**Title**
Virtual Modified Constraint Induced Movement Therapy for Stroke Survivors with Hemiparesis



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**VIRTUAL MODIFIED CONSTRAINT INDUCED MOVEMENT THERAPY FOR STROKE SURVIVORS WITH HEMIPARESIS**

A thesis submitted in partial satisfaction
of the requirements for the degree of

MASTER OF SCIENCE

in

COMPUTER ENGINEERING

by

**LUKE BUSCHMANN**

March 2015

The Thesis of LUKE BUSCHMANN
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**Abstract**

Virtual Modified Constraint Induced Movement Therapy for Stroke Survivors with Hemiparesis

by

Luke Buschmann

Modified constraint induced movement therapy is a focus of rehabilitation research for stroke survivors with hemiplegia that relies on physically constraining a patients unaffected limb to modify a patients behavior and force the use of the affected limb in a rehabilitation setting. In this study, we attempt to cognitively induce a constraint in patients engaging in virtual therapy via a Kinect and Unity based platform. The platform included four games that each utilized a different active range of motion (ROM) exercise for control of game objects.

Five stroke survivors with hemiparesis were recruited for a two week study consisting of five, 25-minute therapy sessions each. Users were allowed to use either their unaffected or affected limb to play each game at any time and allowed their choice of games during each session. For each game, the difficulty level remained at baseline while the user used their affected side to play but the difficulty was increased at varying rates when the user used their unaffected side to play. Results were evaluated for compliance to the therapy (usage rate of affected side), choice of games, performance, efficacy of therapy (ROM), and qualitative behavior of users.

Compliance during virtual mCIT seems to be higher than that of traditional mCIT but a more extensive user test is necessary to validate this result. ROM measurements did not provide a clear trend due to the small size and duration of the data set. Trends were found in several areas of user behavior: (1) users preferred games utilizing only one axis of control and not reliant on orientation of the limb, (2) users also tended to play games in a certain order, (3) user performance increased over time, and (4) users often incorrectly performed the desired active ROM exercise for each game which may indicate the necessity to observe and coach patients during virtual rehabilitation.

ACKNOWLEDGMENTS

Thanks to Cole Buschmann and Leonard Norton for consultation regarding physical therapy practices and range of motion measurements. Qualitative analysis was performed by John-Michael Burke, Molly Graham, and David Narel. Custom music for the rehabilitation games was composed, performed, and recorded by Adam Sporka.

# 1 Introduction

## 1.1 Strokes and Hemiplegia

Stroke, also known as cerebrovascular disease, cerebrovascular accident, or cerebrovascular insult, occurs due to a disturbance of blood flow to the brain that causes loss of brain function due to either a lack of blood flow or hemorrhage. Causes of stroke vary, but age is a significant factor as two thirds of strokes occur in adults over the age of 65 [4]. Due to the increasing number of aging adults in the developed world, the number of strokes had increased by 10% in the developed world between 1990 and 2010, making stroke a leading cause of disability [4]. The CDC reports that 2.7% of all noninstitutionalized adults in the U.S. have had a stroke [6] and strokes are the leading cause of long-term disability in the U.S.[26]. Due to the current population trends, we can expect to continue to see rises in the occurrences of stroke in the developed world.

Stroke survivors suffer from a number of physical, emotional, and cognitive effects after the stroke [1]. Physical conditions include partial or total inability to move the affected side of the body (hemiparesis or hemiplegia), reduction in sensory awareness, fatigue, pain, spasticity, visual impairment, incontinence, difficulty swallowing (dysphagia), and paralysis. Emotional conditions include depression, which affects more than one third of stroke survivors, and is due to the survivor's feelings of anger, frustration, anxiety, sadness, fear, and hopelessness associated with their condition. Cognitive conditions include inability to express and understand language (aphasia), memory loss, and problems with perception and attention. [1] . Stroke has also shown to cause a reduction in overall physical fitness. Each of these conditions may affect the quality of life and physical and emotional well-being of the stroke survivor.

Hemiparesis is a condition that can be caused by stroke, cerebral palsy, multiple sclerosis, brain tumors, other neurological disorders, but is experienced by over 80% of stroke survivors [29]. Hemiplegia, the most extreme form of hemiparesis, is classified as a complete paralysis of one side of the body. Other forms of hemiparesis include right-sided hemiparesis, left-sided hemiparesis, ataxia, and pure motor hemiparesis. Right-sided hemiparesis occurs when the stroke injures the left side of the person's brain of which aphasia is a common condition. Left-side hemiparesis occurs when the stroke injures the right side of the person's brain and typically causes loss of attention span and memory as well as excessive talking. Ataxia occurs when the stroke injures the lower portion of a person's brain and affects muscle coordination, causing difficulties with walking and balance. Pure motor hemiparesis is the most common form and is categorized by weakness in a person's leg, arm, or face [29].

## 1.2 Range of Motion

In reducing mobility, hemiparesis causes a reduction in the range of motion (ROM) of the affected side of an individual. ROM is a measure of the amount of freedom that a joint can move in a certain direction. Typically therapists use a goniometer to measure range of motion but there has been a wealth of research in using RGBd camera data to obtain the same measurements with equal or greater accuracy [11] [21]. These studies have shown error rates of 10% or less on the range of motion angles taken from Kinect data.

ROM measurements taken using goniometers are inherently error prone, depending on the examiner, different patient types, time interval between measurements, and proper alignment of the goniometer [7] [10]. Studies have shown that the reliability of repeated ROM measurements may be influenced by the process of taking the measurements and that certain ROM measurements "did not lend themselves to reliable repetitive measurements" [7]. Physical therapists look at trends of ROM measurements over time to quantify limitations of motion as well as to decide on treatment and assess the effectiveness of treatments [7]. In this study we use ROM measurements to obtain some quantitative sense of the user's mobility before and after the study.

## 1.3 Stroke Rehabilitation

After the stroke survivor's medical status is stabilized, the process by which stroke survivors undergo treatment to return to normal pre-stroke life, adapt to difficulties caused by stroke, and prevent secondary complications whose root cause is stroke is called stroke rehabilitation [20]. Rehabilitation is typically a multidisciplinary field and involves physicians, pharmacists, nurses, occupational therapists, physical therapists, speech therapists, orthotists, psychologists, and social workers working together to treat the various conditions caused by stroke [20]. There is a wealth of current research in various avenues for stroke rehabilitation including motor re-learning, constraint induced movement therapy [13], mental imagery, mirror therapy, electrical stimulation, and neurodevelopmental treatment.

Treatment of hemiparesis requires stroke survivors to learn new ways of moving their affected side. Physical therapists specialize in improving the patient's strength, endurance, range of motion, balance, and coordination [29].

Recovery can be defined in terms of spontaneous or intrinsic recovery and functional or adaptive recovery [28]. Spontaneous recovery occurs initially after the stroke occurs and for a period of 3-6 months after the stroke. After this period ends, functional recovery refers to improvement in self care and mobility and is largely dependent on the patient's motivation, quality of therapy, and social pressures [28]. In this study, we worked with patients that are in the period of functional recovery and working toward improving their mobility. Current research states that younger individuals typically have a more rapid and extensive recovery than older individuals, which correlates with the decline in ability for the aging population to form neurological connections [28]. Also, it has been shown that the brain is "primed" for a recovery response in the few months immediate post-stroke, and that recovery significantly slows as time passes [28].

There are several methods for measuring recovery of a stroke survivor. The Barthel Index measures an individual's level of independence and ability to care for him or herself, the Functional Independence Measure is based on the ability of an individual to fulfill daily activities (13 motor items and 5 cognitive items), and the

Modified Rankin Handicap Scale is a 0 through 5 scale to rate a stroke survivor's level of disability [28]. The research presented in this paper is specific to upper extremity mobility and more specifically to improve range of motion, so it was determined that range of motion measurements were the most appropriate quantitative measure of each user's physical state before and after the study.

There are three types of range of motion exercises: active, active-assisted, and passive [16]. Passive ROM exercises involve a therapist moving the affected limb and are used if the patient does not have the ability to move the affected limb. Active-assisted ROM exercises are used when the patient can move their joints with some help, or experience some pain when they move themselves. A therapist assists the patient in moving their affected limb. Active ROM exercises do not involve a therapist's assistance and are for patients that can exercise their joint or muscle without any help [16]. In passive and active-assisted exercises, the therapist must be very cautious to be gentle enough to not cause pain in the patient but also to stretch the affected limb beyond its limits, which inevitably causes some discomfort [16].

## 1.4 Virtual Rehabilitation

Virtual reality (VR) therapy, or virtual rehabilitation, is a proposed method for optimizing the effects of rehabilitation. A defining characteristic of virtual reality is the ability of user interaction via multiple sensory pathways. In terms of virtual reality therapy, this involves a patient using his or her body movements to control an avatar or game object. Virtual reality therapy has been heavily researched as the relevant technology is becoming more ubiquitous and affordable [12]. Research has focused on both custom framework systems as well as research involving over the counter gaming platforms such as Nintendo Wii, Sony Move, and Microsoft Kinect. In comparison to conventional therapy, VR therapy has been found to have moderate positive benefits and potentially offer more motivation for patients as well as more targeted therapy tasks, potential social interaction, and is more accessible and convenient.

A study in 2013 with a control group (n=20) and experimental group (n=20) of stroke survivors with hemiplegia found significant improvement from baseline values in range of motion of the upper extremity after six weeks of virtual reality training using Kinect [27]. A meta analysis of virtual reality therapy research from 2014 found that virtual reality therapy "demonstrates a significant moderate advantage in body function and activity outcomes when compared to conventional therapy" and failed to find a significant difference between commercial gaming therapy platforms and virtual environment therapy platforms that include additional sensory feedback [12].

### 1.4.1 Microsoft Kinect as RGBd Camera

The Microsoft Kinect is a line of motion sensing input technologies for use with Windows PCs and Xbox 360. The first generation Kinect was released in November 2010 at a retail cost of $150 USD. Microsoft's Kinect was the first low cost consumer RGBd camera available on the market. RGBd refers to the four dimensions of data that a Kinect captures using both an RGB (traditional) camera as well as an infrared (IR) depth sensing camera. The Kinect uses technology developed by PrimeSense and can recognize humans as a collection of (20) skeletal joints, recognize gestures, and recognize faces.

The depth camera outputs x,y,z coordinates of each joint that the camera tracks. Depth sensing cameras allow for users to engage in a game session using their movements to control and also allows therapists to assess how well patients can move their extremities. The Kinect brought the advent of inexpensive RGBd cameras and since its inception RGBd cameras have become ubiquitous in society. Microsoft released a version of the Kinect for Windows in Spring 2011 which included a Software Developer Kit that provided capabilities for developers to build applications in C++, C#, or Visual Basic with access to Kinect sensor data, skeletal/joint tracking, audio processing and recognition, and sample code and documentation.

### 1.4.2 Current Virtual Rehabilitation Platforms

A number of private companies have been developing usable virtual rehabilitation platforms with the intention of achieving a market share in the field of physical rehabilitation via motion capture. Figure 1 shows a typical usage scenario of Jintronix [9], a virtual rehabilitation platform designed for physical and occupational therapy utilizing the Kinect, and claiming to contain "all the activities you would engage in to participate in your physical therapy.". SeeMe Rehabilitation [25] similarly uses a laptop and Kinect to assign rehabilitation activities to patients and track their progress over time. SeeMe promises to adapt to individual needs and goals and offers method for managing patients in a database and generating reports. Certain platforms allow for the administrator to disable to usage of the unaffected side to force the patient to use their affected side for gameplay.


Figure 1: Jintronix[9]: Commercial Virtual Rehabilitation Software

## 1.5 Constraint Induced Movement Therapy and Modified Constraint Induced Movement Therapy

Constraint induced movement therapy (CIMT) was first researched in 1918 by Robert Oden. In his research, he induced a hemiplegic stroke in a monkey and bound the unaffected side to constrain movement in the strong arm, forcing the monkey to use the weak arm. After two weeks, the monkey had regained use of the affected arm. Oden then repeated this experiment on another monkey without binding the unaffected side and found that after six months, this monkey still had not regained mobility in its weak arm [22]. Modern CIMT "involves massed and intensive practice with the more affected upper extremity and includes 2 components: use of the unaffected upper extremity is restrained during 90% of waking hours, and at the same time, the more affected upper extremity receives repeated and intensive training for more than six hours per day" [26]. CIMT has been widely used and studied compared to traditional rehabilitation techniques and "could improve functional performance and increase the usage of the more affected upper extremity" [26]. Although research shows benefits from CIMT, in a survey of stroke survivors, 68% of respondents said they were unlikely to comply with the therapy protocol due to either logistical aspects (length and duration of therapy) or aspects of the therapy itself (wearing a constraint for a long period) [23].

Modified constraint-induced therapy (mCIT) is a form of CIMT that requires less engagement and compliance from the patient. Researchers have designed a modified CIMT that has a shorter intensive training period as well as shortening of the period that the unaffected upper extremity is constrained [26]. For example, a patient may visit a therapist several times per week and in each thirty minute session the patient practices focused exercises using their weak arm. This therapy has been demonstrated to increase the mobility and use of the patient's arm only if they have some mobility remaining in their wrist and fingers. [29].

## 1.6 Reward Theory

Achievement is a main motivation for in-game behavior and functions as a type of reward [24]. A sense of achievement can grow from the accumulation of status, power, or points, the accomplishment of a game task, gaining knowledge, skills, or competence, or perseverance or competition. A game developer must weigh the difficulty of a game with the amount of achievement that a player typically obtains in order to create a productive balance between these elements. Other motivations include immersion and socializing, and one study found that males consider achievement the most important motivator while females consider immersion and socializing more important motivators[24].

Research has quantified the range of motivations that individuals feel toward undertaking a task as their need for achievement [14]. People with a high need for achievement seek to excel and prefer undertaking tasks with moderate likelihoods of success in order to avoid failure, while people with a low need for achievement are more likely to undertake higher risk tasks. Individuals with high need for achievement characteristics stem from many personal factors such as independence in childhood, praise for success, association of achievement with positive feelings, a desire to be challenged, and intrapersonal strength.

## 1.7 Research Outline

Numerous platforms have been developed that offer motion sensing based virtual rehabilitation to patients recovering from stroke. None of these platforms aim to intrinsically motivate users to exercise their affected side or to observe the patient's preferences in rehabilitation tasks as they relate to their physical condition. The following research explores the makeup of patient motivation and preference and attempts to quantify the factors that determine a successful virtual rehabilitation game task. This research had the following goals:

1. Study the behavior of virtual rehabilitation users with hemiparesis

    (a) Preference of gaming gestures as related to physical condition

(b) Preference of side (left or right) in each rehab game

2. Study the effect of incentives/rewards on constraint induced movement therapy in virtual rehabilitation. Can a constraint be induced cognitively via varying task difficulty?

3. Compare the compliance rate of virtual modified constraint induced movement therapy to conventional constraint therapy from previous research

4. Compare range of motion measurements from before and after the user test

In this paper, we introduce the underlying principles that form the basis for this study, explain the design and framework of the system and user study, and then outline results from the user study.

# 2 Methods

This research occurred in several stages:

1. Background research in stroke, hemiparesis, physical therapy, rehabilitation, virtual rehabilitation, exergaming (outlined in the Introduction).

2. Observations of stroke rehabilitation classes at Cabrillo College.

3. Design and development of Unity and Kinect based games for rehabilitation

4. Recruitment of stroke survivors with hemiparesis. Pre-testing of games.

5. Execution of the user study

6. Analysis of results and thesis write up

## 2.1 Game Platform and Interface

Inspiration for the movements that the games are based on stem from observations made during Cabrillo College Stroke and Disability Learning Center's Mobility and Adaptive Yoga classes taught by Leonard Norton in Fall of 2014. In these courses, students exercised opening their body posture, reaching in various directions, and performing mildly strenuous movements without the use of weights or therapist assistance. Students'abilities ranged from very low mobility to near normal mobility and each was encouraged to perform to his or her limits.

The Unity game engine was chosen as a platform for the development of the games due to the availability of Kinect-enabled control, availability of tutorials and documentation, and cost (free). Unity is a game development system that includes a rendering engine integrated with tools and workspaces that enable creation of 2D and 3D interactive content. The Unity Asset Store includes sample code, games, tutorials, and models that allow a streamlined development process. MonoDevelop is Unity's code development platform and manages projects in either C# or Javascript.

Unity projects are built by creating scenes. The basic building block of a Unity scene is the GameObject. Each GameObject contains its transform which consists of its position, rotation, and scale. Unity also allows additional properties such as shape, physics, scripting, and shading to be attached to a GameObject. Cameras, light sources, and standard shapes are pre-loaded into Unity for ease of use. GameObjects are arranged in a hierarchy such that each GameObject can have parents and children. Scripts that execute on a GameObject can modify attributes of that object or locate any other object to modify. By default, scripts execute two functions: Start() and Update(). Function Start() is executed at the start of the scene and contains initialization code. Function Update() is executed on each frame and contains most of the runtime code for the GameObject.

The ZigFu Development Kit (ZDK) is a plugin for Unity that interfaces with RGBd cameras such as the Kinect and allows for a GameObject's transform properties to be linked with a specific joint from the Kinect. For example, a block created as a GameObject could be configured to modify its position, rotation, and orientation according to a left elbow joint that is read as an input by the Kinect.

### 2.1.1 Kinect Parameters

The Microsoft Kinect v1 for Windows was used in the study (pictured in Figure 2). Although the Kinect v2 was available at the time, the features of the Kinect v1 were satisfactory for the purposes of the study. The Kinect v2 offers increased RGBd camera resolution as well as additional joint tracking but requires Windows 8.


Figure 2: Microsoft Kinect v1 for PC[15]

For the purposes of the study in which the user was seated, it was only important to track the movement of the user's upper extremities and upper torso. Because of this, we were able to configure the Kinect for “seated mode” that only tracks the user's arms, neck, and head instead of its “default mode” which tracks the entire skeleton of a user. The default mode tracks twenty skeletal joints and the seated mode tracks the ten upper body joints (shoulders, elbows, wrists, arms, neck and head). Default mode is not optimal for tracking users in a seated position and seated mode provides the best way to detect a skeleton in “near mode”[19]. Figure 3 shows the skeleton tracking in default and seated modes.

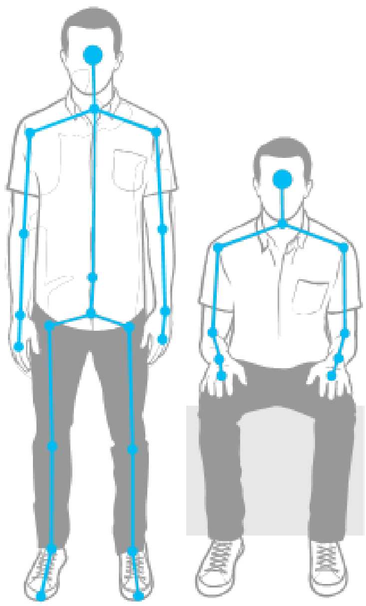

Figure 3: Joint tracking in Kinect's default mode and seated mode[19]

Figure 4 outlines the 20 trackable joints by the Kinect as well as the coordinate system used.

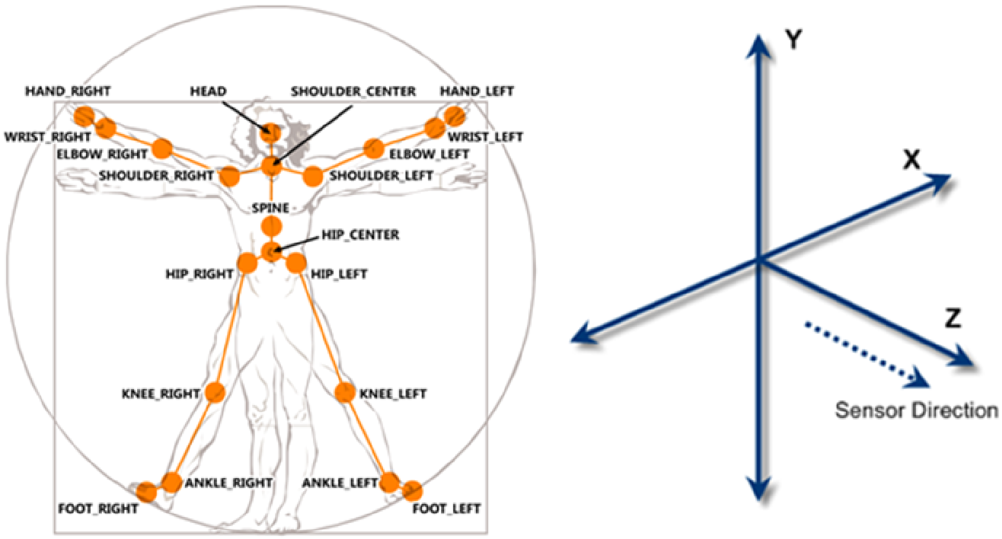


Figure 4: Kinect skeletal joints with labels[17]

Near mode allows tracking of users as close to the sensor as 0.4 meters (1.3 feet) and up to a maximum of 3.0 meters (9.8 feet) instead of the default range of 0.8 meters (2.6 feet) to 4.0 meters (13.1 feet) [18]. Since the study was being completed at users'homes where available space may have been an issue, the games were designed to operate optimally when the user was seated at a range of 5 feet from the Kinect. This also allowed for the user to view the display with greater ease. Figure 5 shows the sensing limits of the Kinect.

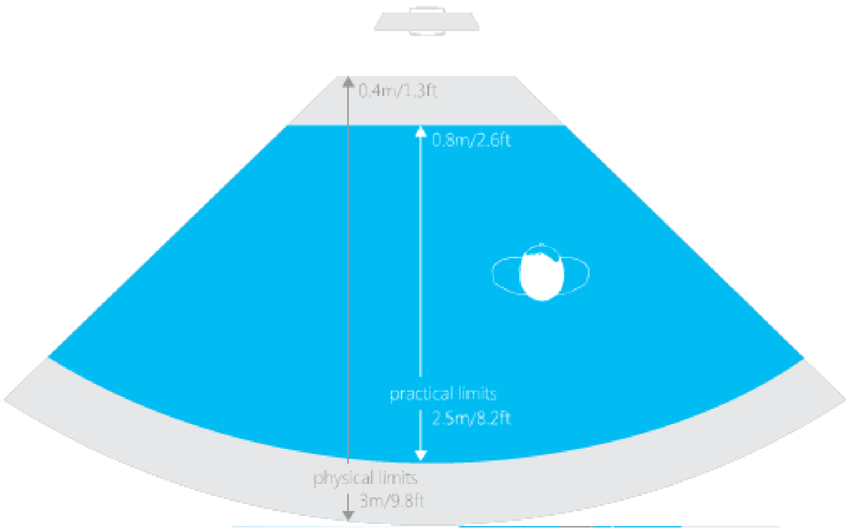


Figure 5: Working range of Kinect[18]

## 2.2 Game Design and Development

For the purpose of the study, the following criteria was used. Games must:

1. Exercise specific upper extremity range of motion
2. Allow the user to use either their left or right side for control
3. Modify the difficulty of each game depending on usage of the unaffected side of the user
4. Maintain similarity to each of the other games while still being distinguishable and recognizable
5. Record usage statistics to a database

The games were designed to involve a variety of motion in the upper extremities, but each game targets a specific movement. The games were designed to each be similar in makeup, color, layout, and style in order to minimize the characteristics by which users could show preference for. The games needed to be distinguishable and recognizable to the users, so some game elements were changed visually from game to game while maintaining a common sense of style and interface. The camera perspective remained consistent throughout each game.

The building block for the first game design was created using a Unity Asset Store tutorial project that included four sample Unity games published by M2H and named “C# Tutorials”. The egg drop game developed for the study was a highly modified version of one of these sample games. The colors palette of the games were chosen from a high contrast color blind safe palette.

The music of the games was a randomized playlist of five songs. Songs were chosen based on observations of classes at Cabrillo College Stroke and Disability Learning Center. During these classes the instructor played gentle marimba band music, so in an effort to maintain a relaxing and enjoyable atmosphere that could cross cultural barriers, similar sounding music was chosen. Sounds from the games were supplied from open license sound clips from freesound.org. Some sounds, such as the egg frying sound was taken from a longer recording of an egg being prepared and cooked. The music playlist contained the following tracks:

- “Level 1” by Adam J. Sporka.
- “Level 2” by Adam J. Sporka.
- “Poppyseed” by Podington Bear. freemusicarchive.org
- “Gentle Marimbas” by Podington Bear. freemusicarchive.org
- “Monkey Island Band” by Eric Matyas. soundimage.org

The platform main screen was the game select screen shown in Figure 6. The user moved either hand to control the cursor and hover over a game to select it.

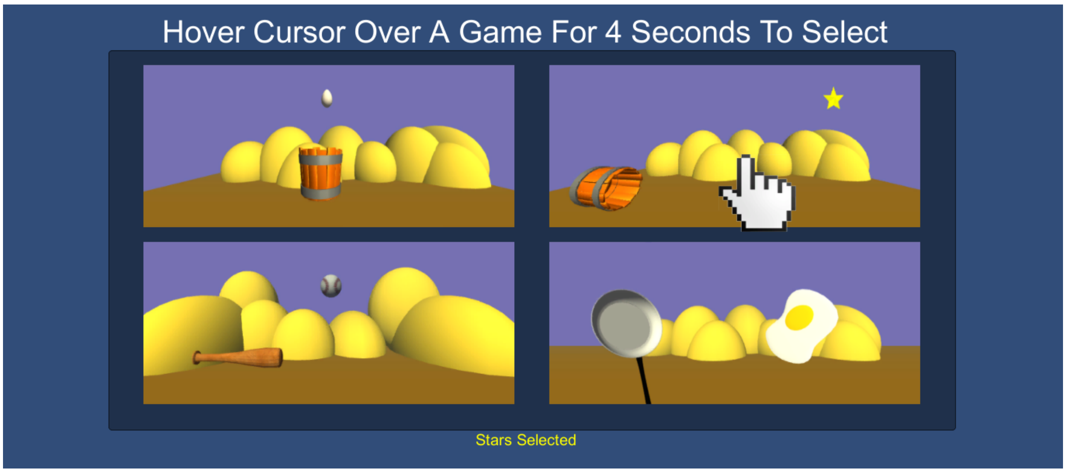


Figure 6: Game Selection Screen

Descriptions of each game are as follows:

#### 2.2.1 Game 1 - "Egg Drop"

User perspective is of a virtual landscape. A bucket is located near the bottom of the screen. Eggs spawn from a random x position on the top of the screen and move toward the bottom of the screen. The user controls movement of the bucket in the x-axis only using motion of his or her left or right hand. The user attempts to use the side to side movement of his or her hand to control the bucket to catch the eggs as they fall from the sky. The gameplay movement is described as follows:

Participant begins seated, with the shoulder flexed to 90 degrees, the forearm should be pronated (so palm is facing floor) and the elbow extended to 180 degrees. While maintaining this position, the participant should actively horizontally adduct/flex and horizontally abduct/extend the shoulder in order to complete the game. An effort should be made to maintain an upright posture, 180 degrees elbow extension, forearm pronation and 90 degrees shoulder flexion during horizontal abduction and adduction through the transverse plane. Common mistakes due to past medical history can include but are not limited to: trunk rotation during horizontal abduction and adduction, shoulder and scapula elevation to compensate for a lack of flexion in the glenohumeral joint.

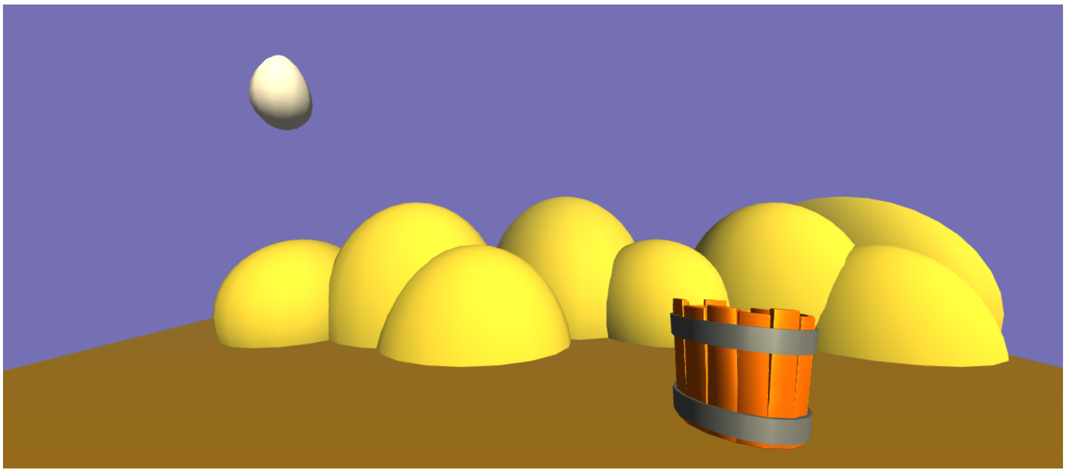

Figure 7: Game 1 - “Egg Drop”

#### 2.2.2 Game 2 - “Stars”

User perspective is of a virtual landscape. A bucket is located near the left side of the screen. Yellow stars spawn at a random y position from the right side of the screen and move toward the left side of the screen. The user controls movement of the bucket in the y-axis only using motion of his or her left or right hand. The user attempts to use the up and down movement of his or her hand to control the bucket to catch the eggs as they fall from the sky. In practice, this movement is similar to reaching up past eye level and is difficult for users with limited mobility. The gameplay movement is described as follows:

Participant begins seated with the shoulder flexed to 90 degrees, the forearm pronated (so palm is facing floor) and the elbow extended to 180 degrees. The participant should actively flex the shoulder between a range of 10 to 160 degrees in order to complete the task. During the game, a best effort should be made to keep an upright posture with the forearm pronated, the elbow at 180 degrees of extension, and the arm moving through the sagittal plane. Common mistakes due to past medical history can include but are not limited to: allowing the arm to move out of the sagittal plane, an inability to flex the glenohumeral joint to 160 degrees, and performing compensatory movements such as scapula elevation, trunk flexion, and trunk extension to make up for a lack of glenohumeral flexion.

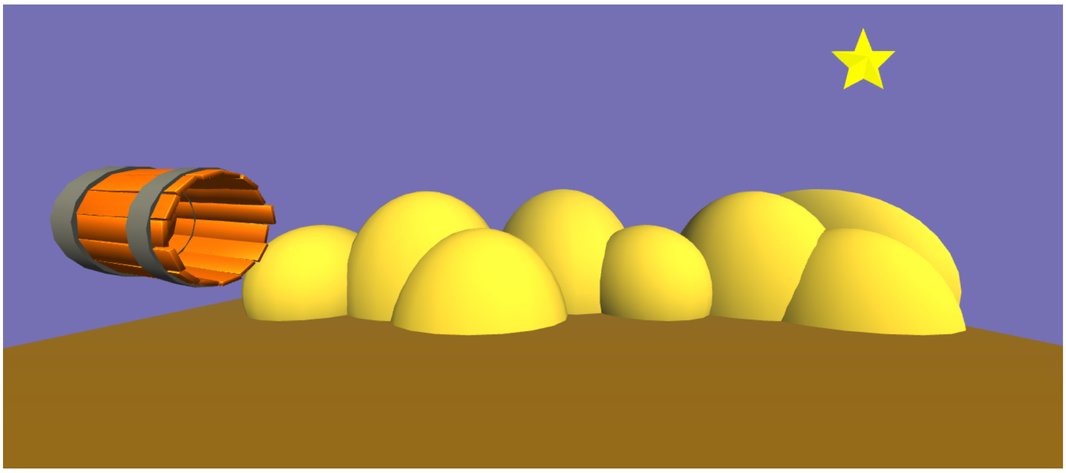

Figure 8: Game 2 - “Stars”

### 2.2.3 Game 3 - “Bat”

User perspective is of a virtual landscape. A baseball bat appears near the center of the screen as the user raises his or her elbow in front of themselves. Baseballs spawn from deep inside the viewer's perspective at a random x position and move toward the user's perspective, similar to a catcher's perspective in a baseball pitch. The user controls movement of the bat in the x and y-axis using motion of his or her left or right elbow. The user also controls the orientation of the bat with the orientation of their forearm. The user uses any motion they can to position the bat to hit the balls as they are pitched toward the screen. The gameplay movement is described as follows:

Participant begins seated with the shoulder flexed and externally rotated to 90 degrees, the elbow flexed to 90 degrees, and the forearm pronated so the palm is facing the midline of the body. The participant should be told that his forearm and elbow will represent a baseball bat, and he/she must attempt to “bunt” an oncoming baseball. The participant should actively horizontally adduct/flex, horizontally abduct/extend, and internally and externally rotate the shoulder through the transverse plane in order to complete the task. The participant should be instructed to not extend the elbow in an attempt to “hit” the ball, as this is a common mistake. Other common mistakes due to past medical history include but are not limited to: trunk rotation when trying to “bunt” the ball, and an inability to internally and externally rotate the glenohumeral joint.

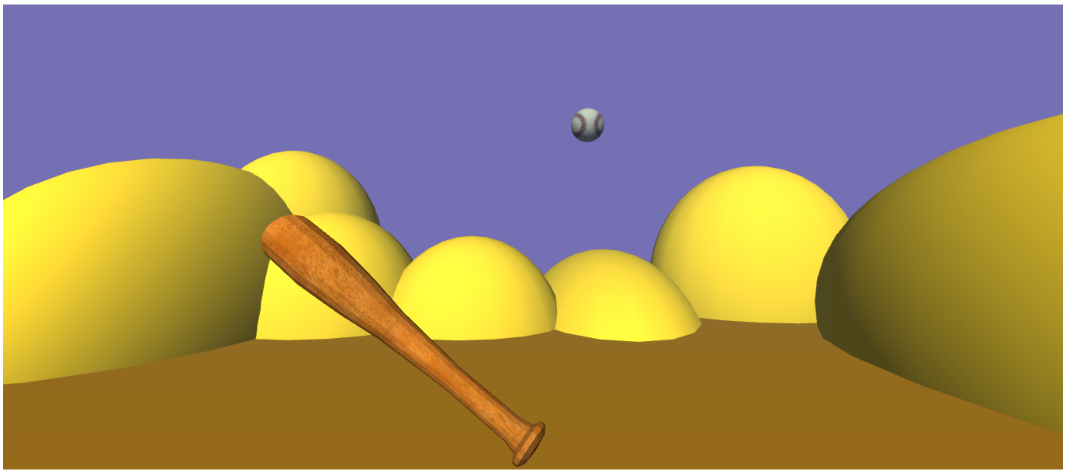

Figure 9: Game 3 - “Bat”

### 2.2.4 Game 4 - “Fried Egg”

User perspective is of a virtual landscape. A frying pan is located near the bottom of the screen. Sunny side up eggs spawn from a random x position on the top side of the screen and move down toward the bottom side of the screen. The user controls movement of the frying pan in the x-axis only using motion of his or her left or right elbow. The user also controls the orientation of the frying pan using the orientation of their forearm. The user must orient their forearm perpendicular to the ceiling in order to orient the pan correctly. The user attempts to use the side to side movement of his or her elbow and forearm to move the frying pan to catch the fried eggs as they fall from the sky. The gameplay movement is described as follows:

Participant begins seated with the shoulder flexed to 90 degrees and the elbow flexed to 90 degrees. The forearm should be pronated so the palm is facing the floor. The participant should be told that their forearm and elbow will represent a frying pan. They are to use the frying pan to catch eggs that fall from above. This will be done by horizontally abducting/extending and horizontally adducting/flexing the shoulder through the transverse plane. The participant should make an effort to avoid actively internally or externally rotating the shoulder, as this will cause the frying pan to tilt. Common mistakes include, but are not limited to: excessive internal and external rotation at the glenohumeral joint, scapula elevation, excessive elbow flexion or elbow extension, and flexing or extending the glenohumeral joint resulting in movement through the sagittal plane.

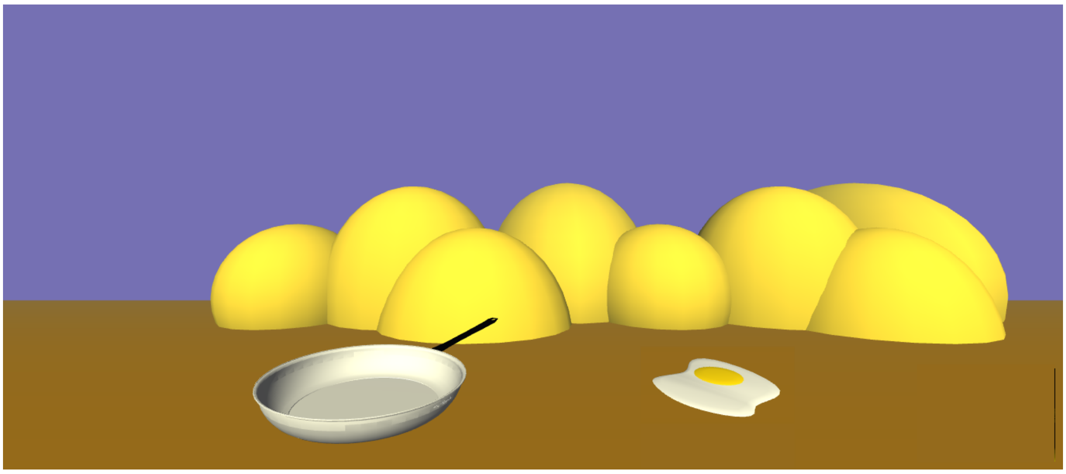

Figure 10: Game 4 - “Fried Egg”

### 2.2.5 Game Design

The most important novel feature of this platform is the dynamic ability to use either side of one's body to control the game object. This feature is based on a simple algorithm that checks which of the user's wrists is located higher in the y-axis. After experimenting with velocity and acceleration algorithms it was found that a simple moving average position algorithm was sufficient to determine the user's active side of use under most conditions.

---

```
// Compare left and right hands position for active hand
          float[] avgPosArrLH = TrackAvgPosition(LHjoint);
          float[] avgPosArrRH = TrackAvgPosition(RHjoint);
          if (avgPosArrRH[1] > avgPosArrLH[1] && rightHandActive==false) {
             Debug.Log ("Right Side Active!");
             rightHandActive = true;
          }
          else if (avgPosArrLH[1] > avgPosArrRH[1] &&
              rightHandActive==true){
             Debug.Log ("Left Side Active!");
```

```
        rightHandActive = false;
    }
```

The games were designed such that when the user used their unaffected side, the game speed would increase the speed of the game by a preset factor via Unity's Time.timeScale static variable. Appropriate game speeds for each difficulty level were calibrated through repeated testing with various participants. Game speeds were chosen to avoid floor or ceiling scoring and essentially set the movement rate of the game objects to modify the game difficulty. Difficulty settings are shown in Table 1.

| | **Difficulty 1** | **Difficulty 2** | **Difficulty 3** | **Difficulty 4** |
|---|---|---|---|---|
| **Egg Drop** | 100% | 135% | 155% | 170% |
| **Stars** | 100% | 140% | 163% | 179% |
| **Bat** | 100% | 139% | 178% | 217% |
| **Fried Egg** | 100% | 134% | 153% | 167% |

Table 1: Relative game speeds at each difficulty level. Note that the game speed only changed when the user used their unaffected side to play. Game speed always remained at 100% while the user used their affected side.

The success of the virtual constraint depends on the ability to modify the user's achievement throughout the therapy sessions. Each 4 minute game consisted of 4, 1 minute rounds with varying incentive structures. Each game always began with a baseline incentive and then was followed by a random sequence of the following incentive structures.

- A (baseline): Game speed remains at baseline speed with usage of both affected and unaffected side
- B: Game speed increases by factor of k with usage of unaffected side. Game speed remains at baseline for affected side.
- C: Game speed increases by factor of 2k with usage of unaffected side. Game speed remains at baseline for affected side.
- D: Game speed increases by factor of 3k with usage of unaffected side. Game speed remains at baseline for affected side.

E.g. a 4 minute game session may be ordered as ACBD, ABCD, ADCB, but not DACB. The baseline (A) round always begins each game. Actual difficulty settings are shown in Table 1.

#### 2.2.6 Integration of Data Capture

For the purposes of the user study, it was important to be able to record as much quantitative data as possible from the user sessions. In order to efficiently and conveniently store this data in a database during execution, we needed to make SQL queries during gameplay to save key game parameters and joint data. The SQLite database engine is a pre-made dynamic link library that is available for download for free at https://sqlite.org/ and can be used with MonoDevelop's Mono.Data.Sqlite library to execute queries. This class includes functions for executing specific database queries using SQLite. The game data was output to the database at the start of each game as well as at the completion of each round in the game as follows:

- time of entry
- round number (0 through 4)
- difficulty level for the current round (1 through 4)
- total number of spawned objects during the round
- total time user spent using their left side during the round
- total number of spawned objects successfully caught by the user's left side
- total time user spent using their right side during the round
- total number of spawned objects successfully caught by the user's right side
- selection of affected side of the user (left or right)
- calibration parameters
  - x scale
  - y scale

– time scale

The system additionally recorded the x,y,z position of each of the ten joints that are tracked in Kinect's seated mode. This creates thirty one columns of data (10 joints * 3 dimensions + timestamp) at a rate of approximately eight per second. The game data did not record to the database in real-time due to performance constraints. The game data recorded by the database at the end of each round. Each session's database table was created as follows:

```
CREATE TABLE IF NOT EXISTS _02_09_15__01_48_23__0 (t DATETIME NOT NULL
    PRIMARY KEY, x1 FLOAT, y1 FLOAT, z1 FLOAT, x2 FLOAT, y2 FLOAT, z2
    FLOAT, x6 FLOAT, y6 FLOAT, z6 FLOAT, x7 FLOAT, y7 FLOAT, z7 FLOAT, x8
    FLOAT, y8 FLOAT, z8 FLOAT, x9 FLOAT, y9 FLOAT, z9 FLOAT, x12 FLOAT, y12
    FLOAT, z12 FLOAT, x13 FLOAT, y13 FLOAT, z13 FLOAT, x14 FLOAT, y14
    FLOAT, z14 FLOAT, x15 FLOAT, y15 FLOAT, z15 FLOAT, gameNum INTEGER,
    roundNum INTEGER, difficulty INTEGER, totalEggs INTEGER, lhTime FLOAT,
    lhCaughtEggs INTEGER, rhTime FLOAT, rhCaughtEggs INTEGER, rhDominant
    INTEGER, xScale FLOAT, yScale FLOAT, timeScale FLOAT);
```

A sample insert joint position entry is shown below. These entries were recorded approximately eight times per second and due to performance constraints, were held in RAM until the round ended and then were written to the database.

```
INSERT INTO _02_16_15__16_54_16__0 (t, x1, y1, z1, x2, y2, z2, x6, y6, z6,
    x7, y7, z7, x8, y8, z8, x9, y9, z9, x12, y12, z12, x13, y13, z13, x14,
    y14, z14, x15, y15, z15) VALUES (2015-02-16 16:54:26.584 , -200.5065,
    396.8086, -1584.628, -202.886, 160.8206, -1582.01, -364.1349, 98.8988,
    -1600.237, -397.7212, -134.3499, -1553.141, -393.8735, -303.0269,
    -1495.399, -359.7707, -342.2535, -1471.251, -51.79168, 103.6802,
    -1592.607, -108.6455, -16.52955, -1432.64, -240.4574, -52.16437,
    -1305.286, -374.2962, -62.68992, -1214.579);
```

A sample insert score entry is shown below.

```
INSERT INTO _02_09_15__01_44_26__0 (t, gameNum, roundNum, difficulty,
    totalEggs, lhTime, lhCaughtEggs, rhTime, rhCaughtEggs, rhDominant,
```

```
xScale, yScale, timeScale) VALUES (2015-02-09 01:44:31.338 , 1, 0, 1,
0, 0, 0, 0, 0, 1, 0.016, 0, 0.63);
```

## 2.3 Range of Motion Measurements

Four range of motion measurements were used to evaluate the users physical mobility at the start and end of the study. These particular measurements use many of the same joint movements as the developed games. Extracting these measurements from Kinect data has been validated by previous research [10] [11].

### 2.3.1 Administering Range of Motion Measurements

1. Shoulder Flexion: with arm (in neutral) at your side, move or elevate your humerus/upper arm so it is in front of the body.

2. Shoulder Abduction: with arm (in neutral) at your side, elevate your arm to the side, up and away from your body.

3. Shoulder Horizontal Extension: this is also known as horizontal abduction; opposite of horizontal flexion/adduction; movement of the humerus or upper arm in a horizontal or transverse plane away from the body/chest/torso. For there to be horizontal flexion or extension, the shoulder must first be in some degree of flexion and/or abduction.

4. External Rotation: movement of the humerus medially around its long axis towards your midline; while keeping your arm at your side, rotate your arm so your your upper arm/bicep is pointing towards your body.

Users were often allowed modified range of motion positions for the measurements. This remained constant throughout the course of the measurements. A custom Unity scene was created to record the range of motion measurements from each user. A sample screen is shown in Figure 11.

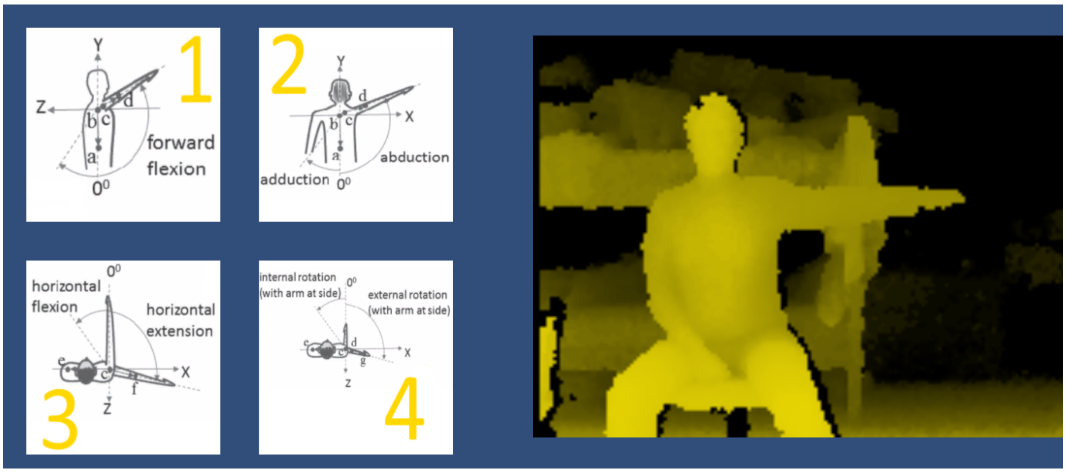


Figure 11: Range of Motion Measurement Scene Screen

### 2.3.2 Analysis of Range of Motion Measurements

MATLAB was used to parse and extract the range of motion measurements from the raw joint position data that was recorded at eight entries per second. Animated plots of the user skeleton in seated mode were used to validate the ROM angle extraction for a valid timestamp. Each of the four ROM angles of interest were extracted from the data by transposing the data onto a 2-d plane. The data was generally timestamped with the ROM number as an entry in the database but it was still necessary to manually adjust the frame window for analysis. After the data was properly segmented, relevant joint angles could be extracted.

A sample 3D plot of the skeleton in seated mode is shown in Figure 12 and sample plots for visualization of the range of motion measurements are shown in Figures 13, 14, 15, and 16. These skeleton animations were used to confirm that the ROM angle extraction was being taken from the correct point in time in the data since some instances did not have correct timestamps. These plots are all 3D projections of the joints mapped by the Kinect.

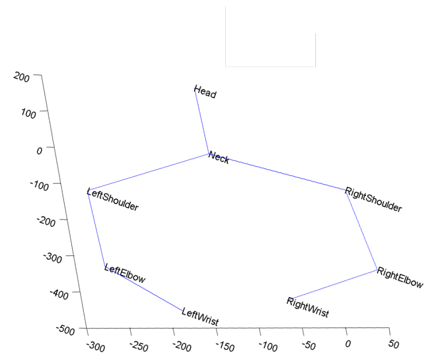


Figure 12: 3D projection of the user's seated mode skeleton was helpful in validating the timestamps of the ROM measurements

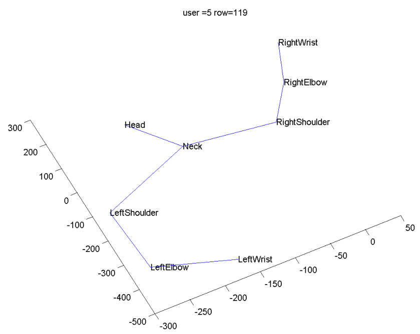


Figure 13: Sample 3D projected plot of user skeleton from joint data during ROM measurement # 1. The user's left arm is raised, right arm is at side

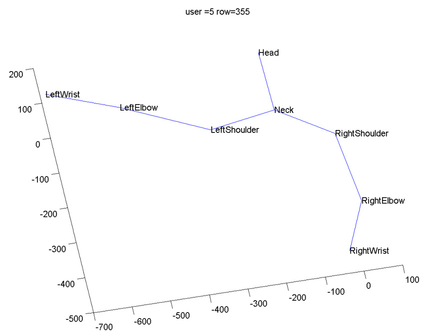


Figure 14: Sample 3D projected plot of user skeleton from joint data during ROM measurement # 2. The user's right arm is raised, left arm is at side.

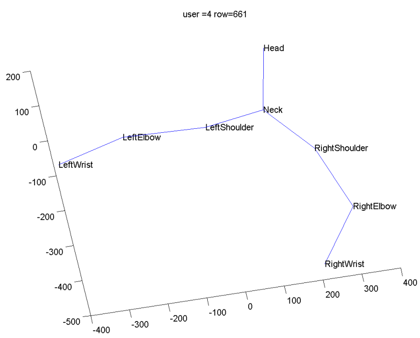


Figure 15: Sample 3D projected plot of user skeleton from joint data during ROM measurement # 3. The user's right arm is raised, left arm is at side.

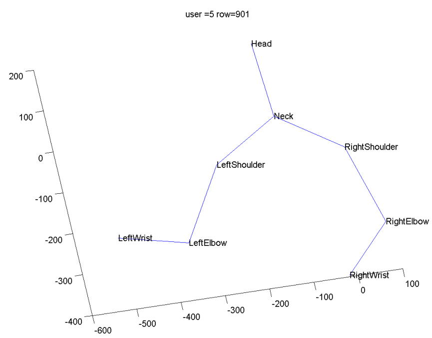


Figure 16: Sample 3D projected plot of user skeleton from joint data during ROM measurement # 4. The user's right forearm is extended, left arm is at side.

Each ROM measurement involves a relevant 2-dimensional plane of motion so any joint movement outside of this plane was not considered in the measurements. This potentially could lead to unreliable measurements due to the variation of modified position between ROM readings. Each of the users had slightly different modified positions for certain measurements but an effort was made to keep measurements consistent for each user.

The shoulder flexion (ROM measurement #1) and relevant axes are pictured below in Figure 17.

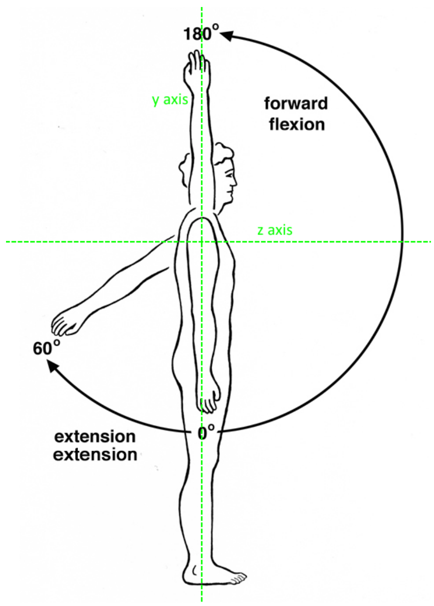


Figure 17: Shoulder flexion range of motion measurement[8] with relevant axes labeled

A sample visualization of the data with the extracted angle from ROM measurement #1 is shown in Figures 18 and 19.

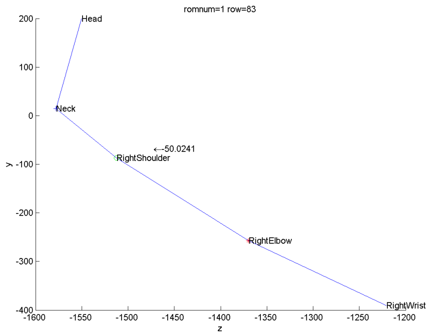


Figure 18: Visualization of forward flexion from joint data before arm is elevated. Note the height of the elbow and wrist joints relative to the shoulder. The user's arm is lowered.

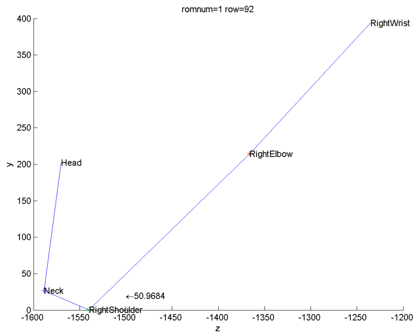


Figure 19: Visualization of forward flexion from joint data after arm is elevated. Note the height of the elbow and wrist joints relative to the shoulder. The user's arm is raised

The shoulder abduction (ROM measurement #2) and relevant axes are pictured below in 20.

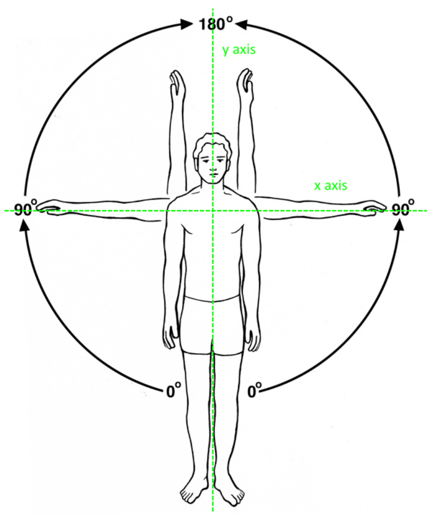


Figure 20: Shoulder abduction range of motion measurement[8] with relevant axes labeled

A sample visualization of the data with the extracted angle from ROM measurement #2 is shown in Figures 21 and 22. Note the height of the elbow and wrist joints relative to the shoulder.

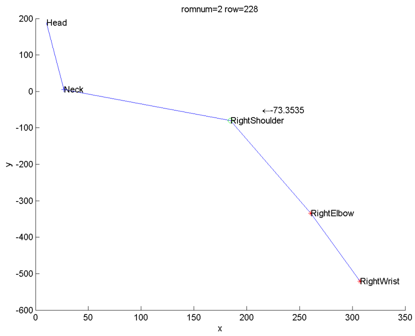


Figure 21: Visualization of shoulder abduction from joint data before arm is elevated. Note the relative height of the elbow and wrist joints are lower than the shoulder.

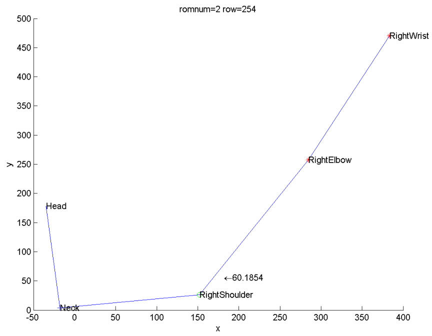


Figure 22: Visualization of shoulder abduction from joint data after arm is elevated. Note the relative height of the elbow and wrist joints are higher than the shoulder.

The horizontal abduction (ROM measurement #3) and relevant axes are pictured below in Figure 23.

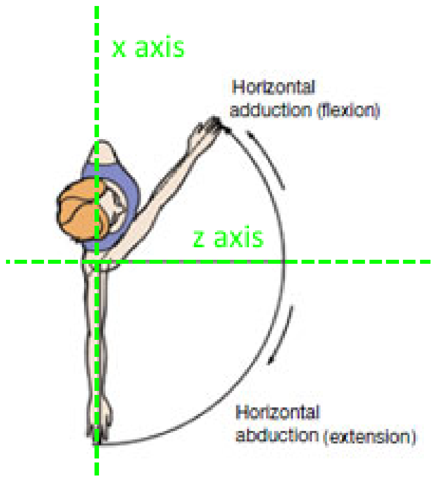


Figure 23: Horizontal abduction range of motion measurement[5] with relevant axes labeled

A sample visualization of the data with the extracted angle from ROM measurement #3 is shown in Figures 24 and 25.

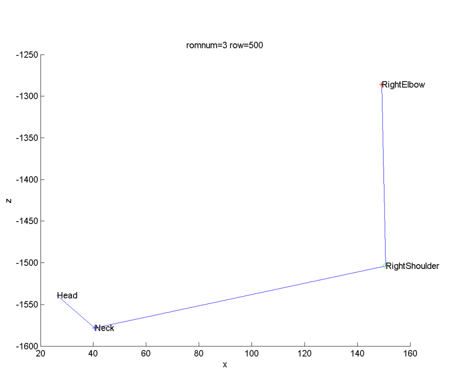


Figure 24: Visualization of horizontal abduction from joint data pre-abduction. The user's arm is at their side (overhead view).

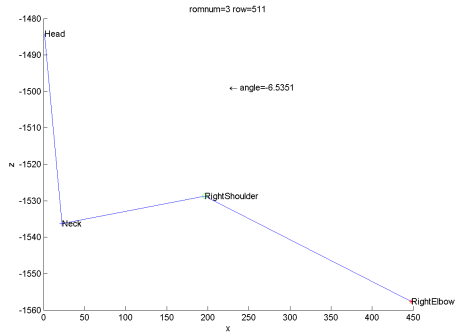


Figure 25: Visualization of horizontal abduction from joint data at abduction. The user's arm is extended to the side and reaching just beyond their shoulder's plane (overhead view).

The external rotation (ROM measurement #4) and relevant axes are pictured below in Figure 17.

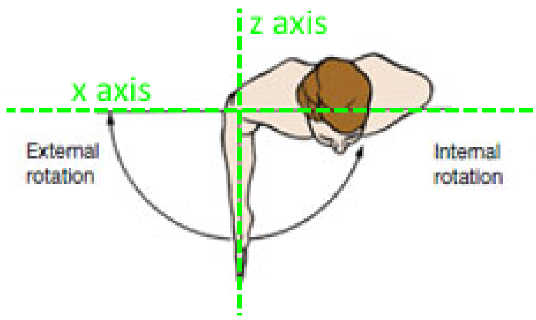


Figure 26: External rotation range of motion measurement[5] with relevant axes labeled

A sample visualization of the data with the extracted angle from ROM measurement #4 is shown in Figures 27 and 28.

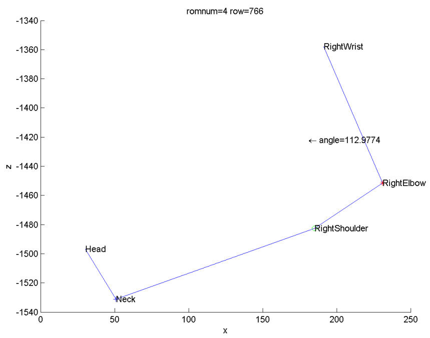


Figure 27: Visualization of external rotation from joint data pre-rotation. The user's arm is at their side (overhead view).

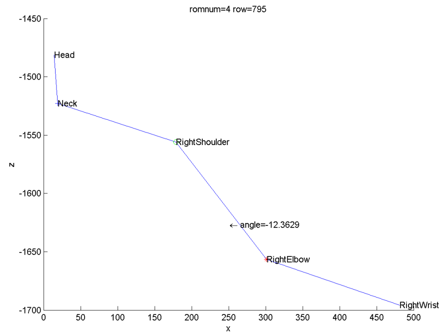


Figure 28: Visualization of external rotation from joint data at rotation. The user's forearm is extended behind their shoulder. Note the relative positions of the wrist, elbow, and shoulder (overhead view).

## 2.4 User Study

### 2.4.1 User Selection

Users were recruited from Cabrillo College Stroke and Disability Learning Center. All users were at least 6 months post stroke, in the phase of functional recovery. Users were not taking classes at Cabrillo College Stroke and Disability Learning Center during the study but some users were participating in other therapies concurrently throughout the study. At least two users had no other therapy sessions during the study.

The study included 5 participants with each being a stroke survivor with hemiplegia between the ages of 50 and 82 (with a mean of 65.8) and a time post-stroke ranging from 7 months to 4 years (with a mean time of 23.6 months). Participants included two males and three females.

### 2.4.2 Platform Setup

A Windows 7 laptop with a 15.6 inch display was used as the system to administer the sessions. The laptop was placed on a table and the user sat in a chair several feet away. Each of the users was evaluated to have sufficient eyesight to adequately play the games on the display. The Kinect is placed on a tripod directly behind the laptop, five feet from the user. A camcorder was arranged somewhere behind or aside the laptop and Kinect and pointed at the user.

Inside the user's home it was important to take notice of the surroundings and conditions in the room. It was necessary to always watch out for issues with Kinect field of view, RGB camera, or IR camera such as:

- Positioning of the user in the Kinect field of view (user's range of movement)
- Baggy clothing
- Clothing that blends with the background
- Dark/Black clothing
- Hats and sunglasses
- Sunlight or open windows
- Reflections or Mirrors
- Candles or other light glare

The participant was in a seated position for all 4 games. A best effort was made to sit upright, with good posture, and perform all motions as described and demonstrated. Due to past medical history, deviations in and difficulty with following prescribed instructions were present.

### 2.4.3 Game Calibration

Several parameters were coded into the games to allow for on the fly game calibration per user in order to accommodate varying ranges of mobility. It was also necessary to configure the proper affected side for each user so the games functioned correctly for each user. The following parameters were implemented:

- Time scale multiplier: adjusts the speed of the game (spawning and object movement)
- Movement sensitivity: multiplies the scale of the motion of the user's body with the controlled game piece

- Movement sensitivity dominant: move sensitivity multiplier for dominant side only. Multiplies after move sensitivity (compounds it)
- Affected side: left or right

After experimenting with the users it was found that a baseline time scale of 63% was appropriate for all users. Additionally, a user requested to adjust the y-axis position of the controlled gameobject to accommodate her limited range of motion. Specifically, the bat's y-position was lowered for her handicap.

### 2.4.4 User Study Sessions

The user test began with User #1 on January 8th, 2015, and concluded the final user session on January 23rd, 2015. Each user completed five sessions, at a rate of one to three per week over the course of two to 2.5 weeks. Each session consisted of an introductory/training period followed by a 20 minute gameplay period that was later analyzed for qualitative and quantitative data.

Sessions were scheduled with each participant and a researcher visited the user's home to administer each session. The researcher brought a checklist of materials including: laptop with latest Unity code and Kinect drivers, camcorder, tripod for camcorder, Kinect, tripod for Kinect, extension cord, surge protector, 3-prong adapter, backup equipment and battery chargers.

Before beginning the first session, the researcher administered several active range of motion measurements and calibrated the system to the user if necessary. Each session began with a 5-10 minute tutorial of gameplay control for each game and explanation of game selection system functionality. The researcher explained and demonstrated the motions and positions used in each of the four game. After the training period, the sessions began with the user starting on the game selection screen. The camcorder was set to record and the 20 minute virtual rehab session began with the user choosing a game. At each session, the user was informed of the following:

1. The researcher will not be observing the session and to act freely in choosing which games to play.

2. Research has shown that using your unaffected side during therapy is more beneficial for effective rehabilitation.

3. The user has a free choice of any five games to play in any order.

4. What to do if there is an issue (call for help)

After completing the five sessions, another set of range of motion measurements were administered to compare with the initial results. At the completion of the five sessions, a survey was administered to ask users how they felt about the games and the study and why they did what they did. Figure 29 shows a typical setup for a user study session. The user sat five feet away from the Kinect camera and the camera is positioned to fit the user in the center of the field of view. Another setup is shown in Figure 30.

Figure 29: Typical improvised PC, camcorder, and Kinect setup at a user's home

Figure 30: View of a user session in progress

### 2.5 Qualitative Analysis

The qualitative analysis was completed by a team of three independent researchers. The team worked individually to analyze the recorded video sessions for any behaviors relevant. Each member of the team emailed the lead researcher a list of behaviors that he/she observed and the researcher compiled these behaviors into themes. A list of themes was emailed back to the qualitative analysis team and they proceeded to code the videos of the user sessions with the themes, recording time and frequency of each theme. The chosen themes are listed below.

- Distracted from game (talking, looking away, etc.)
- Incorrect posture (back rotation, leaning) or unaffected limb assist (using strong side to lift weak side)
- Displaying effort to fix posture, correct position, or improve muscle control
- Displaying struggle (heavy breathing, strained face, discomfort, etc.)
- Pausing or taking a break during a game

- Switching arms for a short period (less than  5 seconds)
- Visibly frustrated or confused
- Visibly bored
- Displaying happiness

# 3 Results

Two users (shown as user 1 and 2) were unable to use their affected side at all due to their affected limb being completely limp and lacking any mobility. These participants were thought to have partial use of their affected limb and that they could use their unaffected limb to assist their affected limb to enable some amount of compliance. When the study began it became evident that they lacked the required mobility to play the games with their affected side.

User 3 was often observed using their unaffected limb to lift and guide their affected limb while playing the games. The Kinect and algorithm for detecting the user's active side was not designed to accurately distinguish and understand gestures from users using both arms simultaneously. Due to the lack of certain reliable data recorded during these periods, some calculations use only data from users 4 and 5. A small amount of data from sessions was lost due to technical issues including overheating of laptop, crash of Unity, and game scoring bug. Data from 5 of the 125 games played (4%) was lost due to technical circumstances.

## 3.1 Compliance / Usage of Unaffected Side

Compliance varied among the three users that were able to use their affected limb. The percentage of time that was user was actively using his or her affected side compared to the total session time was calculated and is shown in Figure 31

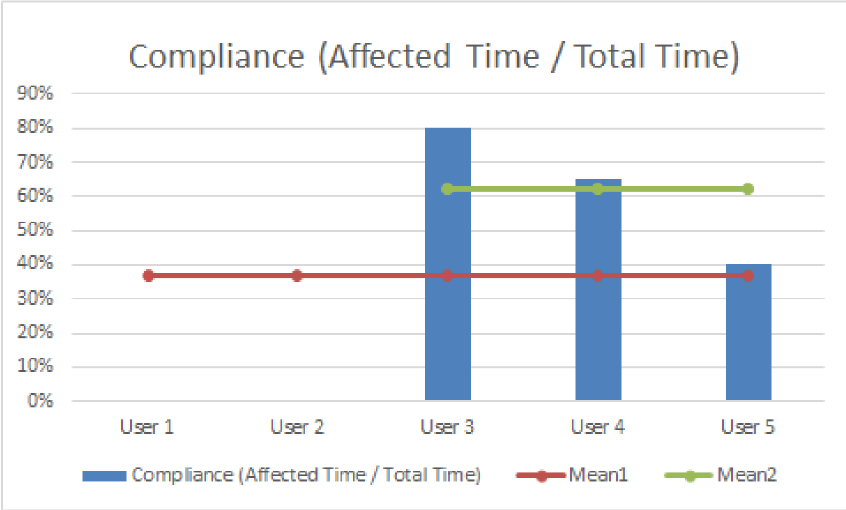


Figure 31: Each user's time usage of their affected side compared to the total time. Mean1 shows the mean compliance of all five users. Mean2 shows the mean compliance of users 3-5.

Users 4 & 5 were the only users to fully utilize both affected and unaffected limbs during gameplay. Figure 32 shows a plot of their compliance (usage rate of affected side) during each of the four games.

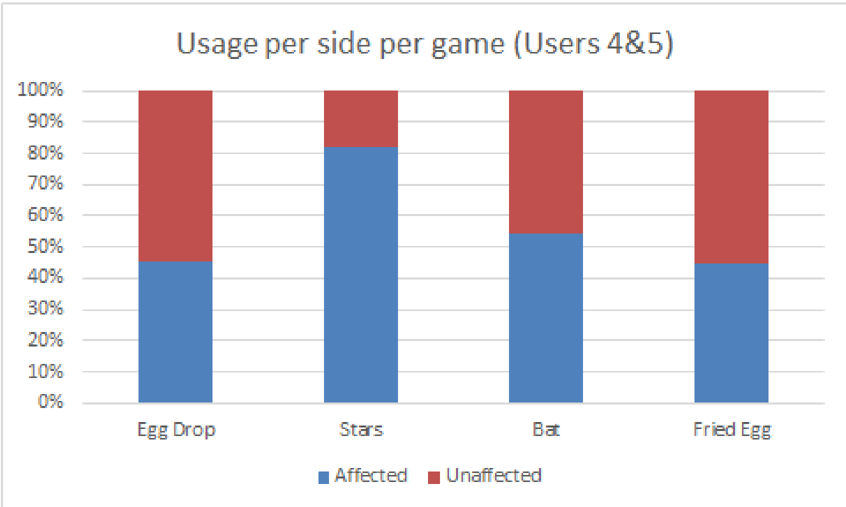


Figure 32: Usage rate of affected side during each of the games

The difficulty level was only modified when the user was using their unaffected limb and then returned to Difficulty 1 (baseline) whenever the user used their affected limb. Their compliance (usage rate of affected limb) at each difficulty level for the unaffected limb is shown in Figure 33 with standard error bars. Due to the high variance in the data, confidence intervals are quite large.

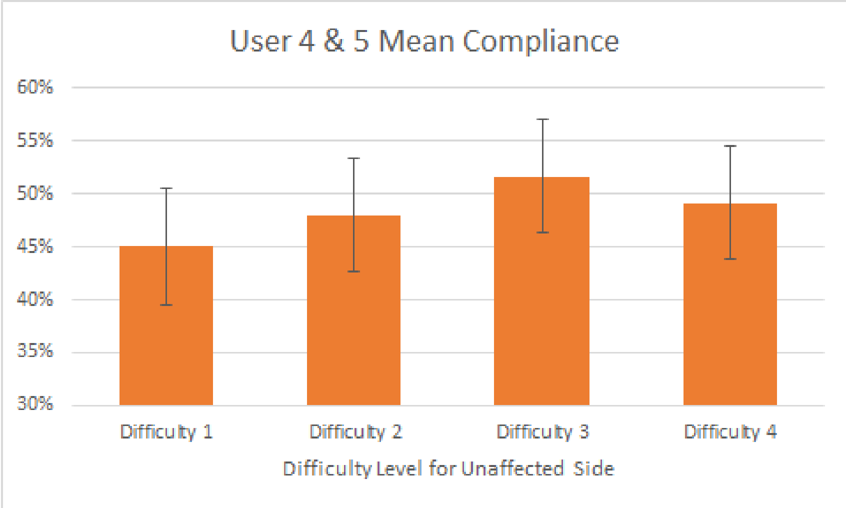


Figure 33: Mean compliance (usage of affected limb) of users 4 & 5 at varying levels of difficulty for their unaffected limb. Difficulty remained at baseline while the affected limb was used but was modified while the user was utilizing their unaffected limb. Standard error bars are shown.

### 3.2 Game Choices

Choices of games varied throughout the user sessions. The frequency of which each game was chosen is shown in Figure 34.

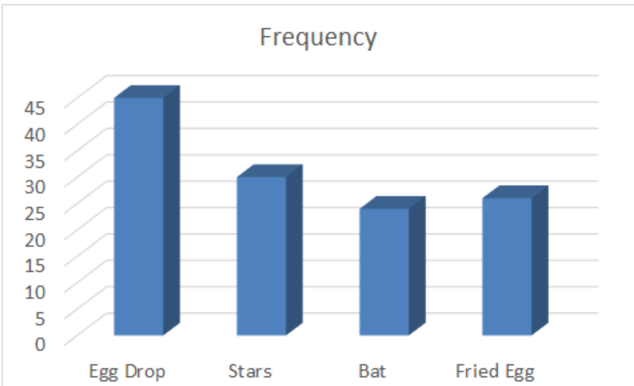


Figure 34: Chosen game frequency summed across all user sessions

Each user participated in 5 sessions over the course of the study. Each session contained 5 choices of games. The frequency of sequences of game choices made by users in each session is shown in Figure 35.

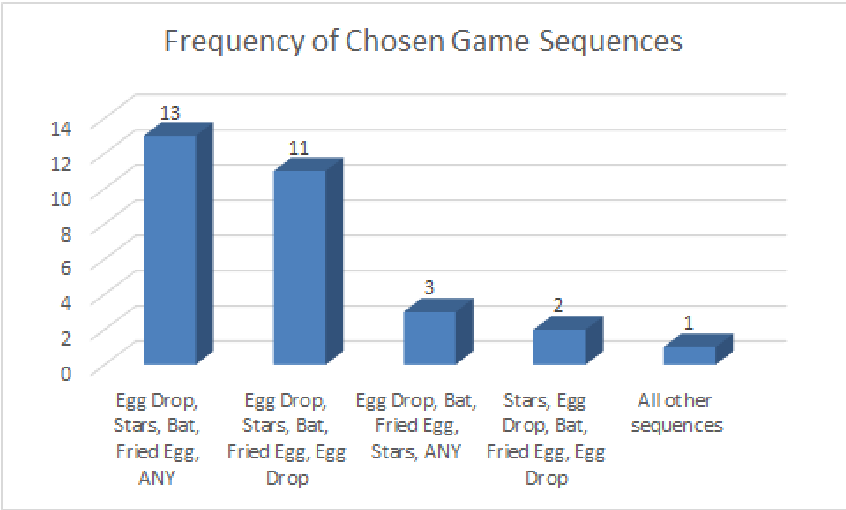


Figure 35: Frequency of users'selected game sequences for all session

### 3.3 Performance/Achievement

Each user's performance on each game was tracked over time. Performance was calculated as a combination of both affected and unaffected side performance as follows:

$$\text{Affected side performance} = \frac{\text{number of objects caught using affected side}}{\frac{l_t}{l_t+r_t} * \text{total number of objects spawned}}$$

$$\text{Unaffected side performance} = \frac{\text{number of objects caught using unaffected side}}{\frac{r_t}{l_t+r_t} * \text{total number of objects spawned}}$$

with

$$l_t = \text{time using affected side}$$

$$r_t = \text{time using unaffected side} * \text{difficulty factor}$$

Where the difficulty factor is the relative game speed at each difficulty level in each game as shown in Table 1.

Median performance of users throughout the study is shown in Figure 36.

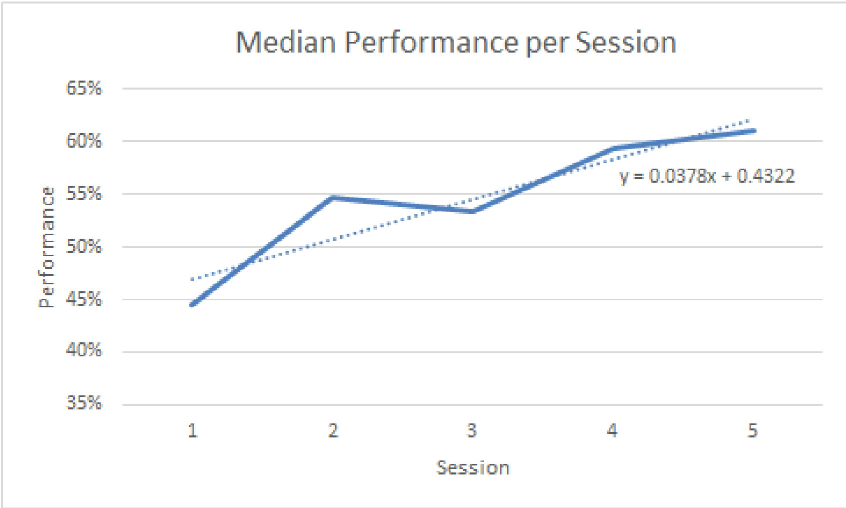


Figure 36: Median performance of all users throughout the study with a linear trendline. Performance includes both affected and unaffected side and increases with time.

Mean performance of users on each game is shown in Figure 37.

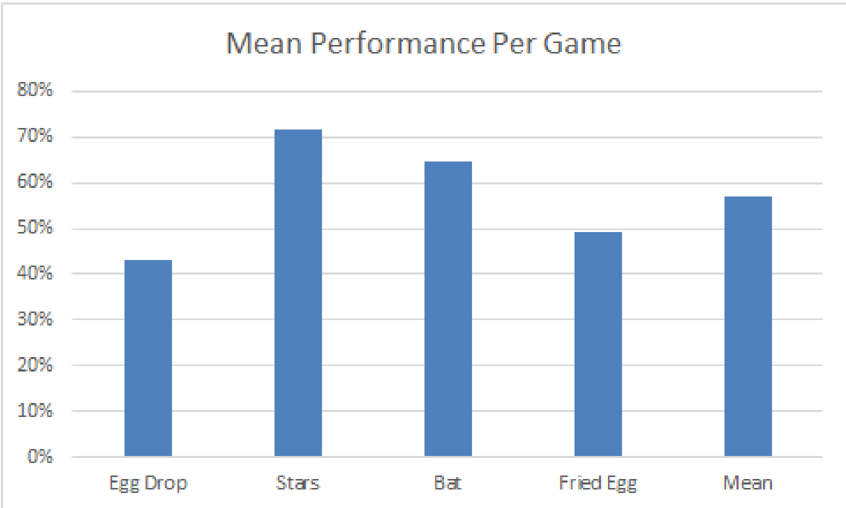


Figure 37: Mean user performance per game

Users 4 & 5 were the only users to fully utilize both affected and unaffected limbs during gameplay. Their performance while using their unaffected limb in each game was calculated at different difficulty levels and the result is shown in Figure 38.

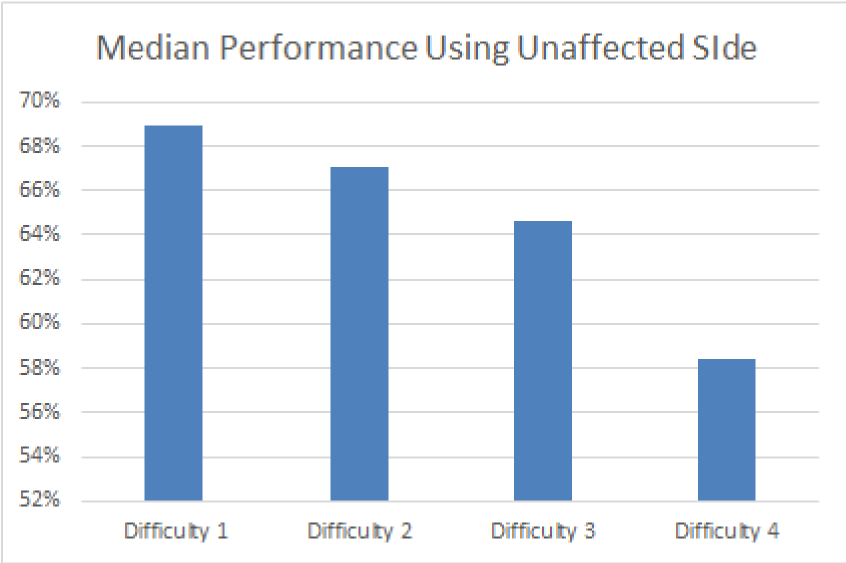


Figure 38: Median unaffected side performance from users 4 & 5 across all games at varying difficulty levels. Difficulty level of 1 is baseline/easiest/slowest setting, 4 is the fastest gameplay setting.

### 3.4 Range of Motion Comparison

Table 2 shows the results of the analyzed range of motion measurement data taken from before and after the study for the shoulder flexion.

| | Affected Side | | Unaffected Side | |
|---|---|---|---|---|
| User | Session 1 | Session 5 | Session 1 | Session 5 |
| 1 | * | * | 155 | 150 |
| 2 | * | * | 168 | 163 |
| 3 | 65 | 100 | 162 | 162 |
| 4 | 125 | 135 | 157 | 157 |
| 5 | 151 | 159 | 191 | 170 |
| Mean | 114 | 131 | 167 | 160 |

Table 2: ROM measurement #1 (Shoulder Flexion) measured in degrees. Users 1 and 2 had no mobility in affected side so ROM measurements were not included.

Table 3 shows the results of the analyzed range of motion measurement data taken from before and after the study for the shoulder abduction.

| | Affected Side | | Unaffected Side | |
|---|---|---|---|---|
| User | Session 1 | Session 5 | Session 1 | Session 5 |
| 1 | * | * | 162 | 169 |
| 2 | * | * | 184 | 190 |
| 3 | 77 | 88 | 144 | 138 |
| 4 | 88 | 89 | * | 167 |
| 5 | 85 | 88 | 180 | 169 |
| Mean | 83 | 88 | 168 | 167 |

Table 3: ROM measurement #2 (Shoulder Abduction) measured in degrees. Users 1 and 2 had no mobility in affected side so ROM measurements were not included.

Table 4 shows the results of the analyzed range of motion measurement data taken from before and after the study for the horizontal abduction of the shoulder.

| | Affected Side | | Unaffected Side | |
|---|---|---|---|---|
| User | Session 1 | Session 5 | Session 1 | Session 5 |
| 1 | * | * | 115 | 101 |
| 2 | * | * | 125 | 119 |
| 3 | 90 | 85 | 145 | 136 |
| 4 | 82 | 90 | 153 | 152 |
| 5 | 90 | 90 | 118 | 133 |
| Mean | 87 | 88 | 131 | 128 |

Table 4: ROM measurement #3 (Shoulder Horizontal Abduction) measured in degrees. Users 1 and 2 had no mobility in affected side so ROM measurements were not included.

Table 5 shows the results of the analyzed range of motion measurement data taken from before and after the study for the external rotation.

| | Affected Side | | Unaffected Side | |
|---|---|---|---|---|
| User | Session 1 | Session 5 | Session 1 | Session 5 |
| 1 | * | * | 53 | 58 |
| 2 | * | * | 64 | 68 |
| 3 | 25 | 22 | 82 | 84 |
| 4 | 37 | 40 | 88 | 90 |
| 5 | 62 | 63 | 84 | 90 |
| Mean | 41 | 42 | 74 | 78 |

Table 5: ROM measurement #4 (External Rotation) measured in degrees. Users 1 and 2 had no mobility in affected side so ROM measurements were not included.

Each measurement's mean range of motion for all users taken just before the first session began and just after the last session ended is shown in Figures 39 40. These figures show standard error bars but do not include the intrinsic error of measuring range of motion, which may be up to 10%.

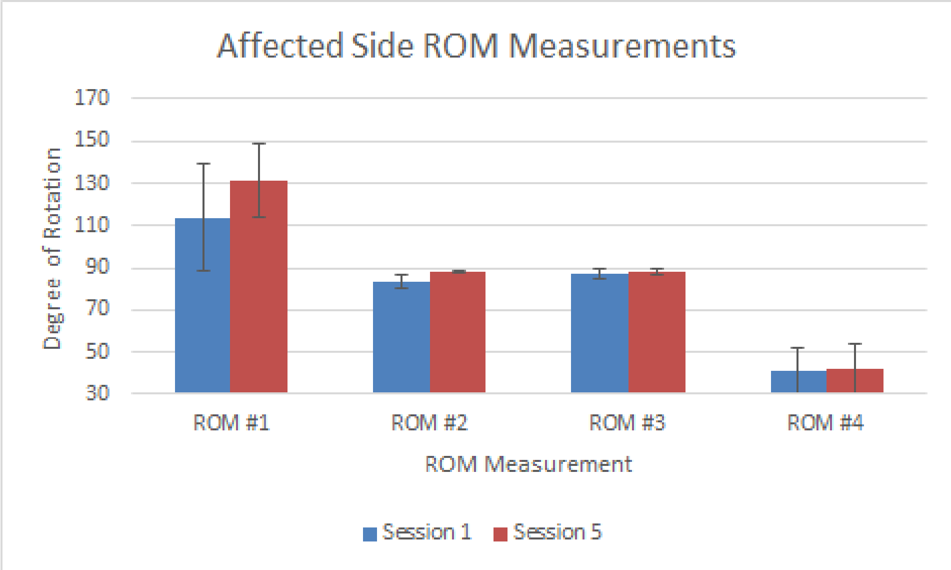


Figure 39: Mean of users'range of motion measurements (in degrees) from the affected side from session 1 to session 5 in each of the four measurements taken. Standard error bars are shown.

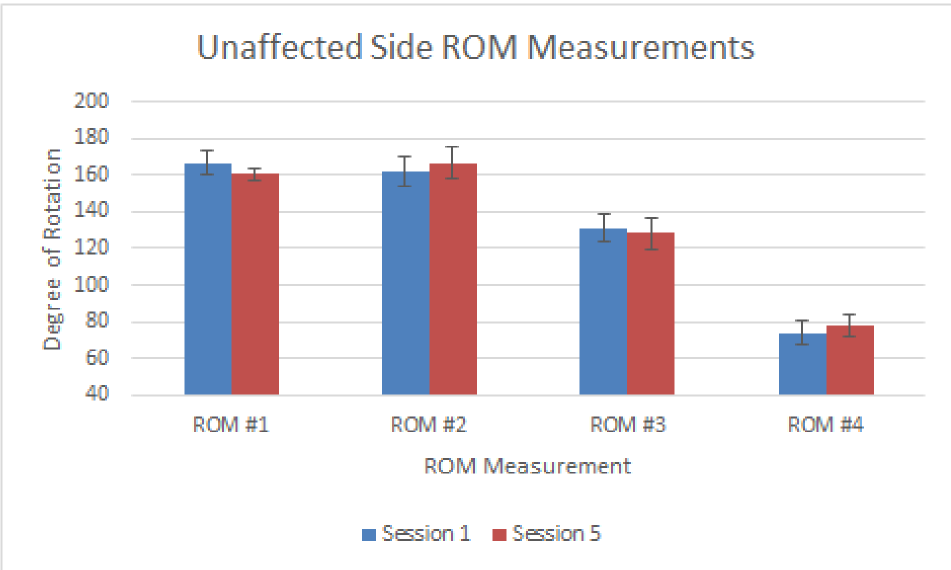


Figure 40: Mean of users'range of motion measurements (in degrees) from the unaffected side from session 1 to session 5 in each of the four measurements taken. Standard error bars are shown.

## 3.5 Qualitative Analysis

The mean frequency per session of each qualitative theme is shown in Figure 41

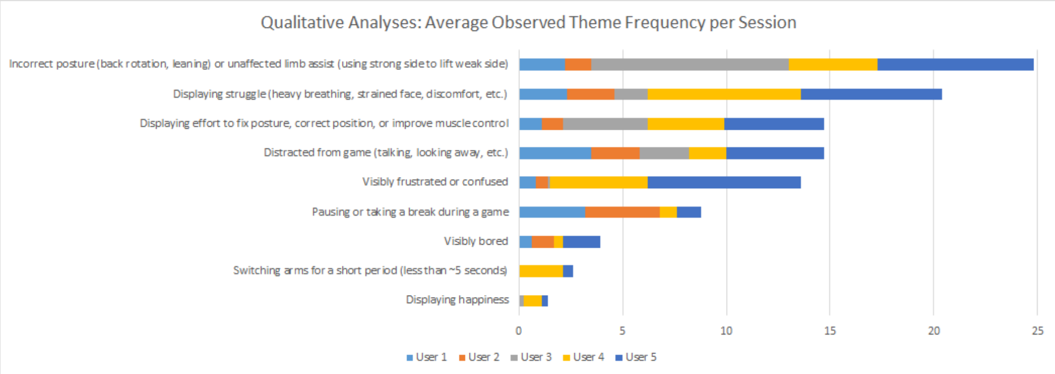


Figure 41: Mean frequency of qualitative themes per session based on two independent qualitative analyses.

## 3.6 User Responses to Follow-up Questions

At the completion of each user's fifth session, a series of questions was asked regarding their preferences, motivations, and additional comments. Here is a summary of their answers to the follow-up questions:

**Q1:** What are things you liked about the games?

- **Two** participants said that they liked the colors used in the games
- **Two** participants said that they liked the background music used in the games
- **One** participant said that they liked the sounds, especially of the egg frying
- **Two** participants said that they liked the competition or challenge of the games
- **Two** participants said that they liked the egg (the shape) used in the egg drop game
- **One** participant said that they liked that playing wasn't monotonous or repetitive

**Q2:** What are things you disliked about the games?

- **Three** participants said that they disliked certain sound effects (bat hitting ball, noises when you caught objects)
- **One** participant said that the provided in-game directions were not clear.
- **One** participant said that they because frustrated when they weren't able to score in a game
- **One** participant said that they disliked the complex control of the bat in the Bat game
- **One** participant said that they did not dislike anything

**Q3/Q4:** Which game was the easiest and why?

- **Three** participants said that the Egg Drop game was the easiest. Reasons: "Not sure. It was fun", "easy to control" and "I had better control of that movement"
- **One** participant said that the Stars game was the easiest because "It was easier to control my arm and hand"
- **One** participant said that the Fried Egg game was the easiest because of the direction of motion, the sound of the frying egg, and that it was the most fun.

**Q5/Q6:** Which game was the most difficult and why?

- **Five** participants said that the Bat game was the most difficult. Reasons listed were:
  - The game required a lot more movement
  - The bat was hard to move correctly
  - The balls were hard to see
  - The game required more complex movements than they were able to perform
  - It was difficult to achieve the correct angle and timing.

**Q7:** What is something that you would change about the system?

- **One** participant recommended including a pause button for the user to pause gameplay. The participant noted that their muscles kept tightening throughout the games and they wanted to be able to pause the game and allow their muscles to relax before continuing.
- **One** participant wanted to be able to play the games with their affected side (this user's affected side was limp and had insufficient mobility to play the games)
- **One** participant wanted to make the bat longer in the Bat game.
- **Two** participants would not change anything in the games

**Q8:** Did the game provide any incentive for you to use your affected (weak) side? (N/A for Users 1 and 2)

- **One** participant preferred the games when the game speed was faster.
- **One** participant said that the increased speed made her have to concentrate more
- **One** participant said they were not motivated by the game to use their affected side

**Q9:** How did you decide when to use your affected or unaffected side? (N/A for Users 1 and 2)

- **One** participant attempted to always use their affected side but sometimes used their unaffected side to assist their affected side due to frustration
- **One** participant used their unaffected side when they got tired of twisting their body
- **One** participant switched to their unaffected side whenever their arms got tired or they encountered a difficult angle, or when they were scoring badly.

**Q10:** Any additional comments about the study.

- “I think this is a good idea and could expand but needs input from therapists to exercise certain muscles and particular movements”
- “Maybe I will start using my Wii”
- “If I had this on my TV, I would use it”
- “I liked it. It was fun. Everything was good.”
- One participant stated that they would like to see the study analysis and that they would have liked if strength training was involved.

# 4 Discussion

Users enjoyed their experience throughout the study. Users remarked that “I liked it. It was fun. Everything was good” and “If I had this on my TV, I would use it”. The Kinect driven platform was able to distinguish a user’s active hand and use their movements to control game objects, record range of motion data, and track game statistics.

The recorded compliance of users ranged from 0% (users unable to lift their affected limb) to 80%. The average compliance among all five participants was 37%, which is slightly higher than the compliance rate found from previous research in traditional CIMT [23]. Excluding the two participants unable to use their affected limb, the compliance among the remaining three participants was 62%. Among these three users, one user never used their unaffected limb by itself but often used their unaffected limb to lift their affected limb in order to better play the games. The remaining two users switched to use their unaffected side to either improve score, ameliorate discomfort, or rest from exhaustion.

The only user data that could be used to calculate the effect of changing the unaffected limb difficulty level was from Users 4 and 5 due to the other users using only their affected side or both sides at once. A trend of increasing compliance as difficulty was increased for the unaffected limb was found but due to the amount of variance in the data and small sample size, the confidence of this trend is questionable. Although the difficulty levels of each round was displayed prior to the round beginning, users noted that they often did not read the prompts or understand when the changes in difficulty were taking place throughout the game rounds.

The Egg Drop and Stars games were most preferred by users. Both of these games involved only one dimension of control (x or y axis). The Bat and Fried Egg games were less played and remarked to be more difficult. These games involved controlling orientation of the game object as well as its position. Several users responded by saying that the Bat game was much more complex and difficult to control. The Bat game required 2 dimensions of control and also involved game objects moving in the z-direction toward the perspective camera which users remarked to be difficult to see and time their reactions. Users tended to comply more while playing the Stars game than any other game. One user noted that they like Stars because it was easy to control with their arm and hand compared to the other games. Stars was designed to be the most simplistic game and required only one axis of motion and was the only game where the orientation of the user's arm was not used.

The most common sequence of chosen games was to choose Egg Drop, Stars, Bat, and then Fried Egg "in order" and then one additional game, which was usually Egg Drop. This sequence became a strong trend among users during the 4th and 5th sessions. The games were not numbered but were presented to the user in that order and positioned on the game select screen as Egg Drop: top left, Stars: top right, Bat: bottom left, Fried Egg: bottom right.

Users' average performance generally increased throughout the study. The performance increase from the first to the second session was found to be statistically significant by single factor ANOVA (p=0.05). This could likely be due to the familiarity and comfort that was gained throughout each session, allowing the user better control. The median rate of improvement per session was 3.7%. Although trending toward statistical significance, due to the high variance of this data among users, the change in performance throughout sessions two through five of the study was not found to be statistically significant by a single factor ANOVA.

The points scored by the users did not affect their preference of game (e.g. users chose Egg Drop as their favorite game but had the poorest performance relative to the other games, see Figure 37). Users remarked that the Bat game was most difficult but they scored better on the Bat game than Egg Drop or Fried Egg on average.

When asked if the difficulty level of the game affected their choice of game, only one user (User 5) responded with a Yes. Users 3 and 4 responded that they were not motivated by the games to use a particular arm. User 5 said that they preferred the games with the increased difficulty level and said that they had to concentrate more to play. This response was not backed by the user's quantitative data where it showed increased compliance at higher unaffected usage difficulty levels. There is a likelihood that the user was cognitively overwhelmed and not consciously making decisions

Qualitative results suggest that users generally exercise poor posture while engaging in unassisted virtual therapy so an intervention or coaching to correct posture may be beneficial toward the progress of the individual. It was the most common observed qualitative theme (from Figure 41). Roughly half as common were the occurrences of the users displaying an effort to fix their posture or physically correct themselves. The analysis also suggested that the users did visibly struggle at an average rate of once per minute throughout each session. One participant noted that their muscles kept tightening throughout the games and they wanted to be able to pause the game and allow their muscles to relax before continuing. The qualitative analysis also suggested to implement a method for allowing a completely limp affected limb to control game objects.

ROM measurements were able to be taken with ease. Several users required modified positions to perform the required movements. The measurements can properly be extracted from the joint data from the Kinect depth sensing camera but due to the slight inherent unreliability in individual ROM measurements, two data points taken weekly were not a significant enough sample to accurately extract trends in users recovery. ROM measurements are one measure of a person's recovery from stroke but were not consistently reliable enough during a two week study to provide data on the minute and incremental recovery that patients may have had.

## 5 Conclusion and Future Work

This thesis described the background, methodology, design, implementation, user test, and analysis of results of a virtual rehabilitation platform created to test concepts in rehabilitation, motivation, and behavior. This platform fulfilled the desired design criteria and can be used to build a more complete platform and as a seed for future research. A study was conducted on stroke survivors with hemiparesis in order to test the following hypotheses:

1. By modifying the level of achievement that a user obtains during gameplay, virtual rehabilitation platforms can extrinsically motivate users to use their affected side during therapy

2. If given the choice, users choose rehabilitation games that require less effort over more complex or difficult rehabilitation games

3. Compliance rate of virtual mCIT is higher than traditional mCIT

4. Virtual rehabilitation using active range of motion exercises can improve or maintain a user's range of motion over time

The development of mCIT for stroke patients provides a method of short, intense, targeted rehabilitation to treat hemiplegia. By experimenting with individuals need for achievement, it is likely that modifying the difficulty of a task can affect the behavior of certain individuals and that these principles can be applied to cognitively or virtually induce a constraint in a user during virtual rehabilitation sessions. Virtual mCIT may be an option for stroke survivors that are unwilling to wear a physical constraint for a period of time or cannot logistically manage to undergo traditional CIMT or mCIT. Compliance during virtual mCIT seems to be higher than that of traditional mCIT but a more extensive user test is necessary to validate this result.

User behavior in a game that offers rewards for achievement varies based on their individual need for achievement and intrinsic motivation. In this study it was found that users were largely intrinsically motivated and not clearly influenced by the extrinsic motivation presented in the games, however, users in the study were not evaluated for levels of need for achievement characteristics. These characteristics may play a role in explaining the behavior of the users since people with a high need for achievement may shy away from more difficult tasks while people with low need for achievement may engage in a task regardless of the achievement gain. A follow up study to evaluate intrinsic need for achievement could be helpful to explain the study results.

Range of motion measurements were used to quantify user progress over time. The measurements did not provide a clear trend due to the small size and duration of the data set. Ideally, range of motion data can be taken weekly over a period of tens to hundreds of weeks to better understand trends in the user's recovery. The same is true for other assessments (Fugl-Meyer, Barthel Index). Due to environmental and neurological variations, ROM measurements naturally fluctuate and are susceptible to daily variations.

Qualitative analysis revealed the most common themes among users were of users displaying bad posture during gameplay, showing effort to fix their posture, and displaying visible struggle while engaging in the therapy. These themes indicate that an unsupervised virtual rehabilitation therapy session, while effective in engaging a user, may require a method of coaching the user to correct issues with posture during therapy.

More research can try to develop understanding of how therapist intervention during virtual therapy sessions could affect the outcome by coaching the user and offering advice on posture and other corrective methods of improving technique. This intervention may also be virtual whereby the rehabilitation platform monitors the user for circumstances that would trigger an intervention to provide corrective measures.

It is also necessary to develop research in areas that would allow greater insight into patients' behavioral motivations during therapy. Behavioral patterns were observed in unexpected places, such as how users became habituated to playing the games in a certain order. From this finding it may be useful to study how the ordering of a sequence of games can be used to accomplish a specific goal, such as allowing a patient to warm up and peak their therapy session at a certain point. Users also tended to prefer simpler games that did not require proper orientation of the arm for game control and only moved in one axis of motion. Users also tended to comply while playing the game with one axis of rotation and without any control of orientation. More research is required to understand how the complexity of game control affects the user's recovery and experience.

Future work may also try to quantify specific aspects of the games that users enjoyed such as particular objects, sounds, colors, or shapes. It may be possible to cater to specific user's interests in game design to improve the user experience. Users were interested in adapting and customizing therapy session movements to the their own condition, choosing relevant games for each user (with appropriate sounds and colors). Customizing a virtual therapy plan with custom visual and design aspects may provide a user with greater benefit than the current therapy trends.

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