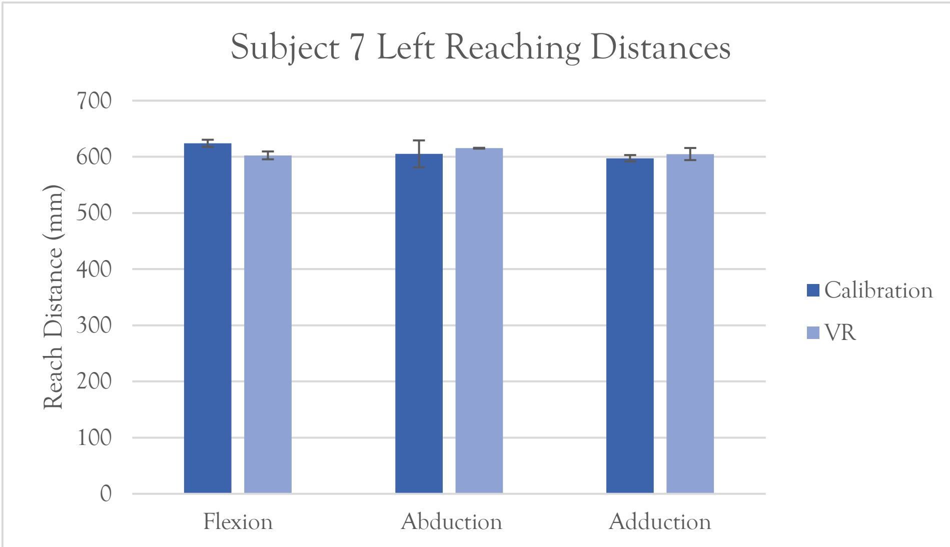
APPENDIX A

Complete Simple Reaching Data

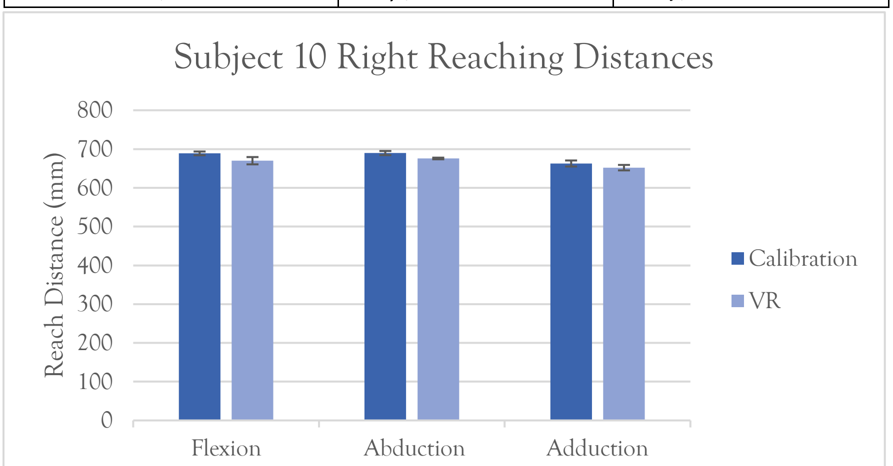
All data is presented first with a bar graph, labeled with the subject and arm. Each graph is then followed by the data that supplied that graph.



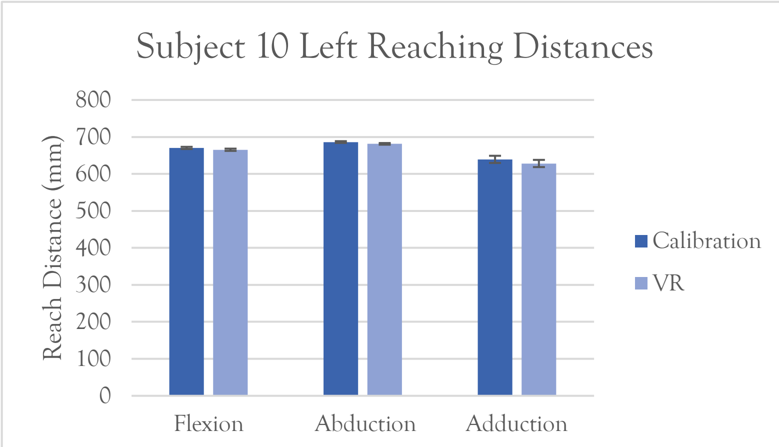
Subj 7 Right		
Names	Means	SD
Flexion Cal	614.21	27.09
Flexion VR	551.30	18.59
Abduction Cal	628.03	1.75
Abduction VR	620.90	6.43
Adduction Cal	614.94	9.38
Adduction VR	620.03	2.04



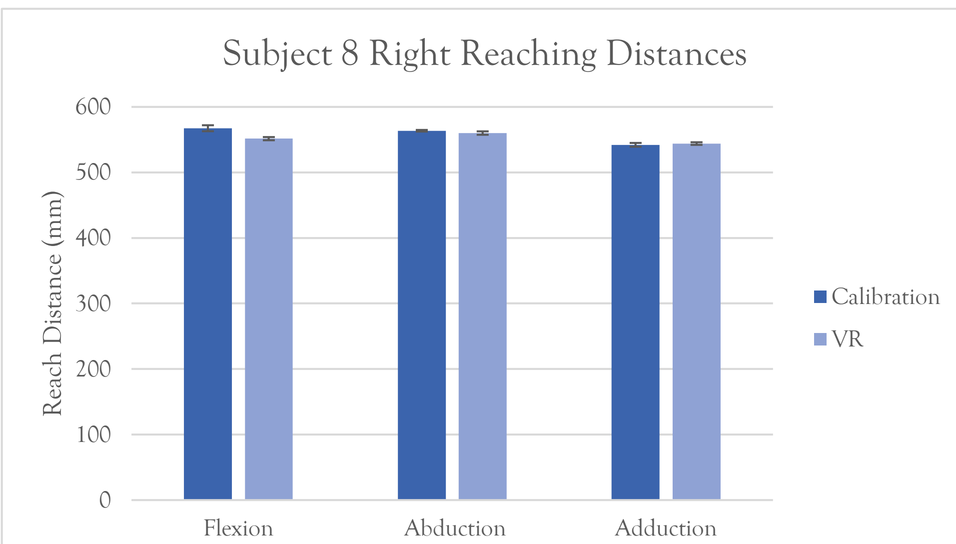
Subj 7 Left		
Names	Means	SD
Flexion Cal	624.08	6.26
Flexion VR	602.57	7.00
Abduction Cal	605.14	24.09
Abduction VR	615.25	0.77
Adduction Cal	597.51	5.57
Adduction VR	604.91	10.79



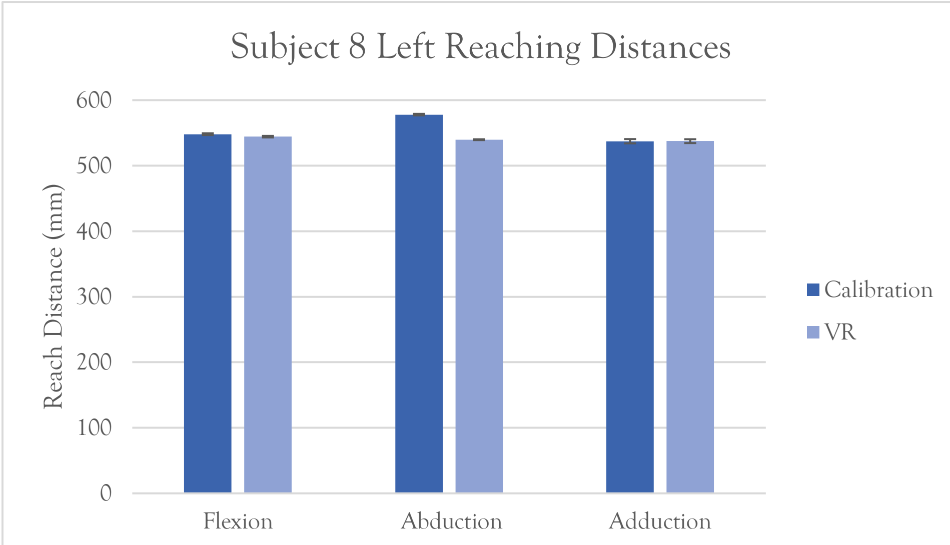
Subj 10 Right		
Names	Means	SD
Flexion Cal	688.73	4.86
Flexion VR	669.87	9.43
Abduction Cal	689.64	5.33
Abduction VR	675.67	2.12
Adduction Cal	662.69	7.82
Adduction VR	651.98	7.03



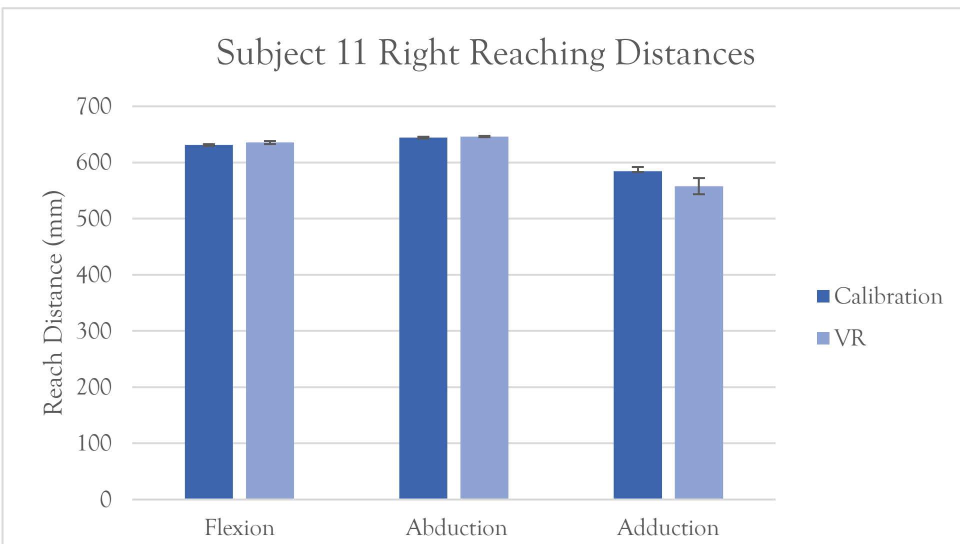
Subj 10 Left		
Names	Means	SD
Flexion Cal	670.35	2.86
Flexion VR	665.38	3.02
Abduction Cal	686.10	2.53
Abduction VR	681.27	2.26
Adduction Cal	639.39	9.71
Adduction VR	628.23	9.74



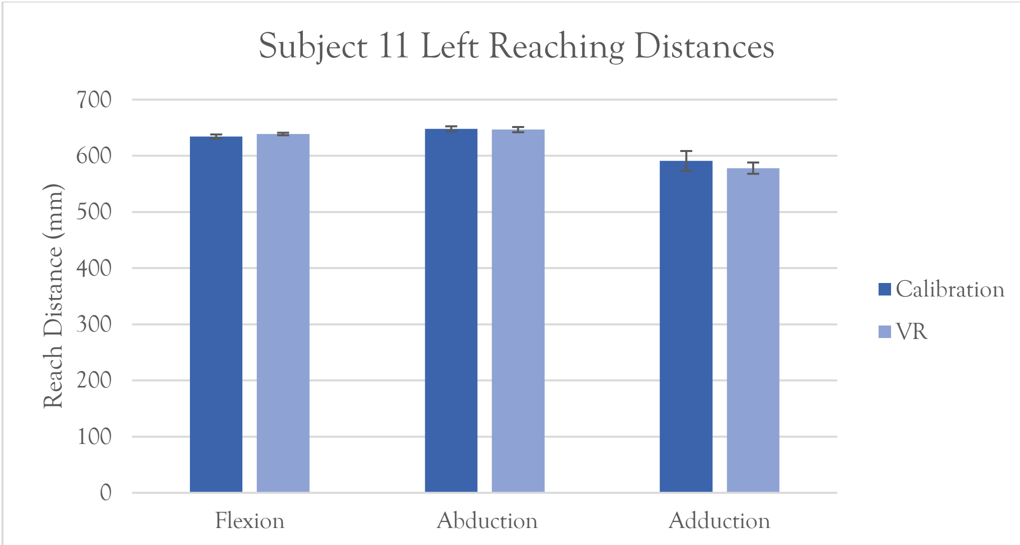
Subj 8 Right		
Names	Means	SD
Flexion Cal	567.50	4.56
Flexion VR	551.55	2.44
Abduction Cal	563.65	1.24
Abduction VR	560.08	2.63
Adduction Cal	542.12	2.90
Adduction VR	544.08	1.99



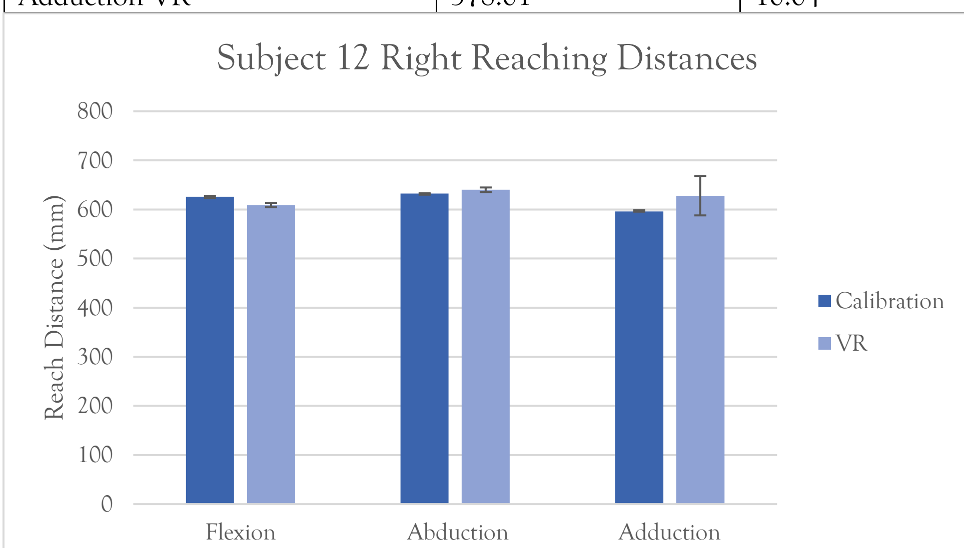
Subj 8 Left		
Names	Means	SD
Flexion Cal	548.08	1.40
Flexion VR	544.30	1.16
Abduction Cal	577.93	1.16
Abduction VR	539.68	0.65
Adduction Cal	537.35	3.22
Adduction VR	537.43	2.94



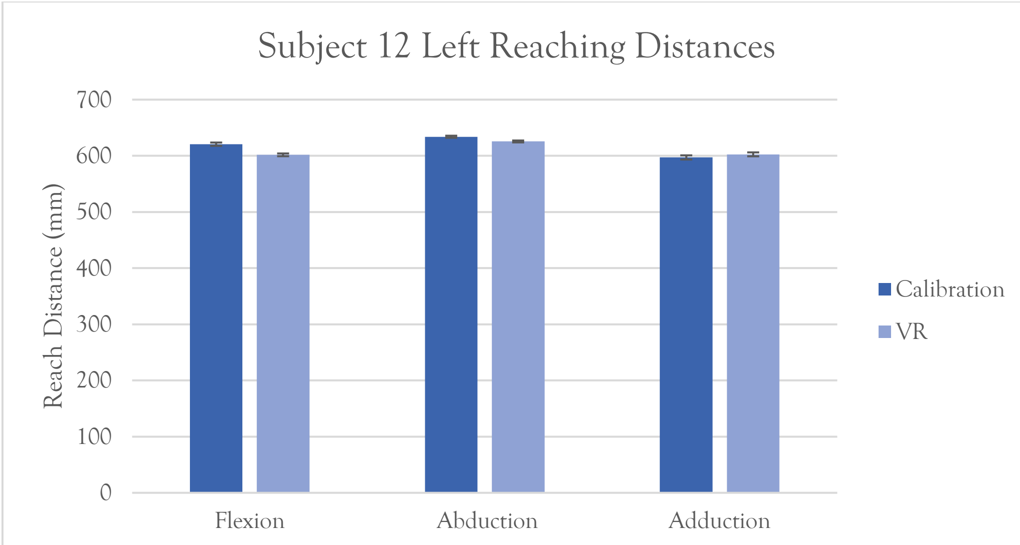
Subj 11 Right		
Names	Means	SD
Flexion Cal	631.08	1.62
Flexion VR	635.51	2.70
Abduction Cal	644.25	1.49
Abduction VR	646.16	1.08
Adduction Cal	584.45	7.47
Adduction VR	557.86	14.36



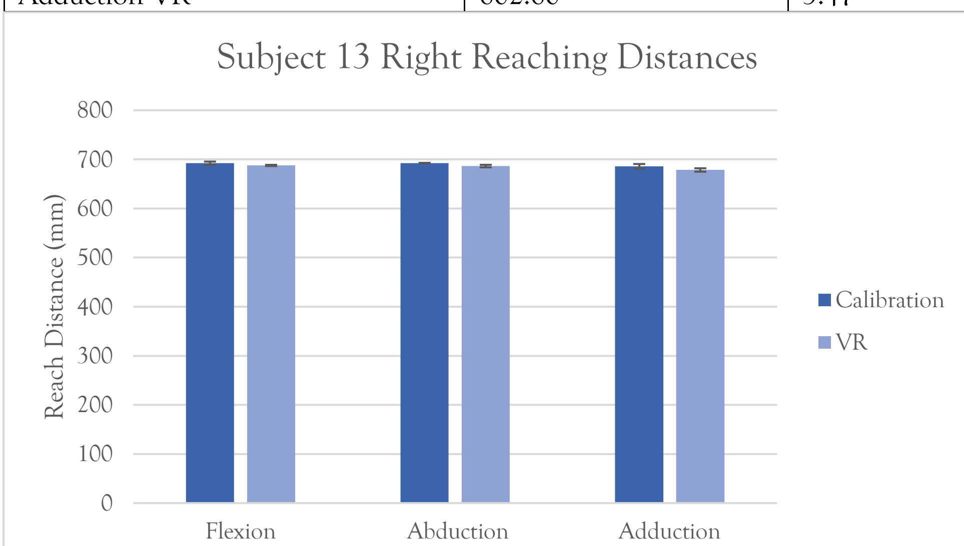
Subj 11 Left		
Names	Means	SD
Flexion Cal	634.29	3.70
Flexion VR	638.83	2.23
Abduction Cal	648.04	4.47
Abduction VR	646.61	4.64
Adduction Cal	590.75	17.75
Adduction VR	578.01	10.04



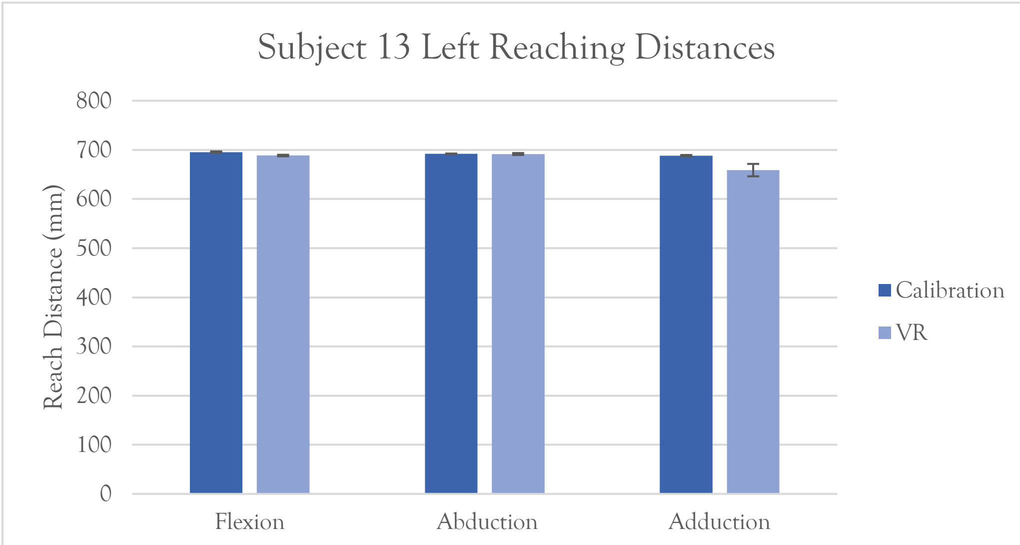
Subj 12 Right		
Names	Means	SD
Flexion Cal	625.62	2.21
Flexion VR	609.14	4.39
Abduction Cal	632.33	0.66
Abduction VR	640.24	4.62
Adduction Cal	596.23	2.24
Adduction VR	628.15	40.19



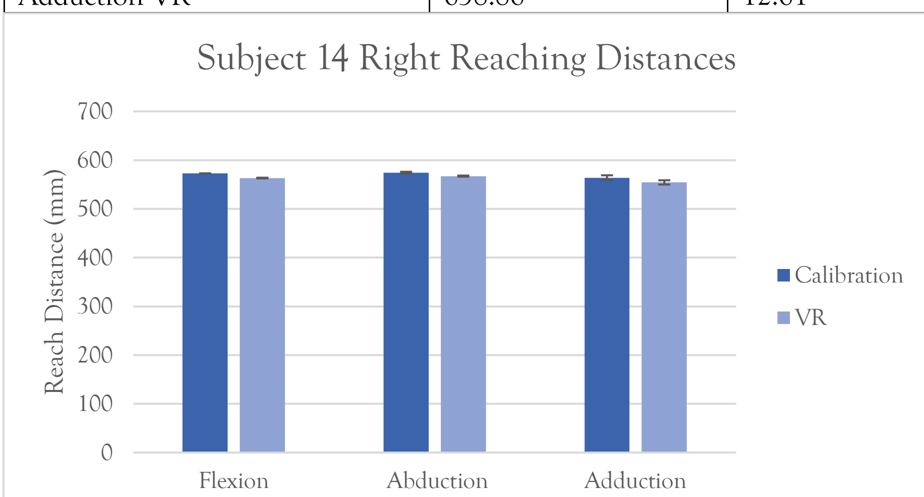
Subj 12 Left		
Names	Means	SD
Flexion Cal	620.65	2.97
Flexion VR	601.73	2.45
Abduction Cal	633.94	1.82
Abduction VR	625.54	1.70
Adduction Cal	597.08	3.72
Adduction VR	602.60	3.47



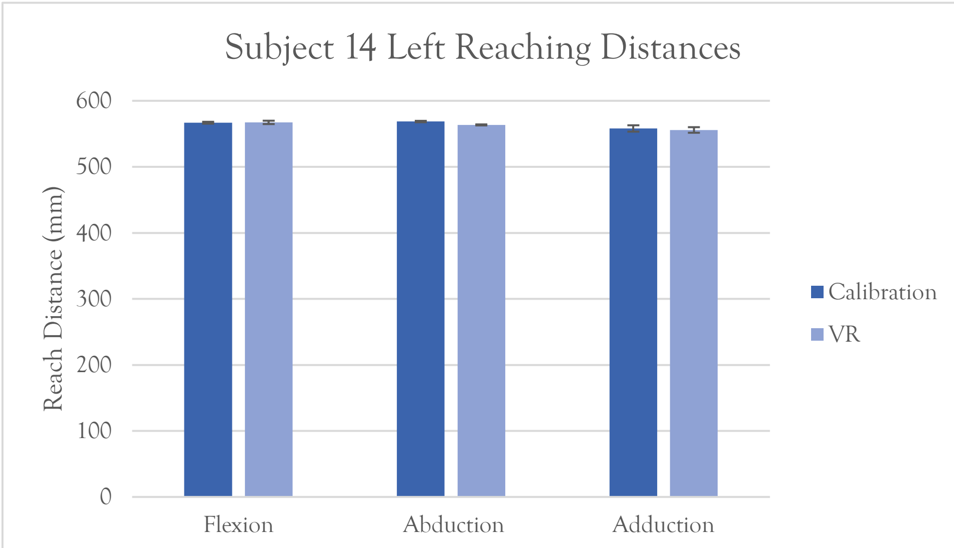
Subj 13 Right		
Names	Means	SD
Flexion Cal	692.27	3.27
Flexion VR	687.69	1.24
Abduction Cal	692.44	0.23
Abduction VR	686.41	2.58
Adduction Cal	685.61	4.99
Adduction VR	678.48	3.46



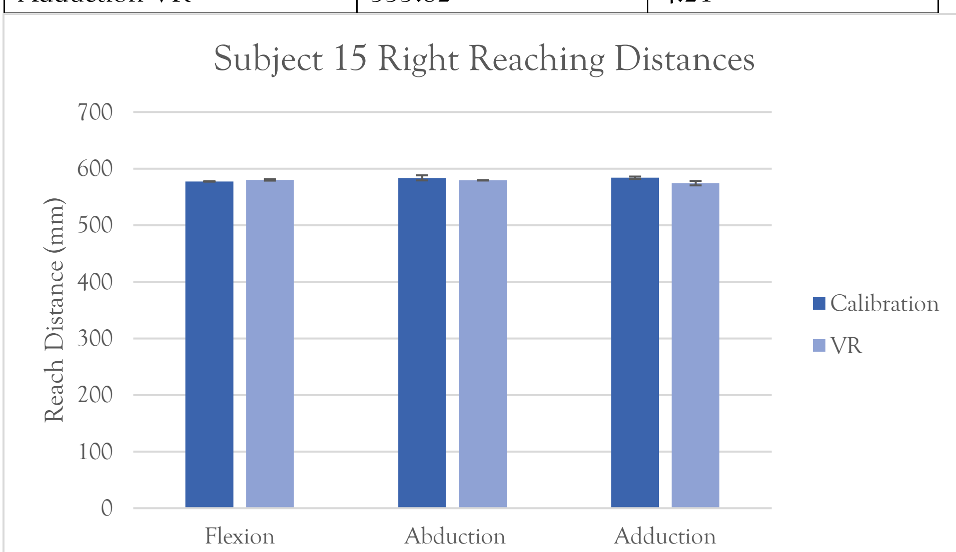
Subj 13 Left		
Names	Means	SD
Flexion Cal	695.47	1.49
Flexion VR	688.51	1.57
Abduction Cal	691.94	0.61
Abduction VR	691.57	1.97
Adduction Cal	688.21	1.42
Adduction VR	658.86	12.61



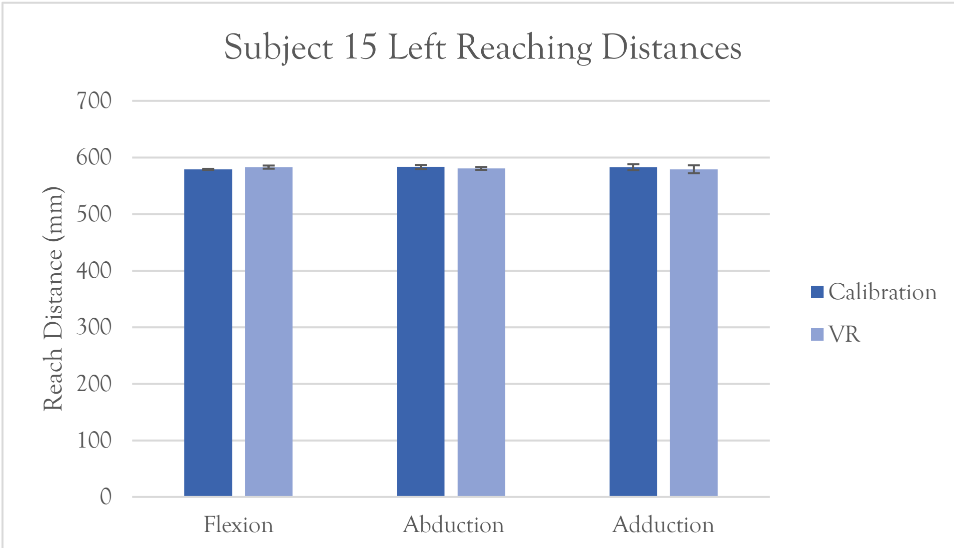
Subj 14 Right		
Names	Means	SD
Flexion Cal	572.72	0.27
Flexion VR	563.23	0.71
Abduction Cal	574.15	1.92
Abduction VR	567.23	1.11
Adduction Cal	563.75	5.16
Adduction VR	554.26	4.38



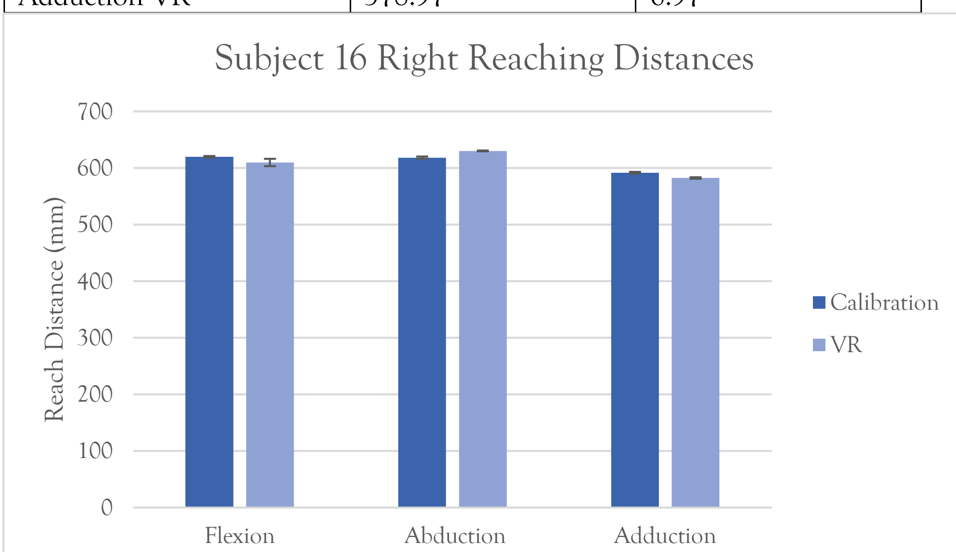
Subj 14 Left		
Names	Means	SD
Flexion Cal	566.80	1.42
Flexion VR	567.32	2.56
Abduction Cal	568.61	1.04
Abduction VR	563.48	0.78
Adduction Cal	558.11	4.80
Adduction VR	555.82	4.21



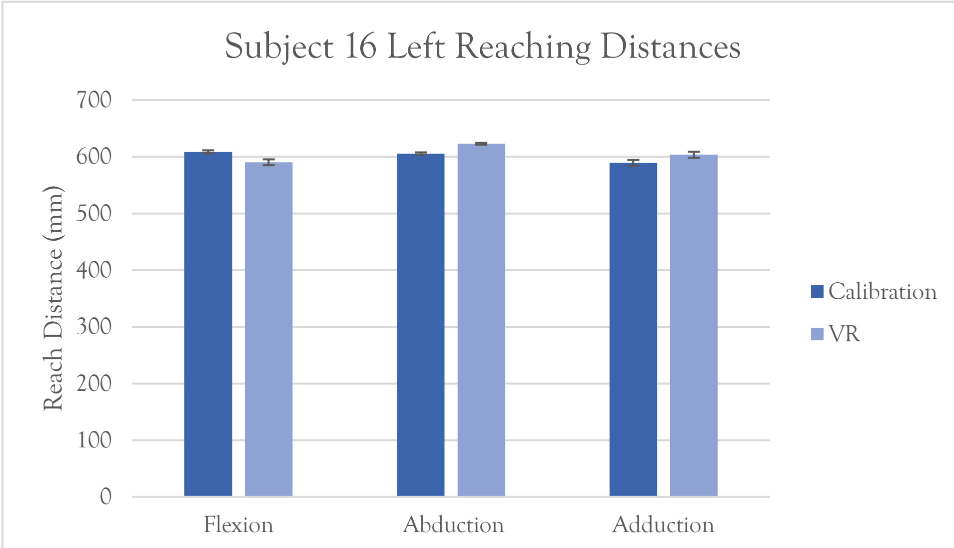
Subj 15 Right		
Names	Means	SD
Flexion Cal	577.34	0.37
Flexion VR	580.18	1.34
Abduction Cal	583.62	4.47
Abduction VR	579.37	0.41
Adduction Cal	583.88	2.12
Adduction VR	574.31	3.94



Subj 15 Left		
Names	Means	SD
Flexion Cal	578.84	0.96
Flexion VR	582.81	2.78
Abduction Cal	583.08	3.53
Abduction VR	580.56	2.53
Adduction Cal	582.78	5.24
Adduction VR	578.97	6.97



Subj 16 Right		
Names	Means	SD
Flexion Cal	619.80	1.42
Flexion VR	609.80	6.50
Abduction Cal	618.40	1.97
Abduction VR	630.26	0.77
Adduction Cal	591.63	1.60
Adduction VR	582.42	1.36



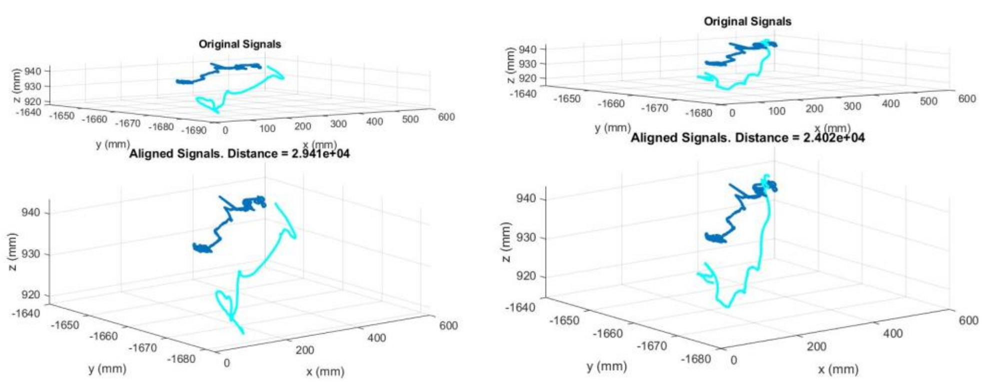
Subj 16 Left		
Names	Means	SD
Flexion Cal	608.48	2.74
Flexion VR	603.50	5.21
Abduction Cal	605.66	1.93
Abduction VR	622.81	1.56
Adduction Cal	588.98	5.19
Adduction VR	590.09	5.36

APPENDIX B

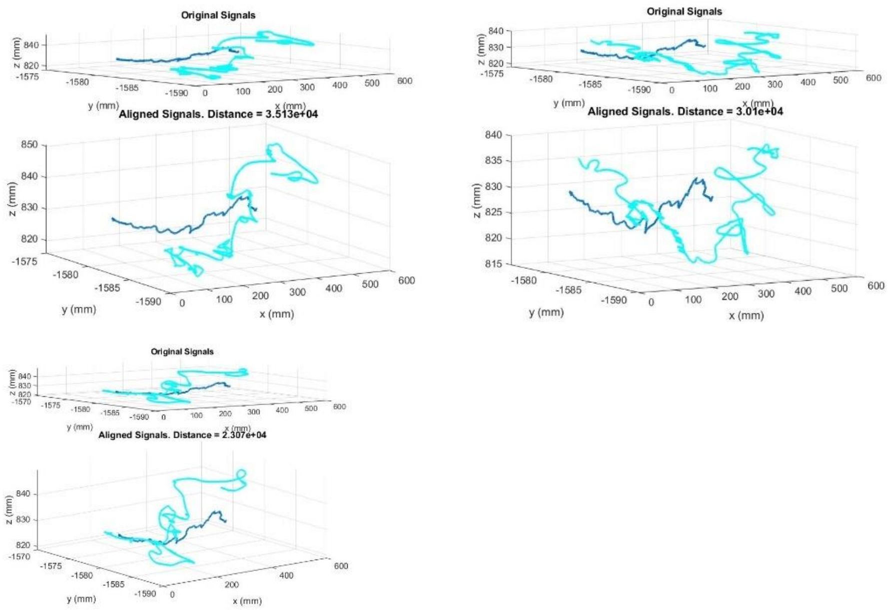
Complete Tracing Graphs

The graphs for the sagittal traces for all subjects appear first, followed by the transverse traces. All trials for each subject are shown. All subjects have three trials, except for subject 7, which has two. In all graphs the darker line is the original drawing and the lighter line is the trace. Axis are labeled. The X axis runs ventral-dorsal, and the Y axis runs left-right. The Z axis runs up and down. In all graphs the original signals are displayed on top, and the signals after DTW are displayed in the bottom graphs. All graphs are shown at a three-quarters view, though some graphs may be rotated slightly to give a better view.

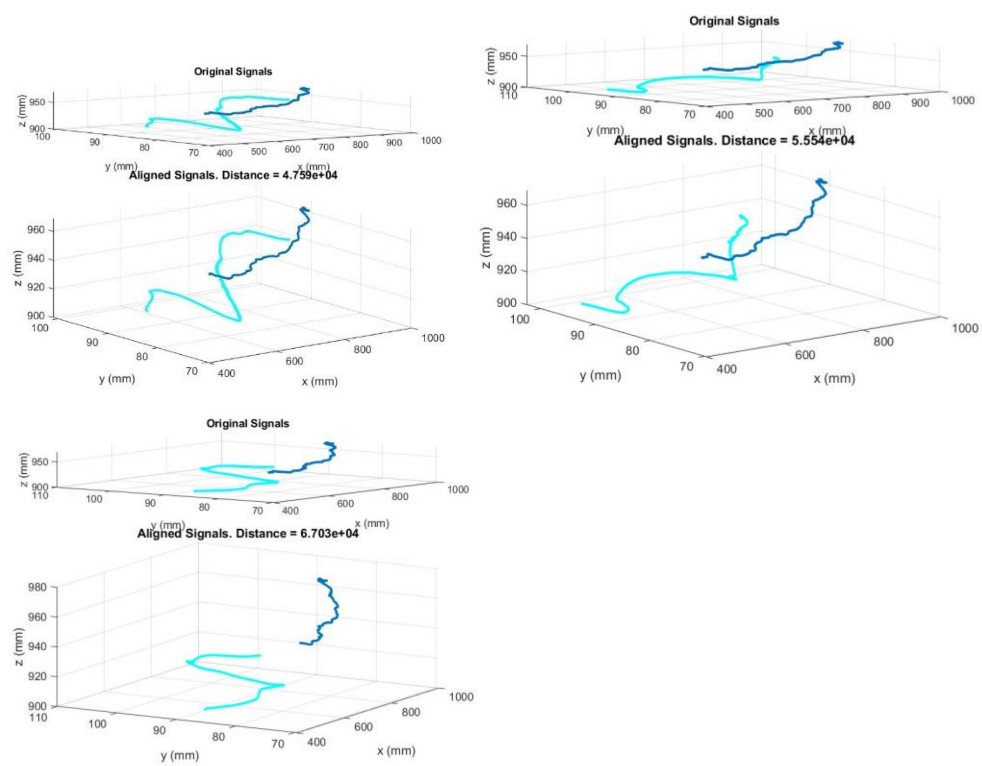
Subject 7 sagittal Traces 1 &2



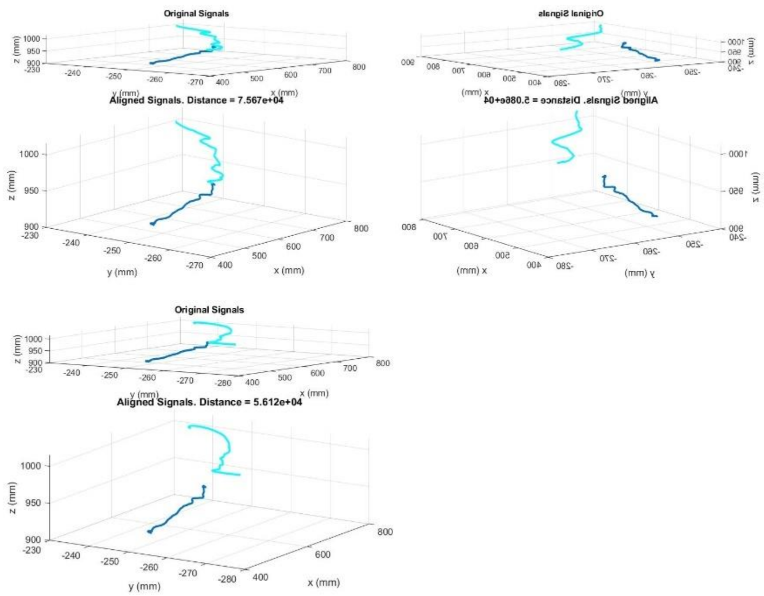
Subject 8 Sagittal Traces1, 2, & 3



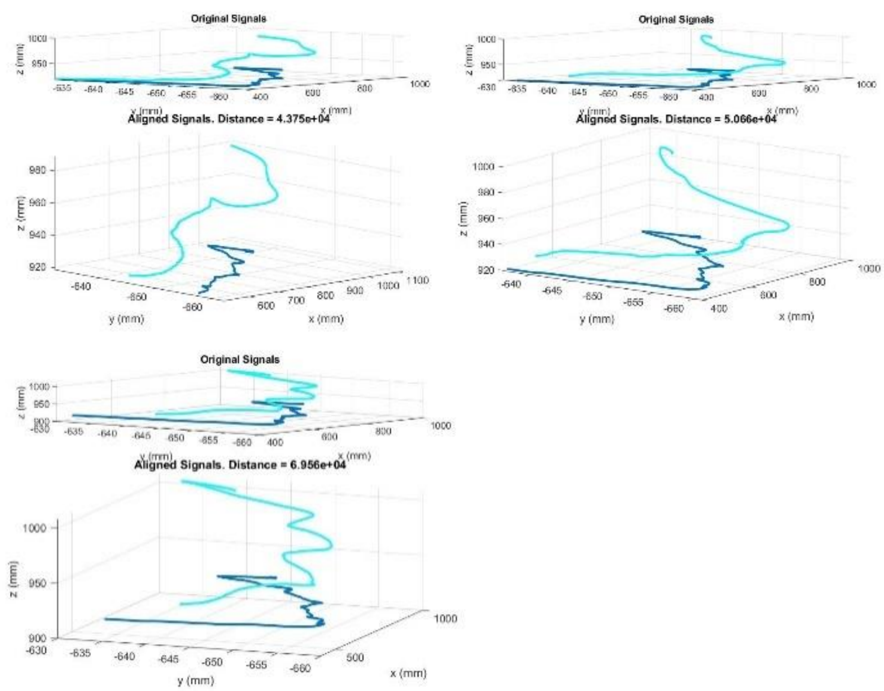
Subject 10 Sagittal Traces 1, 2, & 3



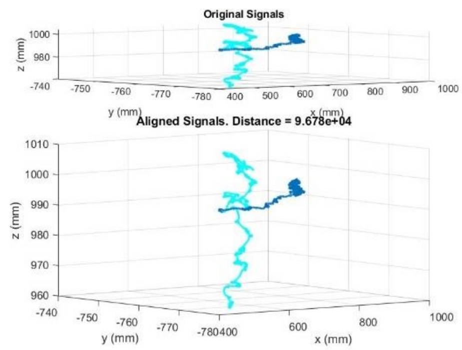
Subject 11 Sagittal Traces 1, 2, & 3

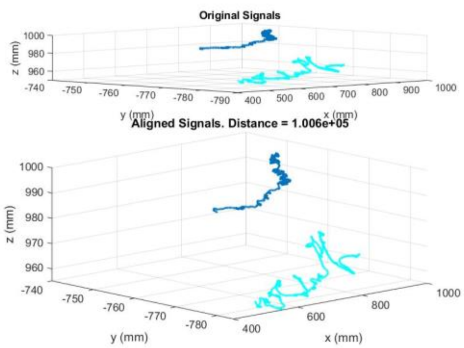


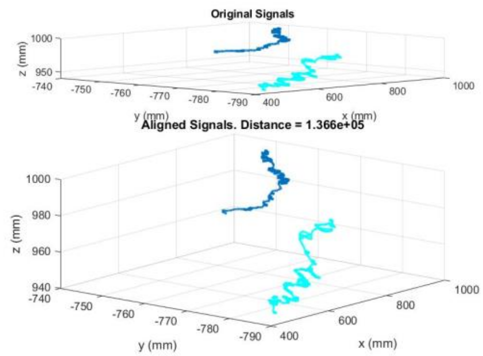
Subject 12 Sagittal Traces 1, 2, & 3



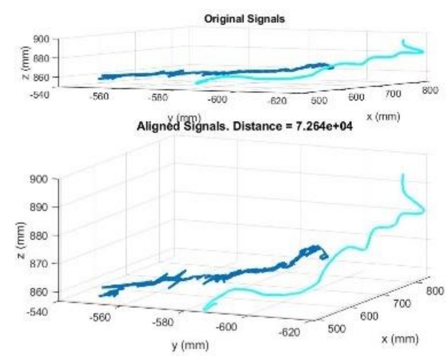
Subject 13 Sagittal Traces 1, 2, & 3

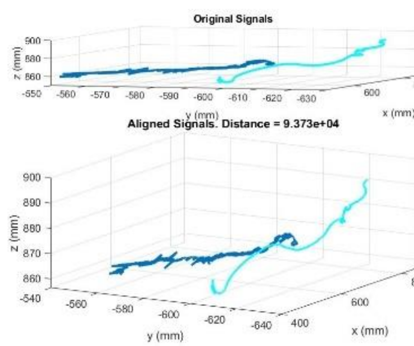


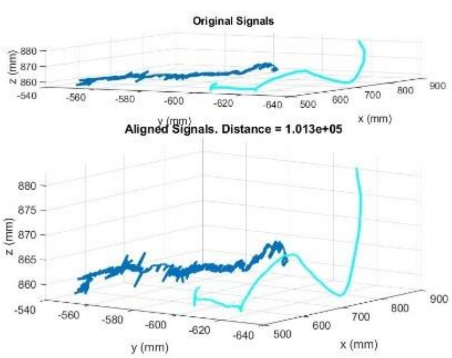




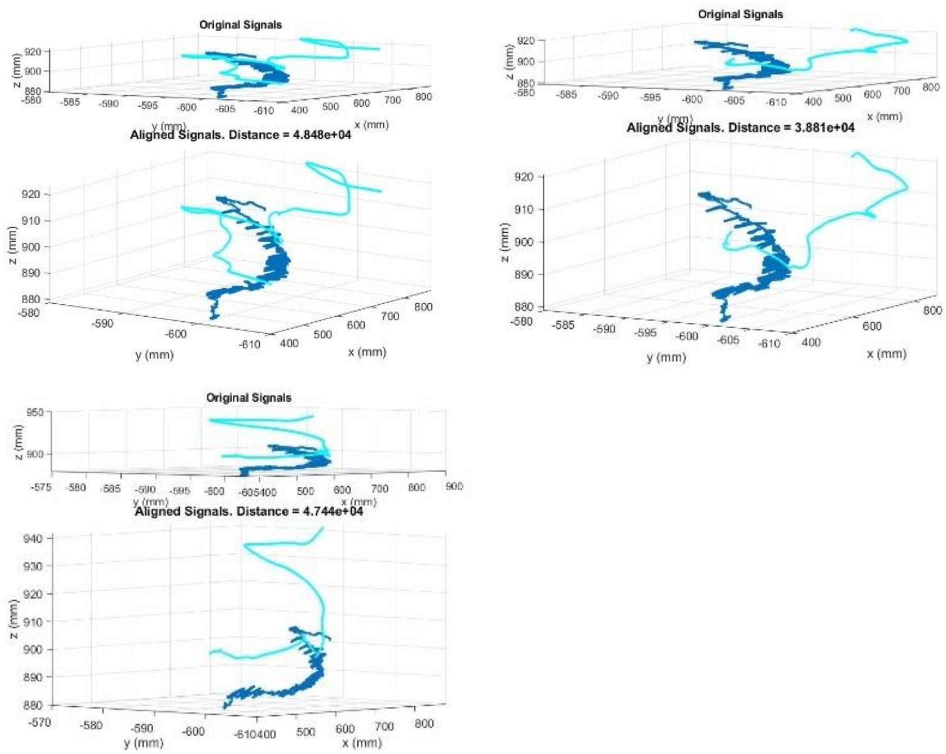
Subject 14 Sagittal Traces 1, 2, & 3



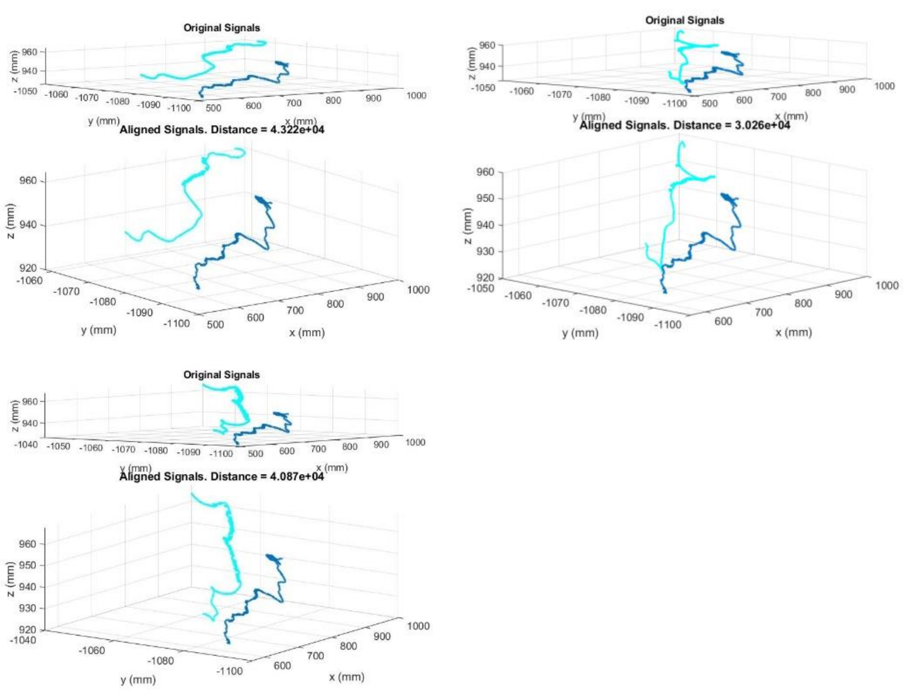




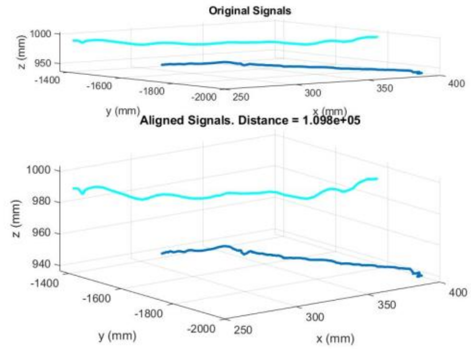
Subject 15 Sagittal Traces 1, 2, & 3

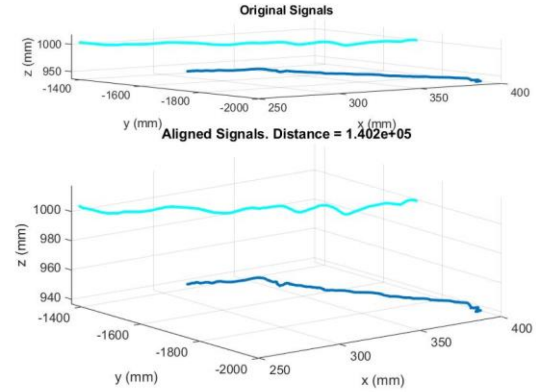


Subject 16 Sagittal Traces 1, 2, & 3

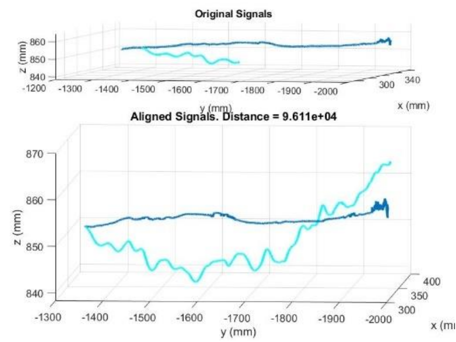


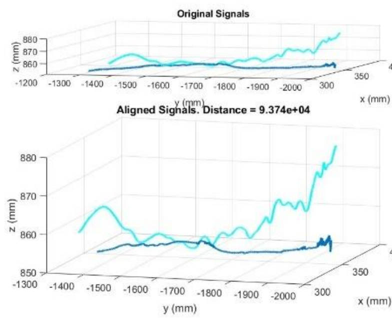
Subject 7 Transverse Traces 1 & 2

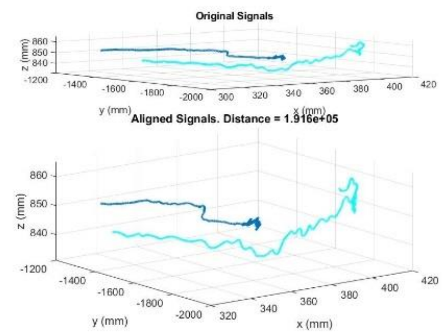




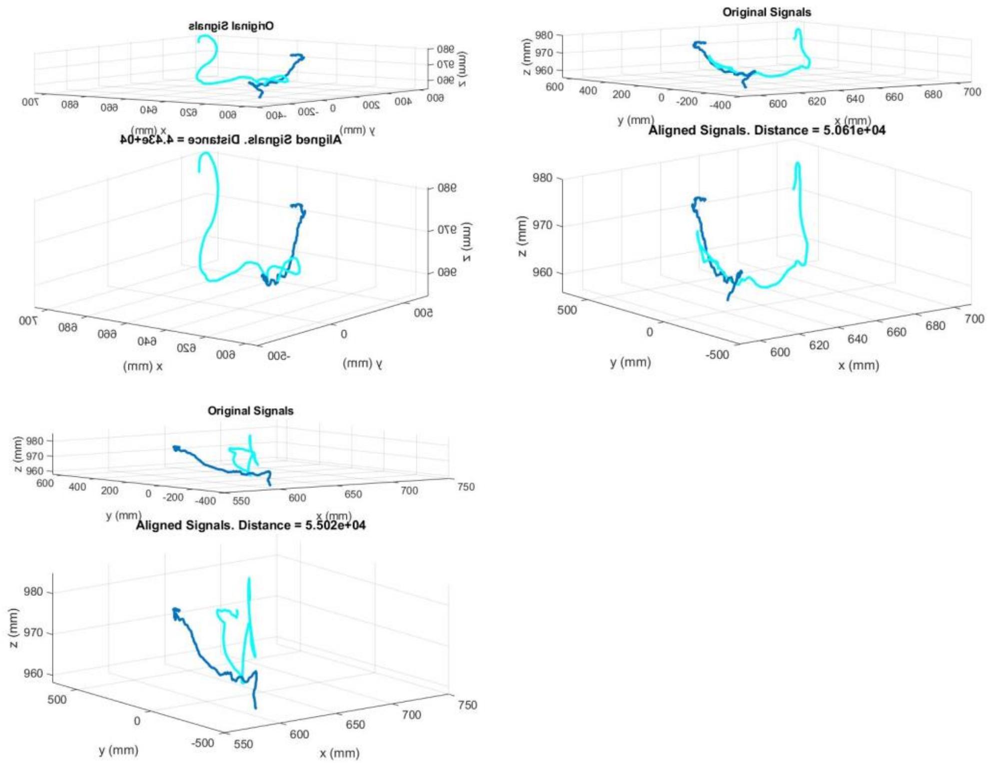
Subject 8 Transverse Traces 1, 2, & 3



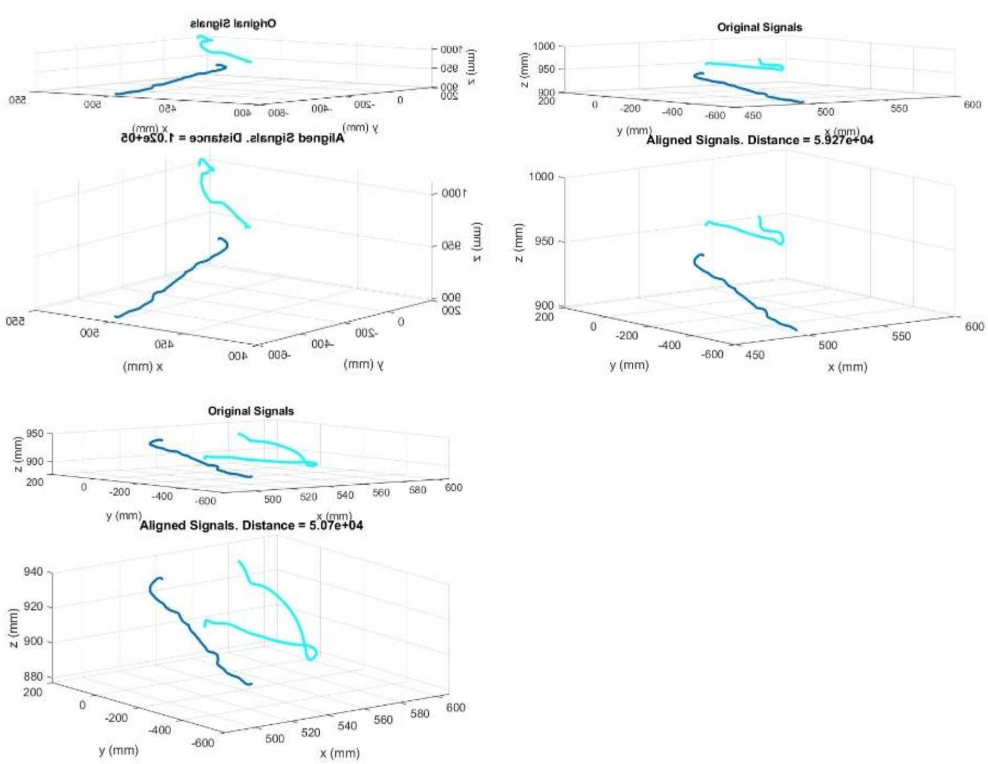




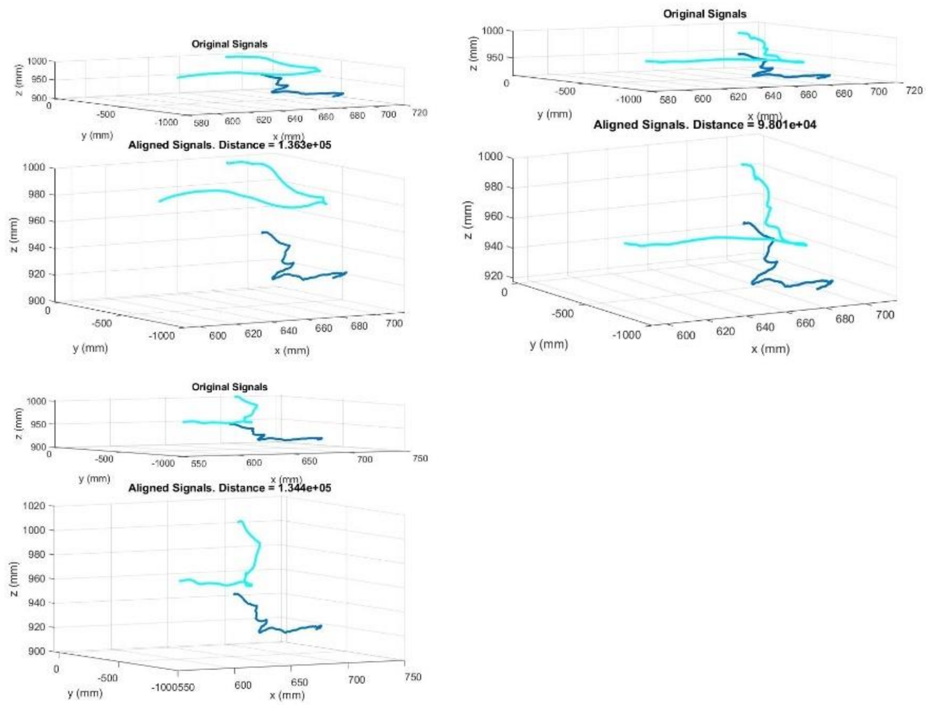
Subject 10 Transverse Traces 1, 2, & 3



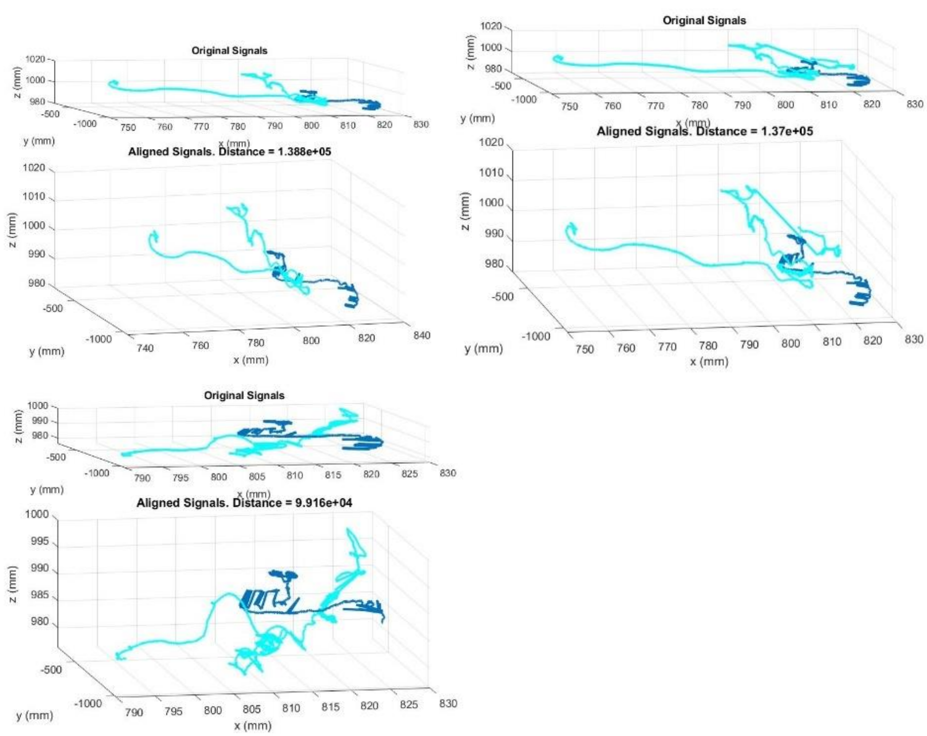
Subject 11 Transverse Traces 1, 2, & 3



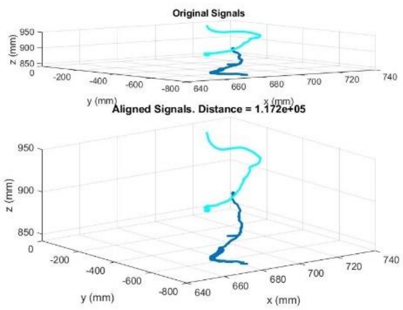
Subject 12 Transverse Traces 1, 2, & 3

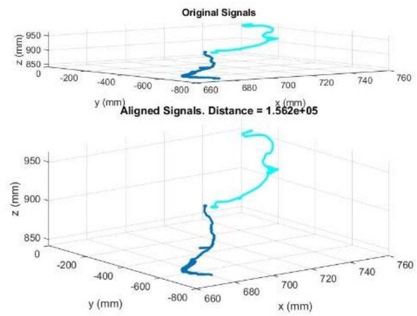


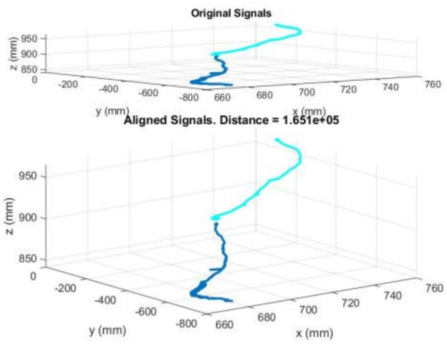
Subject 13 Transverse Traces 1, 2, & 3



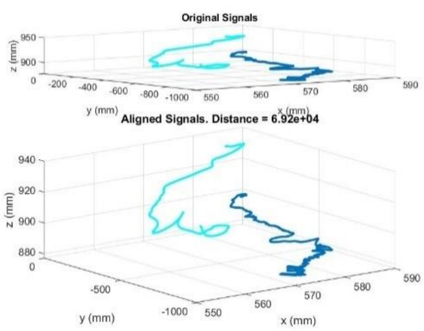
Subject 14 Transverse Traces 1, 2, & 3

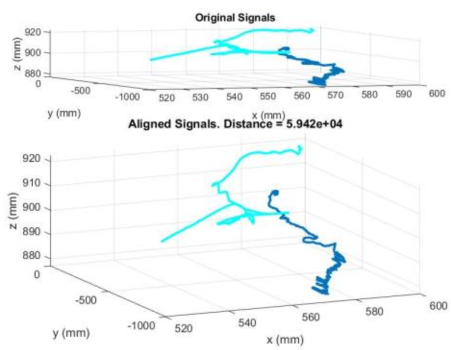


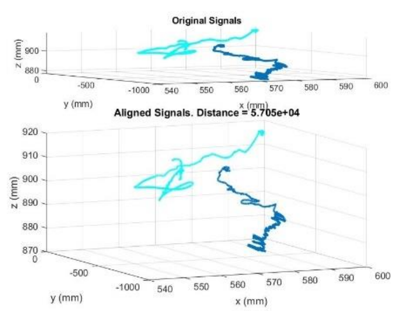




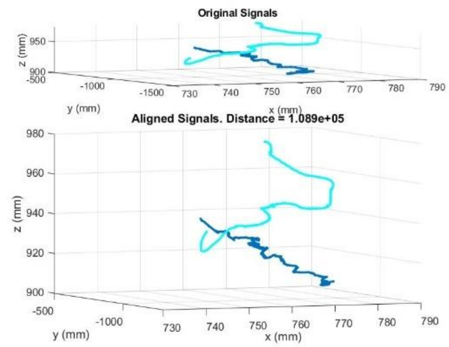
Subject 15 Transverse Traces 1, 2, & 3

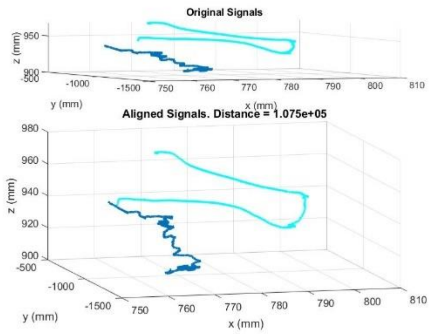


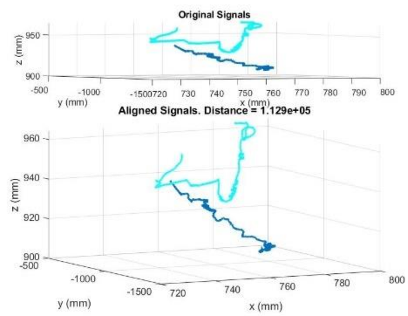




Subject 16 Transverse Traces 1, 2, & 3







BIBLIOGRAPHY

Abboudi, Hamid, Mohammed S. Khan, Omar Aboumarzouk, Khurshid A. Guru, Ben Challacombe, Prokar Dasgupta, and Kamran Ahmed. "Current Status of Validation for Robotic Surgery Simulators – a Systematic Review." *BJU International* 111, no. 2 (n.d.): 194–205. https://doi.org/10.1111/j.1464-410X.2012.11270.x.

Acosta, Ana Maria, Hendrik A. Dewald, and Jules P. A. Dewald. "Pilot Study to Test Effectiveness of Video Game on Reaching Performance in Stroke." *Journal of Rehabilitation Research and Development* 48, no. 4 (2011): 431–44.

Anglin, J. M., T. Sugiyama, and S.-l Liew. "Visuomotor Adaptation in Head-Mounted Virtual Reality versus Conventional Training." *Scientific Reports (Nature Publisher Group); London* 7 (April 2017): 45469. http://dx.doi.org/10.1038/srep45469.

Borrego, Adrian, Jorge Latorre, Roberto Llorens, Mariano Alcaniz, and Enrique Noe. "Feasibility of a Walking Virtual Reality System for Rehabilitation: Objective and Subjective Parameters." *Journal of Neuroengineering and Rehabilitation; London* 13 (2016). http://dx.doi.org/10.1186/s12984-016-0174-1.

Christiansen, Charles, Beatriz Abreu, Kenneth Ottenbacher, Kenneth Huffman, Brent Masel, and Robert Culpepper. "Task Performance in Virtual Environments Used for Cognitive Rehabilitation after Traumatic Brain Injury." *Archives of Physical Medicine and Rehabilitation* 79, no. 8 (August 1, 1998): 888–92. https://doi.org/10.1016/S0003-9993(98)90083-1.

Cirstea, M.C., and M.F. Levin. "Improvement of Arm Movement Patterns and Endpoint Control Depends on Type of Feedback During Practice in Stroke Survivors." *Neurorehabilitation and Neural Repair* 21, no. 5 (September 1, 2007): 398–411. https://doi.org/10.1177/1545968306298414.

Corbetta, Davide, Federico Imeri, and Roberto Gatti. "Rehabilitation That Incorporates Virtual Reality Is More Effective than Standard Rehabilitation for Improving Walking Speed, Balance and Mobility after Stroke: A Systematic Review." *Journal of Physiotherapy* 61, no. 3 (July 1, 2015): 117–24. https://doi.org/10.1016/j.jphys.2015.05.017.

Cruz-Neira, C., J. Leigh, M. Papka, C. Barnes, S. M. Cohen, S. Das, R. Engelmann, et al. "Scientists in Wonderland: A Report on Visualization Applications in the CAVE Virtual Reality Environment." In *Proceedings of 1993 IEEE Research Properties in Virtual Reality Symposium*, 59–66, 1993. https://doi.org/10.1109/VRAIS.1993.378262.

Cutti, Andrea Giovanni, Gabriele Paolini, Marco Troncossi, Angelo Cappello, and Angelo Davalli. "Soft Tissue Artefact Assessment in Humeral Axial Rotation." *Gait & Posture* 21, no. 3 (April 1, 2005): 341–49. https://doi.org/10.1016/j.gaitpost.2004.04.001.

Dukelow, Sean P., Troy M. Herter, Stephen D. Bagg, and Stephen H. Scott. “The Independence of Deficits in Position Sense and Visually Guided Reaching Following Stroke.” *Journal of NeuroEngineering and Rehabilitation* 9, no. 1 (October 4, 2012): 72. https://doi.org/10.1186/1743-0003-9-72.

Ebrahimi, Elham, Sabarish V. Babu, Christopher C. Pagano, and Sophie Jörg. “An Empirical Evaluation of Visuo-Haptic Feedback on Physical Reaching Behaviors During 3D Interaction in Real and Immersive Virtual Environments.” *ACM Transactions on Applied Perception* 13, no. 4 (July 29, 2016): 1–21. https://doi.org/10.1145/2947617.

Fugl-Meyer, AR, L Jaasko, I Leyman, S Olsson, and S Steglind. “FUGL-MEYER ASSESSMENT UPPER EXTREMITY (FMA-UE) Assessment of Sensorimotor Function.” University of Gothenburg, 205AD.

“Full Body Modeling with Plug-in Gait - Nexus 2.6 Documentation - Vicon Documentation.” Accessed December 1, 2018. https://docs.vicon.com/display/Nexus26/Full+body+modeling+with+Plug-in+Gait#FullbodymodelingwithPlug-inGait-MarkersetsforPlug-inGaitfullbodymodeling.

Gamito, Pedro, Jorge Oliveira, Nuno Santos, José Pacheco, Diogo Morais, Tomaz Saraiva, Fábio Soares, Catarina S. Mayor, and Ana F. Barata. “Virtual Exercises to Promote Cognitive Recovery in Stroke Patients: The Comparison between Head Mounted Displays versus Screen Exposure Methods.” *International Journal on Disability and Human Development; Berlin* 13, no. 3 (2014): 337–42. http://dx.doi.org/10.1515/ijdhd-2014-0325.

Gerig, Nicolas, Johnathan Mayo, Kilian Baur, Frieder Wittmann, Robert Riener, and Peter Wolf. “Missing Depth Cues in Virtual Reality Limit Performance and Quality of Three Dimensional Reaching Movements.” *PLoS ONE* 13, no. 1 (January 2, 2018): e0189275.

Grealy, Madeleine A., David A. Johnson, and Simon K. Rushton. “Improving Cognitive Function after Brain Injury: The Use of Exercise and Virtual Reality.” *Archives of Physical Medicine and Rehabilitation* 80, no. 6 (June 1, 1999): 661–67. https://doi.org/10.1016/S0003-9993(99)90169-7.

Hammer, Gary D. *Pathophysiology of Disease: An Introduction to Clinical Medicine.* S.l.: McGraw-Hill Education, 2018.

Kamper, Derek G., Alicia N. McKenna-Cole, Leonard E. Kahn, and David J. Reinkensmeyer. “Alterations in Reaching after Stroke and Their Relation to Movement Direction and Impairment Severity.” *Archives of Physical Medicine and Rehabilitation* 83, no. 5 (May 1, 2002): 702–7. https://doi.org/10.1053/apmr.2002.32446.

Kantak, Shailesh, Steven Jax, and George Wittenberg. “Bimanual Coordination: A Missing Piece of Arm Rehabilitation after Stroke.” *Restorative Neurology and Neuroscience* 35, no. 4 (August 8, 2017): 347–64. https://doi.org/10.3233/RNN-170737.

Kelly, Jonathan W., Lucia A. Cherep, and Zachary D. Siegel. "Perceived Space in the HTC Vive." *ACM Trans. Appl. Percept.* 15, no. 1 (July 2017): 2:1–2:16. https://doi.org/10.1145/3106155.

Kizony, Rachel, Noomi Katz, and Patrice L. (Tamar) Weiss. "Adapting an Immersive Virtual Reality System for Rehabilitation." *The Journal of Visualization and Computer Animation* 14, no. 5 (December 1, 2003): 261–68. https://doi.org/10.1002/vis.323.

Laver, Kate E, Stacey George, Susie Thomas, Judith E Deutsch, and Maria Crotty. "Virtual Reality for Stroke Rehabilitation." In *Cochrane Database of Systematic Reviews*. John Wiley & Sons, Ltd, 2015. https://doi.org/10.1002/14651858.CD008349.pub3.

Lee, Baekhee, Mina Lee, Myeung Sook Yoh, Heecheon You, Hyunji Park, Kihyo Jung, Byung Hwa Lee, Duk L. Na, and Geon Ha Kim. "The Effects of Age, Gender, and Hand on Force Control Capabilities of Healthy Adults." *Human Factors* 57, no. 8 (December 1, 2015): 1348–58. https://doi.org/10.1177/0018720815599284.

Levin, Mindy F., Patrice L. Weiss, and Emily A. Keshner. "Emergence of Virtual Reality as a Tool for Upper Limb Rehabilitation: Incorporation of Motor Control and Motor Learning Principles." *Physical Therapy* 95, no. 3 (March 1, 2015): 415–25. https://doi.org/10.2522/ptj.20130579.

Lindley, Richard I. *Stroke*. Oxford, UNITED KINGDOM: Oxford University Press, 2017. http://ebookcentral.proquest.com/lib/bayloru/detail.action?docID=4838056.

Lintern, Gavan, Stanley N. Roscoe, and Jonathan E. Sivier. "Display Principles, Control Dynamics, and Environmental Factors in Pilot Training and Transfer." *Human Factors; Santa Monica, Calif.* 32, no. 3 (June 1, 1990): 299.

Mani, Saandeep, Pratik K. Mutha, Andrzej Przybyla, Kathleen Y. Haaland, David C. Good, and Robert L. Sainburg. "Contralesional Motor Deficits after Unilateral Stroke Reflect Hemisphere-Specific Control Mechanisms." *Brain* 136, no. 4 (April 1, 2013): 1288–1303. https://doi.org/10.1093/brain/aws283.

McNulty, Penelope A., Angelica G. Thompson-Butel, Steven G. Faux, Gaven Lin, Pesi H. Katrak, Laura R. Harris, and Christine T. Shiner. "The Efficacy of Wii-Based Movement Therapy for Upper Limb Rehabilitation in the Chronic Poststroke Period: A Randomized Controlled Trial." *International Journal of Stroke* 10, no. 8 (December 1, 2015): 1253–60. https://doi.org/10.1111/ijs.12594.

Murray, Ingram Andrew. "Determining Upper Limb Kinematics and Dynamics during Everyday Tasks." Newcastle University, 1999. https://theses.ncl.ac.uk/dspace/handle/10443/185.

"Nexus Model Documentation - Nexus Reference Documentation - Vicon Documentation." Accessed December 1, 2018. https://docs.vicon.com/display/NLD/Nexus+model+documentation?preview=/71239849/71239855/Model_UpperLimb_ProductGuide_Rev1.0_2007Jul.pdf.

Nichols-Larsen, Deborah, and Deborah Kegelmeyer. "Stroke." In *Neurologic Rehabilitation: Neuroscience and Neuroplasticity in Physical Therapy Practice*. New York, NY: McGraw-Hill. Accessed June 28, 2018. https://accessphysiotherapy-mhmedical-com.ezproxy.baylor.edu/content.aspx?sectionid=120048133&bookid=1760&jumpsectionID=120048138&Resultclick=2#1125979755.

Niehorster, Diederick C., Li Li, and Markus Lappe. "The Accuracy and Precision of Position and Orientation Tracking in the HTC Vive Virtual Reality System for Scientific Research." *I-Perception* 8, no. 3 (June 1, 2017): 2041669517708205. https://doi.org/10.1177/2041669517708205.

Parry, Ruth H, Nadina B Lincoln, and Maria A Appleyard. "Physiotherapy for the Arm and Hand after Stroke." *Physiotherapy* 85, no. 8 (August 1, 1999): 417–25. https://doi.org/10.1016/S0031-9406(05)65500-9.

Proffitt, Rachel, and Belinda Lange. "Considerations in the Efficacy and Effectiveness of Virtual Reality Interventions for Stroke Rehabilitation: Moving the Field Forward." *Physical Therapy* 95, no. 3 (March 1, 2015): 441–48. https://doi.org/10.2522/ptj.20130571.

Sand, K. M., G. Wilhelmsen, H. Næss, A. Midelfart, L. Thomassen, and J. M. Hoff. "Vision Problems in Ischaemic Stroke Patients: Effects on Life Quality and Disability." *European Journal of Neurology* 23, no. S1 (2016): 1–7. https://doi.org/10.1111/ene.12848.

Schmitt, Yuko S., Hunter G. Hoffman, David K. Blough, David R. Patterson, Mark P. Jensen, Maryam Soltani, Gretchen J. Carrougher, Dana Nakamura, and Sam R. Sharar. "A Randomized, Controlled Trial of Immersive Virtual Reality Analgesia, during Physical Therapy for Pediatric Burns." *Burns* 37, no. 1 (February 1, 2011): 61–68. https://doi.org/10.1016/j.burns.2010.07.007.

Semrau, Jennifer A., Troy M. Herter, Stephen H. Scott, and Sean P. Dukelow. "Robotic Identification of Kinesthetic Deficits After Stroke." *Stroke* 44, no. 12 (December 2013): 3414–21. https://doi.org/10.1161/STROKEAHA.113.002058.

Sheehan, Riley C., Christopher A. Rabago, Jonathan H. Rylander, Jonathan B. Dingwell, and Jason M. Wilken. "Use of Perturbation-Based Gait Training in a Virtual Environment to Address Mediolateral Instability in an Individual with Unilateral Transfemoral Amputation." Physical Therapy, December 1, 2016. https://doi.org/10.2522/ptj.20150566.

"Structured Wii Protocol for Rehabilitation of Shoulder Impingement Syndrome: A Pilot Study - ScienceDirect." Accessed August 1, 2018. https://www-sciencedirect-com.ezproxy.baylor.edu/science/article/pii/S1877065716305164.

Subramanian, Sandeep K, and Mindy F Levin. "Viewing Medium Affects Arm Motor Performance in 3D Virtual Environments." *Journal of NeuroEngineering and Rehabilitation* 8, no. 1 (2011): 36. https://doi.org/10.1186/1743-0003-8-36.

Sukal, Theresa M., Michael D. Ellis, and Julius P. A. Dewald. "Shoulder Abduction-Induced Reductions in Reaching Work Area Following Hemiparetic Stroke: Neuroscientific Implications." *Experimental Brain Research* 183, no. 2 (November 1, 2007): 215–23. https://doi.org/10.1007/s00221-007-1029-6.

Swan, J. E., G. Singh, and S. R. Ellis. "Matching and Reaching Depth Judgments with Real and Augmented Reality Targets." *IEEE Transactions on Visualization and Computer Graphics* 21, no. 11 (November 2015): 1289–98. https://doi.org/10.1109/TVCG.2015.2459895.

"Tilt Brush by Google." Accessed April 14, 2019. https://www.tiltbrush.com/.

VICON. "Vantage Motion Capture Camera." VICON. Accessed April 9, 2019. http://www.vicon.com/products/camera-systems/vantage.

"VIVE™ | Discover Virtual Reality Beyond Imagination." Accessed December 11, 2017. https://www.vive.com/us/.

Wilson, P. N., N. Foreman, and D. Stanton. "Virtual Reality, Disability and Rehabilitation." *Disability and Rehabilitation* 19, no. 6 (June 1, 1997): 213.

Wolf, SL, PA Caitlin, M Ellis, A Link, B Morgan, and A Piacento. "Wolf Motor Function Test (WMFT)." Whitaker Insitiutute, 2011. https://doi.org/10.13072/midss.257.