ABSTRACT

Investigating the Impact of Interacting with Real World Objects in Virtual Environments

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Virtual reality (VR) systems allow users to be fully immersed in a virtual world. Incorporating physical objects such as stairs in to virtual reality could provide better immersion and create new uses for these systems. This study investigated what impact interacting with a physical object in the virtual environment has on human motion. A small change in motion in the virtual environment was seen, with average increases in knee flexion of 5.2° and 6.3° in the virtual room and forest environments, respectively and a decrease in percent of foot on step (PFOS) of 4.2% and 6.2%. There was a marked difference in the PFOS while subjects had a full body model instead of a feet only model, with 6.6% less with the full body model in the forest and 5.0% in the room. Overall, incorporating physical objects in VR shows promise as a tool for clinical and training purposes.

Investigating the Impact of Interacting with Real World Objects in Virtual Environments

by

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A Thesis

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DEDICATION

To my family. Thank you for always believing in me more than I did in myself.

CHAPTER ONE

Introduction

Definition of Virtual Reality

Over the past decade, virtual reality (VR) has grown beyond being used solely for video games and entertainment, spurred by the release of systems such as the HTC Vive and Oculus Rift. More recently the second generation of virtual reality consoles has been released, with much of the focus on the Valve Index, HTC Vive Cosmos, Oculus Quest, and Oculus Rift S. Each of these systems fits into the most often thought of definition of virtual reality, where the system dynamically moves with the user and reflects the motion within the headset. However, this is not the only definition of virtual reality used across the literature. Some classify anything that occurs in a virtual environment as virtual reality, whether they are traditional, 3rd person perspective video games or 1st person fully immersive virtual reality video games. The distinction between these two types of video games comes entire from hardware. 3rd person games rely on a stationary console with separate controllers, while virtual reality games rely on the primary part of the system to dynamically move with the user. Along with these two primary classifications are systems such as the Xbox Kinect (a game system that tracks the position of the user to interact with the games) and Nintendo Wii (a game system that tracks the position of game controllers to interact with the games). Both of these systems complicate the discussion of what is and is not virtual reality. For example, Schroeder states that virtual reality technology is “a computer-generated display that allows or compels the user (or users) to have a sense of being present in an environment other than the one they are actually in , and to interact with that environment" [1]. Using this definition, both the Xbox Kinect and Nintendo Wii can loosely be considered virtual reality, considering they both use a computer-generated display and let them interact with the virtual environment with their movements. While this may have been a correct definition when it was written, the technology has progressed to make the use of a single definition to define virtual reality difficult even when there is an obvious difference between the modern head-mounted systems and traditional video games.

With this in mind, it is logical to think of virtual reality and related technology on a spectrum ranging from the real world to completely immersive virtual environments. Using the virtuality continuum defined by Milgram and Kishino[2], modern virtual reality systems can be considered the furthest from the real world. To best determine where a system falls on this continuum, three separate continuums can be used. These describe how much of the world the computer is able to track and understand (extend of world knowledge), the quality with which the computer can display the intended images (reproduction fidelity), and the degree to which the user feels fully present in the displayed scene (extent of presence metaphor). Current modern virtual reality systems are on the far end of each of these continuums towards the more virtual end, creating an entirely virtual environment.

The extent of world knowledge continuum describes how much knowledge the computer has about the position of each object in the world and the viewer's attempts to change the world. Prior systems such are the Xbox Kinect would do well with the computer knowing the position of objects in the world since they are able to track gross body movements, but they do not know much about how the user interacts with the world or the orientation of the user within the system. Comparatively, modern virtual reality systems are much more extreme on the extent of world knowledge continuum since the computer tracks the position of the body in the system while also knowing the position of the user within the world and the orientation of said user. If the user attempts to interact with the environment, the computer is able to detect this in modern systems even if the user does not actually change anything. Likewise, modern systems are on the extreme end of the reproduction fidelity continuum by having a high-quality display that is continuing to improve with each successive system. Compared to the HTC Vive, the Valve Index works similarly with the most improvements being on the visual display in the head mounted display(HMD) [3]. Finally, since modern virtual reality systems are fully immersive to the point of being able to walk around the virtual environment and have real-time imaging, they provide a great sense of presence for the user. Systems such as the Kinect and Wii lacked that sense of presence because the user is still able to see and interact with the physical world around them. With these capabilities, modern systems are on the extreme end of the extent of presence metaphor continuum.

Another area that needs defining within this definition of virtual reality is the different types of modern systems. There are two classifications of virtual reality systems based on how motion is tracked: outside-in tracking and inside-out tracking. Outside-in tracking relies on external base stations, often two set in opposing corners of the intended play area, while inside-out tracking relies on infrared emitter built in to the head mounted display itself and does not require any external base stations[4]. There is also the distinction between PC-driven and standalone VR systems. All PC-driven systems require an external computer to produce high quality graphics, while standalone systems have all of the computing power needed built in to the system itself. The Valve Index, used in this study, is an outside-in tracking PC-driven virtual reality system in the second generation of modern systems.

Having such a variety of systems to choose from at varying costs has led to different researchers investigating the limits of virtual reality and how it can be used to assist in different aspects of life. Since the cost of healthcare in America is often exceedingly high, the possibility of using virtual reality to help lower this cost is enticing for clinicians.

How Virtual Reality Systems Operate

Despite frequent use, there are currently no papers published by HTC, Valve, or OculusVR (makers of the HTC Vive and Vive Cosmos, Valve Index, and Oculus Quest/Rift S, respectively) regarding how the technology in their virtual reality systems work. A Valve engineer, Alan Yates, did give a presentation that is available on YouTube[5] on the basic concept of how the HTC Vive works, which is a good starting point for other virtual reality systems. This system has two tracking components. First is an inertial measurement unit (IMU), which combines an accelerometer and a gyroscope and is located in the neck of the Vive controller. Second is an optical system that emits infrared (IR) light from, two towers, called base stations, that are often placed in opposite corners of the play space. The IMU in the controller is able to determine location by integrating the acceleration of the controller twice. However, this produces large amounts of error due to the nature of the signal and noise that is produced when integrating signals. To counter this, the base stations correct the position by emitting IR light that is received by the controllers. Position is determined by the time delay between the IR leaving the base station and it being received by the controller. By placing the base stations in opposite areas of the room, the controllers are able to distinguish between which base station is emitting the IR it has received. This also allows the two base stations to optically sync with each other. However, the base stations update slower than the IMU, with the base station at approximately 100Hz and the IMU updating at approximately 1000Hz[6]. Since the base stations only correct the position approximately 1/10th as often as the IMU is updating, there are instances in which tracking relies solely on the IMU.

Figure 1.1: Valve Index HMD, Controllers, and Vive Trackers

While the Valve Index is a new system that does not have any detailed information for how the system works, there are many similarities in the setup between it and the Vive. The controllers for the Index continue to use IMUs to track the position and rely on upgraded base stations to correct the inaccuracies of the IMU[7]. A primary difference is that the new base stations do not use optical syncing to assist in determining where the base stations are in relation to the controllers, allowing for more flexibility in the setup of the virtual reality system[8]. Besides this, the Valve Index works similarly to the HTC Vive for tracking position.

Valve Index Specifications

The Valve Index is a virtual realty system developed by Valve Corporation. The system comes with a head mounted display (HMD) that has a resolution of 1440x1600 pixels per eye[3] and has an adjustable frame rate that can be 80, 90, 120, or 144Hz. The Index also comes with two controllers that strap to the user's hands and the base stations mentioned previously. Additional accessories called Vive Trackers, developed by HTC, are also available separately. These Trackers use a similar technology as the controllers, but have a different light to digital converter and circuit board[9]. By placing these on physical objects or strapping them onto parts of the body the user can create a more interactive experience. Vive Trackers can also be used to set the location of a virtual object onto a physical object at the beginning of the game before being removed to prevent any physical interference such has hitting or stepping on them. Since the Valve Index is PC-driven, a computer is needed to run the system and record any data from the Index itself.

Virtual Reality in Physical Therapy

Serious games are defined as "the use of computer games that have a main purpose that is not pure entertainment"[10]. Exergaming is a similar idea, but the term tends to refer more to games where physical activity is the primary focus of the game[11]. Both of these types of games have great obvious potential applications in physical therapy. For most people, performing standard physical therapy tasks is repetitive and monotonous. By gamifying these tasks, the experience for the user could become more enjoyable and the user would be more likely to stick to their at home therapy schedule. Additionally, the physical therapist could have a built-in coaching and feedback system to help the user move correctly for the different therapy tasks. Doing so could help prevent injuries when the user is performing these tasks at home. Solving both of these issues with a single system.

Accuracy and Precision Needs for Physical Therapy

One concern for clinicians when considering using virtual reality systems for physical therapy is the accuracy and precision of the existing systems. While for more qualitative tasks such as the Berg Balance Scale the accuracy and precision of the system do not matter as much, any quantitative task would require a certain level of precision. Some quantitative tasks, such as the Functional Reach Test, require approximately an inch of precision[12]. In order for virtual reality systems to be viable in the rehabilitation environment they must have at least an inch of precision. While the HTC Vive has been shown to have approximately one millimeter precision [13],[14] there have been no such studies on the Valve Index. However, since the Index works off of similar principles as the Vive and is considered an upgrade in hardware it is safe to assume that it would have a similar level of precision until a study is conducted to determine the accuracy and precision of the Index.

While the controllers and HMD for the HTC Vive and similar virtual reality systems have been tested for their accuracy and precision, one important component has not. The Vive Trackers, commonly used for full-body tracking, have little data supporting their accuracy and precision. For purely visual purposes, this is not a major issue as shown by Ahir et al. when using them track the feet and hands of a user during normal human movements [15]. However, if these are to be used at all in physical therapy to record the motion of users limbs, the accuracy must be checked. In one of the few studies investigating this issue, it was found that the Trackers had a positional accuracy of .58 ± .89 cm and a rotational accuracy of 1.46 ± 0.62° when compared to a gold standard Vicon camera setup [16]. In order to obtain these values, both dynamic human motion and controlled robotic motion were performed the data were recorded in both systems. However, the accuracy during dynamic motion was significantly worse than the controlled motion, ranging from 0.45 to 3.69 cm compared with the controlled motion accuracy of 0.02 to 0.05 cm. Such a difference in controlled and dynamic motion is expected but does present concerns when considering recording the data from these Trackers for therapeutic purposes. It also shows that the Trackers have a much lower accuracy and precision than the HTC Vive controllers. Further investigation would be necessary to fully define the accuracy of these devices and their clinical usability.

Prior Virtual Reality Therapy Studies

While the use of virtual reality as a therapy intervention method is still relatively new, many studies have employed these systems and compared their effectiveness with traditional, real world interventions. In the study from Pazzaglia et al. patients with Parkinson's disease were randomly assigned to either a virtual or conventional rehabilitation program [17]. While the virtual reality system NIRVANA (BTS Spa, Garbagnate Milanese, Milan, Italy) used in the study does not have the user wear an

HMD or use controllers, it is still highly immersive. Optoelectric infrared-red devices tracked the patient's movements without any markers while screens on the floor and walls provided a fully immersive audio-visual experience for the user. Each patient in both programs performed similar tasks for six weeks, with the primary difference between the virtual and conventional programs being the gamification of the virtual therapy tasks. At the end of the study multiple tests were performed, including the Berg Balance Scale (BBS), Dynamic Gait Index (DGI), and the Disability of the Arm, Shoulder, and Hand (DASH). The Berg Balance Scale measures changes in standing balance over time, while the DGI characterized the ability of the patient to adapt their walking to complex walking patterns needed in community environments. DASH measurements measure the physical function of the patient's upper limbs. For both the BBS and DGI, there was a significant improvement after six weeks only for those in the virtual intervention program, while both programs saw an improvement in DASH measurements. Since balance relies on multiple senses, including sight, touch, as well as the motor control system to coordinate, having the patients in a virtual environment that can stimulate each of these could be beneficial in any patient that have stability issues. Patients also found the virtual therapy to be more enjoyable than the conventional intervention. Overall, this study demonstrates some of the potential that virtual reality, regardless of the form, can have on patients in physical therapy.

Another area of therapy that is being explored as a possible area for virtual reality is in stroke patients. Many people who have suffered from a stroke have difficulty walking again afterwards without assistance, so physical therapy is used to help them regain their ambulation if possible. Yang et al. tested the impact virtual reality on stroke patients walking recovery compared to a traditional treadmill therapy [18]. Once again, the virtual reality system used in this study did not involve an HMD and was not fully immersive. Instead, it consisted of a game being projected on three large computer monitors in front of the treadmill in which the patient must react to various on-screen changes, such as an obstacle they must walk over or a change in elevation. The control group performed similar tasks on the treadmill but were told by the physical therapist when to perform the tasks rather than seeing them on a screen.

After three weeks of the different therapies, the experimental virtual reality group showed significant improvement in walking speed ($0.69 \pm .3\frac{\mathrm{m}}{\mathrm{s}}$ to $0.85 \pm .31\frac{\mathrm{m}}{\mathrm{s}}$) while the control group did not, with an increase of only $0.06\frac{\mathrm{m}}{\mathrm{s}}$. Additionally, the amount of time patients in the experimental group needed to complete a set of community walking tasks that involved more complex motions decreased significantly from 23.12 ± 19.15 minutes to 16.98 ± 18.39 minutes. Each of these results also extended to a follow up session that was conducted a month after the completion of the therapy, in which the walking speed increased to $0.86 \pm .33\frac{\mathrm{m}}{\mathrm{s}}$ and the time decreased to 15.76 ± 19.25 minutes. From these results it is clear that the participants receiving the virtual reality treatment saw a greater improvement in their walking capabilities than those with traditional therapy. Whether the difference is simply because the patient enjoyed the virtual therapy more or if there is any neurological reason is still unknown. There have been some studies that looked at the effect of virtual reality on the neural organization. One such study found that the use of VR may have caused positive changes to neural organization and in turn impacted the associated functional ambulation in chronic stroke patients[19]. More research is needed to determine the full impact of virtual reality in this way.

Using fully immersive VR systems is beginning to become popular among researchers to determine their effectiveness in physical therapy. A case study performed by Cortes-Perez et al. compared the effectiveness of conventional physiotherapy to using an HTC Vive and ready-made games for physiotherapy. The patient receiving conventional therapy performed standard therapy tasks, such as walk training and stretching, for eight weeks. Conversely, the patient receiving virtual therapy played four different games in SteamVR (Valve Inc.). These games had the patient walking around, move virtual planets, climbing a virtual wall, and cook virtual pancakes. Each of these tasks mirrors tasks that would be performed in traditional therapy but does so in a gamified way that makes it more interesting for the patient. In addition to this, the patient must be standing for each of the VR tasks and therefore is forced to balance while standing the entire time instead of being able to sit for some exercises like in traditional therapy.

Many studies have been performed so far on the overall effect that virtual reality can have on a patient's recovery, but not many have been done to determine if there is any change in how the patient moves their body. For walking tasks, does the patient lift their leg more than necessary? Or do they reach differently than normal for reaching tasks? This is a relatively unexplored area of study that is important to the viability of using virtual reality in clinical work. A recent study established a protocol for comparing reaching kinematics in the real and virtual world [20] using the HTC Vive. By establishing this, the possibility of some of these questions being answered soon is improving.

Virtual Reality in Training

For many companies and organizations such as police and firefighters, a large amount of training is necessary to ensure new workers are prepared for the job. However, there are some parts of training which can be quite expensive due to needing to transport the trainees, pay overtime, and pay people to work the training [21]. Time is also a concern, as many of these test sites are not located near much due to the need to shoot targets or have active fires. Combining these concerns leads to a lack of training in many cases. Even when training does take place, it may not be the most realistic training. In the case of shooting training for police, inanimate paper targets are often used to simulate people but do not give the same level of interaction as an active target. By using virtual reality, the trainee can interact with more realistic targets that appear to move freely and react to the target in a more natural manner without endangering anyone. It would also give easy access to training if an individual does not feel comfortable in certain scenarios yet by eliminating the need for an entire testing site.

Other scenarios that lend themselves to virtual training for police officers is learning how to de-escalate a situation with a suspect. For example, in a study by Garcia et al., training focused on police use of force was performed using the HTC Vive [22]. The goal of the training was to teach the officers how to recognize when shooting a suspect would be necessary and acceptable while not requiring anyone to act as the suspect. Instead, a non-player character (NPC) was programed as the suspect with an automated series of events to perform in response to specific actions taken by the officer.

While virtual reality has been used before for training, it often is either not fully immersive or does not require full body engagement from the trainee. In one study by

Narisco et al. looking at using VR for training firefighters, an Oculus Rift headset was used with a custom designed game being shown [23]. However, the only movement the participate can could control with the virtual reality system with the rotation of their head. All other movement was controlled with an Xbox 360 controller. To assess the physical response to the simulation electrocardiograms (ECGs) were placed on the upper body and tracked the user's heart rate variability. It was assumed that if the simulation was realistic and provoked the same response in the user's body as actual training, such as fear or anxiety, then the virtual training would be successful. Unfortunately, it was shown that there was little heart rate variability. Despite the user feeling immersed in the situation, their body was not responding in the same way it should and therefore the resulting training was not as effective as possible.

Other systems that have been created for virtual firefighter training are similar, such as the one detailed by Lee et al. in which the trainee sits in front of two monitors and can see their avatar's body move in the virtual environment through an augmented reality system. While not technically virtual reality, using augmented reality in this way allows the designers to have up to six participants in the virtual environment at the same time and work together in their training. This would once again assist in the decreased need to send firefighters to training facilities as it allows for both individual and team training using the same equipment. The setup also includes heat radiation equipment to help give the firefighters a greater sense of presence when putting out a virtual fire. With this experimental training setup, the path forward for how to properly create a virtual firefighter training is becoming more clear and closer to a reality.

Prior Work on Physical Interactions in a Virtual World

One area in which not much research has been done is how virtual training is changed when interacting with a physical object. While all virtual reality games have many objects that could be interacted with, they are rarely mapped on top of a real object, but rather just a game object. Changing this trend would open up the possibility for more realistic games to be created with the subject fully experiencing what they are seeing in the environment. One attempt at this was done in a stair climbing study from Asjad et al [24]. A series of flights of stairs was developed in Unity3D for subjects to walk up in different environments while using the HTC Vive. While the purpose was to look at height perception in virtual reality, it also included one of the few attempts at physical interactions in VR. By creating a series of wooden slats that represented the edge of each step, Asjad gave some haptic feedback to the user to actually feel like they are walking up stairs. One major difference, however, is the obvious lack of height change which could affect the user's movement and perception of where they are in space. One interesting outcome of the study was discovering that the passive haptic feedback received from these fake steps did not have any impact on the user's height perception. This shows that, at least in some instances, even with mild feedback there is not a difference in how the user perceives the world around them. Instead, the most helpful change for the user was the addition of the ability to see their feet in virtual reality. By attaching Vive Trackers to the user's shoes, virtual white sneakers were able to be overlaid on top of their real shoes. Giving this visual feedback showed to be the most helpful change made to the virtual space for the user's feeling of presence.

Purpose

The purpose of this study was to investigate the impact that virtual reality has on human movement when interacting with a physical object in a virtual environment. This was done by having 10 subjects perform the same task of walking up and down a set of stairs in the virtual environment and real environment. A series of trials were performed at the beginning of each subject's data collection to allow them to familiarize themselves with the stairs and the virtual reality system. In order to compare how people responded to visual stimulus in the virtual environment, the environment itself was changed between two scenarios and the visualization of their body in the environment was changed up to three different ways. Analysis of the subject's walking patterns could indicate how useful virtual reality is for physical therapy and training purposes. The primary aims of this research are as follows:

Aim 0: To determine the movement tracking capability of current, off-the-shelf virtual reality systems that would be capable of implementing VR training. Prior work has been done on some of the older modern systems, but not much has been done with the latest generation of systems. Testing the Vive Tracker peripherals on human motion tracking would also benefit future studies that seek to track motion besides the head and hands.

Aim 1: To determine if there is a difference in human movement during a single, every-day task that requires full-body dynamic engagement when interacting with a physical object in the real world vs. interacting with the same object in a virtual environment. Does the user lift their foot more in the virtual environment? Bend their knee differently? It is hypothesized that there will be some differences between the real and virtual environments, but that they will not be significantly different. This would give more studies in which subjects interact with physical objects confidence that doing so does not affect their motion significantly.

Aim 2: To investigate the learning behavior of virtual reality users over time. Does the user begin to behave more similarly to normal in the virtual environment after have some exposure and learning how to adjust to it, or do they have no noticeable difference? It is hypothesized that there will be a significant learning effect in the first few virtual reality trials in which the subject starts by walking abnormally then over time matches their normal walking pattern and are consistent for the remainder of the initial virtual stairclimbing trials.

Aim 3: To determine if the look of a virtual environment influences the user's perception and movement. Does having a realistic virtual environment lead to more regular motion? Does an unrealistic environment have a negative effect? Does the ability to see their full body change how their motion compared to just seeing their feet? It is hypothesized that there will not be a significant difference between the two virtual environments but there may be some difference between the visualization of the body trials. While both environments have the same starting and ending points on the stairs, losing the ability to see much of the body could cause the user to feel disoriented and decrease their comfort in the environments.

CHAPTER TWO

Developmental Work

As with any project, there were many issues that had to be overcome in order to move forward with the project and systems that had to be put in place for everything to work properly. For this project, these ranged from testing the accuracy of the Oculus Rift S, developing a custom virtual reality game in Unity3D, and working around infrared light interference between virtual reality and motion capture systems.

Oculus Rift S Validation in Controlled Movement

While it has been established that there are a few studies testing the tracking capabilities of the HTC Vive, little information is currently available on the accuracy of the Oculus Rift S (Facebook Technologies, LLC). This is especially true when comparing the accuracy of this system to that of a gold-standard motion capture system and testing the rotational accuracy of the system. One study analyzed the positional accuracy of the Oculus Touch controllers that are a part of the Oculus Rift system but compared the controllers to a custom-made grid system with location measured with dial calipers [25]. While this is an acceptable method of testing accuracy, it did not measure rotational accuracy and has a greater potential for inaccuracies in measuring than with a passive motion capture system. Being one of the most advanced inside-out tracking virtual reality systems, testing the tracking capabilities of the Rift S and comparing them to outside-in tracking systems such as the HTC Vive could provide valuable insight into how the two methods of tracking compare.

Testing Method

A framework developed by Jost [13] was used in the testing of the Oculus Rift S system. In order to repeatably move the controller and HMD, a Universal Robots UR5 (Universal Robots, Odense, Denmark) was used. The UR5 has a precision of ± 0.1mm [26], making it a prime candidate for validating motion tracking systems with its consistency and repeatability.

For recording the motion of the Rift S in space, a 14 camera optoelectric motion capture system with sub millimeter precision (Vantage Cameras, Vicon Motion Systems LTD, Oxford, UK) was used as the gold standard [27]. Reflective markers were placed on the robot arm's gripper and collar. The gripper on the robot arm rigidly held either the HMD or controller for all movements when recording the data. In order to collect the position and orientation data of the Rift S, a custom game was developed in Unity using the Oculus Integration Unity asset provided by Oculus.

The robot arm moved the HMD and controller 400 mm at either 500 mm/s or 1000 mm/s in either the X, Y, or Z direction determined by the robot's own coordinate system. For each of these six conditions the controller or HMD was moved 30 times to create a total of 360 trials. From each system's output, the total Euclidean distance was calculated from the start of the movement to the end of the movement. Then the absolute distance between the travel distance of the object in the world and the travel distance from the Rift S was calculated.

Both the controller and HMD performed three orthogonal rotations (yaw, pitch, and roll) about each of the three orthogonal axes (X, Y, Z) defined by the robot's coordinate frame, adding up to nine total rotation types. For each configuration, the robot arm was rotated 90° and was repeated 30 times at 1000 mm/s to create 540 trials. Due to the controller having a unique curved shape a custom designed holder was 3D printed and used to ensure the controller could be reoriented 90° consistently.

Using the three reflective markers placed on the robot's gripper and collar, a rotation matrix describing the orientation of the HMD or controller was obtained. Unity gave the orientation of the HMD or controller directly as a quaternion. After converting the quaternion to a rotation matrix, the total angle rotated by the device θ can be determined using the starting and ending orientation. The rotation matrix Q can then be used to relate the starting and ending rotation matrices (R_1 and R_2):

$$Q \triangleq R_1 R_2^T \tag{1}$$

Then the trace of Q can be defined as:

$$tr(Q) = 1 + 2\cos(\theta) \tag{2}$$

Finally, the total angle θ can be found:

$$\theta = \cos^{-1}\left(\frac{tr(Q) - 1}{2}\right) \tag{1}$$

Oculus Rift S Validation Results

Across all controller trials, the mean difference in distance traveled was 4.36 ± 2.91 mm and 1.66 ± 0.74 mm for all HMD trials. The mean difference in angle rotated for all controller trials was 1.13 ± 1.23° and 0.34 ± 0.38° for all HMD trials.

With these results, we can see that the Oculus Rift S has a translational accuracy of less than 5 mm and a rotational accuracy less than two degrees for all components, with the HMD being much more accurate. Since the controllers rely on the HMD's camera sensors, it was expected that the controllers would have a slightly worse accuracy and precision. To best replicate a realistic scenario, a research assistant wore the headset and watched the controller move from a close position for every trial, replicating the approximate distance the user would have the controller away from their face. No direction proved to be statistically less accurate the any others for both the controller and HMD and the speed at which they were moved did not show any significant impact on results. The only movement that proved to be consistently less accurate than others was rotating about the Z-axis. It is unclear what the cause of this was, but the controller was still able to report its position with less than 6° of error. Therefore, these results demonstrate that the Rift S should be able to be used in a range of clinical applications while retaining accurate and precise tracking.

Discussion

Compared with the HTC Vive, the Oculus Rift S has a slightly worse accuracy and precision, as can be seen in Table 2.1, where the HTC Vive data is taken from a study perform by Jost [13] using the same methodology as was performed on the Oculus Rift S. No HMD tracking data was recorded during that study but the comparison between the controllers is likely to follow the same trend for the HMDs. It is hypothesized that this large difference in accuracy is due to the inside-out tracking nature of the Rift S. By utilizing inside-out tracking, the Rift S controllers depend on the headset for the signal that corrects the IMU positional data, but it is unknown if the movement of the headset could affect this accuracy and create a compounding error. Conversely, the HTC Vive's use of outside-in tracking with base stations is shown to have a high degree of accuracy potentially due to the broad tracking area from the stable base stations. Either system could be used for clinical purposes, but for this study the HTC Vive was chosen because it would give a more accurate virtual model for the virtual reality user. Additionally, the HTC Vive is compatible with the Vive Tracker accessories, which were needed to track the user's feet and waist, further directing the choice away from the Rift S.

Table 2.1: Translational and Rotational Accuracy of the HTC Vive and Oculus Rift S Virtual Reality Systems

System	Component	Translational Accuracy (mm)	Rotational Accuracy (degrees)
Oculus Rift S	Controller	4.36 ± 2.91	1.13 ± 1.23
	HMD	1.66 ± 0.74	0.34 ± 0.38
HTC Vive	Controller	0.74 ± 0.42	0.46 ± 0.42
	HMD	N/A	N/A

However, the benefits that come from using inside-out tracking could out-weigh the difference in accuracy for clinicians. Firstly, the Rift S is cheaper than most outside-in tracking setups, only costing $399 for the entire system as compared to $699 for the HTC Vive Cosmos, $1,199 for the HTC Vive Pro, or $999 for the Valve Index, which are all outside-in tracking second generation virtual reality systems after the HTC Vive. Secondly, the lack of any base stations gives clinicians more flexibility in the space they use for virtual reality and is easier to give to patients to perform tasks at home. Rather than needing to set up base stations around the play space, the user simply has to plug in the Oculus Rift S to a computer capable of running it and draw a virtual boundary for their play space to get started. Human motion presents several issues that controlled motion does not consider, such as soft tissue artefact, a looser grip, and small fluctuations from constantly moving body parts. Each of these issues would likely lead to the system being less accurate and precise during regular use. Future concerns for virtual reality system tracking also includes irregular movements caused by a variety of diseases such as Parkinson's or Cerebral Palsy. Such movements would test the limits of the system's tracking capabilities during difficult motions. More information is needed comparing the accuracy and precision of the Rift S and other virtual reality systems during more realistic motion to get an idea of how they would behave during therapeutic use before it can be definitively stated that it is suited for clinical use.

Infrared Interference

In the early stages of this study, the HTC Vive was planned to be used instead of the Valve Index. However, there was one issue that the Vive could not overcome: infrared interference. Both the Vicon Vantages cameras used for motion captures and the SteamVR 1.0 base stations used by the HTC Vive work by emitting infrared light and receiving the light back to their sensors, or with the controller and headset sensors in the case of the virtual reality system. This created a problem because the two systems used a very similar signal, both with an approximate wavelength of 850nm [9]. While not much of an issue for the Vive's HMD and controllers, the Vive Trackers were unusable with the Vantage cameras turned on. Vive Trackers have a different light-to-digital converter that is more sensitive to IR interference, causing the base stations to lose tracking of them and not be able to regain tracking due to the amount of IR light flooding the area.

When the SteamVR 2.0 base stations were released, they were said to be a solution to these sorts of interference issues. Due to switching to a single laser sweep instead of an omnidirectional blinker, the new base stations are supposed to have better immunity from motion capture systems [8,28]. Since the Vive Trackers are compatible with the SteamVR 2.0 base stations, these stations were acquired along with the Valve

Index system because the HTC Vive is not compatible with the new base stations. Upon setup, the Trackers quickly showed promise, being able to be tracked occasionally when the Vantage cameras were on. However, the interference was still too strong to allow for proper use of the Trackers with everything running at its base level. After much testing, is was found that decreasing the strobe intensity on the Vantage cameras had a significant impact on the interference experienced by the Tracker. However, this also decreased the effectiveness of the motion capture system, as decreasing the strobe intensity is essentially decreasing the amount of light being projected by the cameras. With less light, there is a higher chance that a marker will be occluded from a camera completely and create gaps if it is seen by less than two cameras.

Ideally, the solution to the interference problem would balance the tracking capability of the Vive Tracker and the quality of the motion capture data. In order to achieve this, the maximum percent strobe intensity that the Tracker could handle was used, 14%. This is less than ideal for the motion capture system but proved stable enough that it could be used for the study. Additionally, the capture frequency of the Vicon Nexus system was changed from the default 120Hz to 150Hz. It appeared that since the virtual reality system has a refresh rate of 120Hz, having the motion capture system run at the same frequency caused the entire Index system to lose tracking regardless of the strobe intensity.

Virtual Room Development

For this study, a virtual environment was created in Unity (Unity Technologies). In this environment, a set of stairs were modeled based off of the dimensions of the set of four steps that were to be used in the study. A custom script had to be written that would map the virtual staircase on top of the real stairs. To accomplish this, a centroid was created on the corner of the top virtual step, which was used as the set point for the physical stairs. A Vive Tracker was modeled as a cube in the game and was placed on the corner of the physical stairs to mark the intended position of the centroid. Then the script would be used to overlay the centroid onto the Tracker's cube to align the two staircases properly once a button was pressed in the Unity game. Around this staircase, two environments were created. One of these is an unrealistic forest that was designed to test how to user responds to interacting with the stairs in an environment that would not make sense to have stairs (Figure 2.1). The other is a room that more closely resembles a physical space that one could expect to find a staircase, with added elements to give the room a more realistic feel (Figure 2.2).

In addition to the different environments, two different models were used to represent the subject's body. First was a full body military pilot model shown in Figure 2.3 obtained from as part of the FinalIK Unity asset (RootMotion) which had joints that behaved similarly to true human kinematics based on the motion of the Knuckles controllers and Vive Trackers. Second was a pair of white sneakers that overlaid onto the subject's shoes using solely the Vive Trackers, shown in Figure 2.4. These sneakers along with the built-in models of the Knuckles were the only parts of the body represented in the virtual environment for the feet condition trials. An optional condition was given that did not include either the sneakers or pilot models. Instead, no visual representation of the user was given.

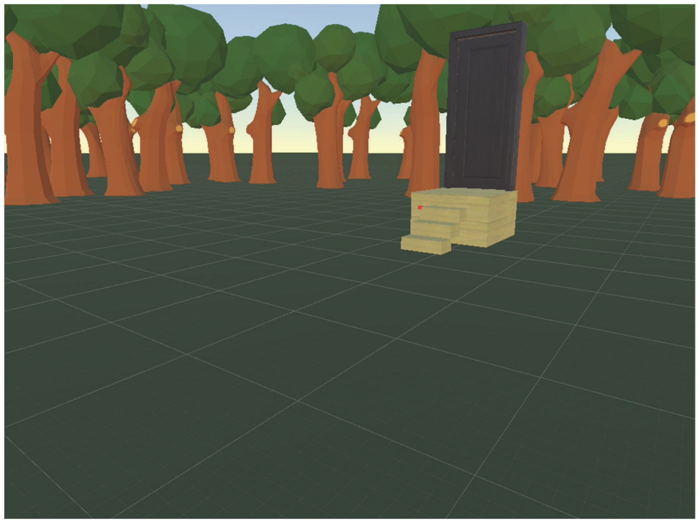

Figure 2.1: Forest environment designed in Unity, with stairs in an open field surrounded by trees

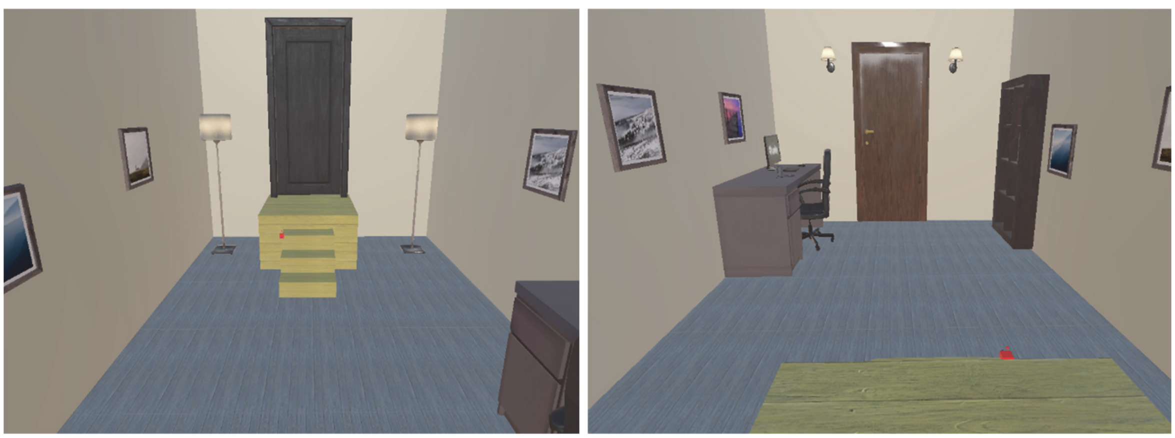

Figure 2.2: Room environment designed in Unity. Left is the view from opposite the staircase, right is the view from the top of the staircase

Figure 2.3: Pilot model designed in Unity for full body conditions

Figure 2.4: Sneaker models in Unity for feet only conditions

CHAPTER THREE

Methods

The Baylor University Internal Review Board (IRB) reviewed and approved this study. One researcher performed all studies with help from assistants to run the computer during data collection. The same researcher completed the consent forms, gave all instructions throughout the data collection session, and applied the motion capture markers to the subject. All collections were performed in the BioMotion Lab at the Baylor Research and Innovation Collaborative (BRIC).

Room Set Up

Prior to the arrival of the subject, a moveable staircase was positioned in the center of the laboratory and bolted down securely. A larger platform was positioned at the top of the stairs for the subjects to turn around on easily after ascending the stairs, seen in Figure 3.1. Markers were placed at the front and back of each step on both sides in order to define where the steps were in relation the global coordinate system. Then a Vive Tracker was placed on the corner of the top stair step in the position circled in red in Figure 3.1. This same position was defined in the Unity program as the centroid of the virtual staircase. When the Tracker was placed on the corner of the real stairs, a button was pressed in the Unity program that automatically set the centroid of the virtual staircase on top of the Tracker's position. If the Tracker was placed in the correct position, then the virtual stairs were quickly properly aligned with the physical staircase. If not, then the Tracker was adjusted, and the button was pressed again to ensure proper alignment.

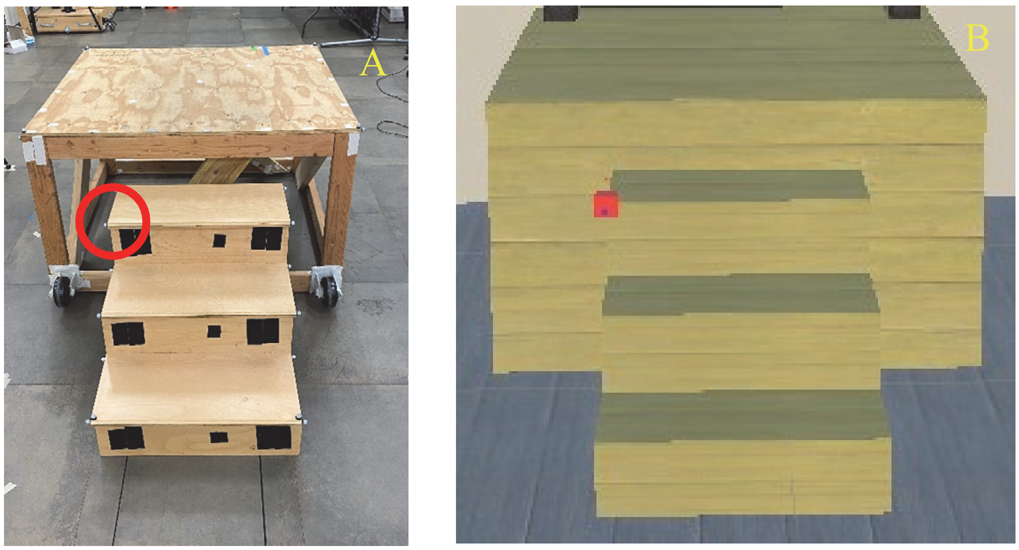

Figure 3.1: A) Real staircase B) Virtual staircase in Unity

Data Collection

The primary system used for data collections was a 14-camera Vicon Vantage optoelectric motion capture system (Vicon Motion Systems, LTD, Oxford, UK). Markers placed on the subject according to the lower-body Plug-in Gate model in Figure 3.2 were used to track the subject's movement along with an additional marker at the edge of each toe. Markers were not labeled if at least two cameras could not track them in a given frame (creating gaps in the data). The system was set to collect at 150 Hz because the VR system had less issues retaining tracking capabilities with this frequency. Before any marker trajectories were output or model angles were calculated, all trajectories were filtered by a Woltring filter used by Vicon to smooth marker trajectories[26].

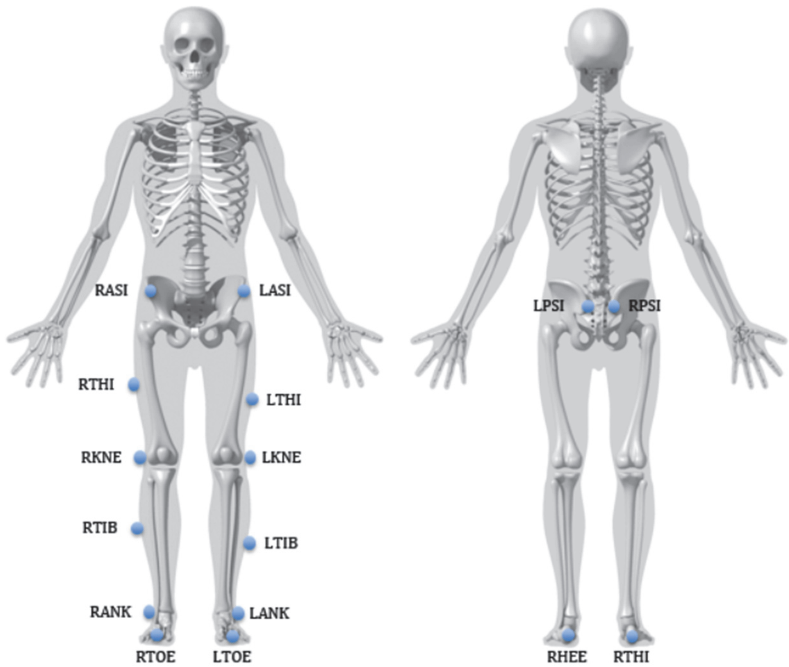

Figure 3.2: Vicon Plug-in Gate lower body model

Set Up of the Valve Index

Before each data collection session, the Valve Index was calibrated using a built-in room-scale setup procedure. For each collection, the base stations were placed approximately 16.5 feet apart and angled down between 30-45 degrees. Two Vive Trackers were used in this study to track the user's feet. In order to securely fix them to the user's shoes, the trackers were placed in the laces of the shoes worn by the user as shown in Figure 3.3. A third Tracker was placed on a TrackBelt (Rebuff Reality) and fixed around the user's waist, as shown in Figure 3.4. The Valve Knuckles controllers were strapped to the subject's hands with the built-in straps that allowed the subjects to open or close their hands however was most comfortable while still tracking their hand position. For all trials involving the subject being in VR, the head-mounted display was worn by the subject. At the start of the first trial in the virtual environment, the user was asked to stand with their toes touching the base of the stairs. Then the virtual model was adjusted to match their foot size and location in the real world using the controls in Unity. The tracker on the subject's waist was used to control the pelvis position of the virtual full body model, so it was also used to calibrate the model's height to correspond to the user.

Figure 3.3: Vive Trackers secured in the laces of the user's shoes

Participants and Recruitment

A total of 11 subjects took part in this study. A summary of the demographics is shown below (Table 3.1). Prior to beginning data collection all participants completed the consent forms. Participants were recruited through word of mouth. The following criteria were used to ensure only healthy adults that could walk up stairs were included in this study:

- Be at least 18 years of age
- Have a BMI under 30
- Be able to maintain moderate, intermittent physical activity for an extended period of time
- Not be pregnant
- Not have any condition or prior injury which would potentially alter normal motion (such as an ACL tear, stroke, lower back injury, neuromuscular disorder, etc.)
- Not experience motion sickness from virtual reality

Figure 3.4: Vive Tracker on subject's lower back

If the subject met all of the above criteria, a date and time was scheduled for the data collection. Two subjects met most of these criteria but had sustained ACL tears previously. However, because it had been at least a year since they had fully recovered from the injury and they were willing participants during the COVID-19 pandemic, they were included in this study.

Table 3.1: Subject Demographics

Categories	Average Age	Sex	Height (cm)	Weight (kg)	Prior VR Use
All subjects (n=11)	25 ± 5	8 M	182 ± 13	79 ± 15	6
RF Leading (n=6)	24 ± 5	4 M	175 ± 5	71 ± 12	3
LF Leading (n=5)	27 ± 6	4 M	190 ± 12	90 ± 12	3

Stair Climbing Conditions

Each subject went through three phases of the experiment in the same order, with the final phase being broken into a series of random sets. First, 10 trials of walking up and down the stairs with no virtual reality was recorded to set a baseline of the subject's kinematics prior to any VR use. Next, 10 trials were performed in VR with the situation most similar to real life, a virtual room with a full body model for the subject to see. This series of trials was to investigate any potential learning effect that the VR system requires while the user becomes more comfortable with it. The virtual room with full body model was chosen because it was viewed as the most similar to reality and therefore the most comfortable for them to begin with. After these trials were complete, 7 conditions were randomized for the final phase:

1. Virtual room with full body model
2. Virtual room with foot and hand models
3. Virtual room with no visible lower body model (optional)
4. Virtual forest with full body model

5. Virtual forest with foot and hand models
6. Virtual forest with no visible lower body model (optional)
7. No virtual reality

The two conditions in virtual reality that did not include any lower body model were optional for the subject due to the potential safety and discomfort concerns about walking upstairs without being able to see foot placement. For the subjects who chose to do these trials, the randomization was controlled so that these would never be the first trials after the learning effect phase to allow for more familiarity with the virtual environments. Additionally, it was controlled that the second round of no virtual reality trials were not randomized to be the first set to allow the subject to have more time in virtual reality before testing any changes in their natural walking behavior.

Each trial type in the third phase was collected 5 times. For each one, the subject would begin at the base of the stairs and stop once they had reached the platform, at which time the data recording was stopped. Then the subject returned to the base of the stairs for the next trial. For safety purposes, a spotter stood near the subject each time they were using VR to catch the subject if they tripped or fell while unable to see the stairs. No such falls occurred.

At the end of each data collection, the subjects were given a survey to assess their prior VR use and how they felt about during the experiment. This survey is available in Appendix A and includes questions about the user's feelings about the comfort and safety of using the VR system while walking up the staircase. The average results are shown in Table 3.2, with a rating of 10 being the subject felt completely safe or comfortable and 1 being not safe or comfortable as all. One of the largest areas of interest from this survey was if the users experienced any dizziness or disorientation in the VR experience. While five subjects did report some disorientation, when asked when this occurred, every subject said it occurred between trials. This occurred because the Unity program that was used to record positional data of each of the components of the VR system would pause when the data collection for that trials was ended, causing a loading screen to appear in place of the virtual environments created. While this pause was initially very short, barely noticeable to the subject, the time would increase over time up to a few seconds, causing the disorientation due to the sudden changing of colors and light in the field of view. Once the change had ended, the subjects said they did not experience any lasting dizziness that continued during the trials.

It can also be seen that overall, the subjects felt safe in all conditions in the virtual environment, with no averages below 8, and felt comfortable wearing all of the equipment needed for the full VR experience.

Table 3.2: Average Survey Responses

Groups	Prior VR Use	Any Dizziness	Safety: Beginning	Safety: Feet Only	Safety: Room	Safety: Forest	Safety: End	Comfort
All subjects	6	5	8 ± 1.4	8 ± 1.0	9 ± 0.9	8 ± 1.5	10 ± 0.6	9 ± 1.1

Data Processing

After all of the trials were completed, the data was processed in Vicon Nexus by first labeling the markers and filling any gaps in the data. Gap filling ensures that all marker trajectory information is complete when the marker was not visible to the Vicon cameras. Typically gap filling was done with a spline or linear interpolation, which use the position of the marker before and after the gap to fill in the missing information. If there are multiple frames in the gap, the spline interpolation may not be available, and so a pattern fill was used. The pattern fill uses other markers on the same segment of the body to fill in gaps, such as filling a missing toe marker using the position of the heel or ankle markers as a reference. Because the pelvis can be treated as a rigid body, a rigid body trajectory fill can be used for these four markers. However, the rigid body fill requires three reference markers to work. If the rigid body fill did not work, a pattern fill was used for the pelvic markers, and a spline fill was used if the pattern fill was also unavailable. Due to the reduced strobe intensity of the Vicon cameras, the number of gaps varied dramatically from person to person. Additionally, due to the positioning of the spotter, some trials had many gaps along the left side of the subject's body. If these gaps were longer than 100 consecutive frames, the trial was excluded from the study. Once all gaps were filled, Vicon Nexus and Matlab (The MathWorks, Inc., Natick, MA) were used together to calculate the necessary joint angles in all planes of motion.

A set of custom Matlab scripts were created to calculated the desired variables based on the collected data. Maximum knee flexion and pelvic tilt were calculated based on the angles data output from Vicon. Toe clearance was defined as the maximum height above the step that the subject's toe marker reached. To find when the subject set their foot on a new step, the vertical toe marker trajectories were used. Whenever the value increased for a period of time, then decreased and settled, the step frame was taken as the first frame in which the change between it and the previous two and following two frames was less than 0.5 mm. This method was used because it provided reliable step-down times without the use of force plates. From these step-down values the cadence was calculated by averaging the time between left toe strikes and right toe strikes. Step width was calculated at these toe step-down times by taking the difference in right and left heel marker location along the width of the staircase. Finally, the percent of foot on step (PFOS) for each subject was calculated using Equation 3.1, the distance between the toe marker and the front of the step divided by the distance between the toe and heel markers. All variables were calculated for whichever leg the subject first put on the stairs then were averaged across trials in the same category. If a subject switched which leg they started with for one trial, that trial was excluded from the data due to differences in values between the different legs.

Statistical Analysis

The interest in this study focuses on the differences in walking behavior in different real world and virtual environment walking conditions. Therefore all statistical analysis was performed on difference of averages for each subject. For example, to find the change in toe clearance for a subject from the first non-VR stair climbing trials to the second non-VR trials, the average toe clearance for both sets was calculated, then the value from the first set was subtracted from the second. This was repeated for all subjects and the mean and standard error of those values were calculated. Additionally the absolute average was calculated using the absolute value of the individual subject means to compare the amount of difference between conditions regardless of direction. A paired t-test with $\alpha = 0.05$ was performed on each difference to determine if there was a significant difference in the mean variable of interest between the two conditions. While a helpful tool for observing trends in the data, it should be noted that the researchers are aware that the data does not satisfy the requirements for proper use of paired t-tests due to the small sample size. This test was simply used as another method of determining significance.

Along with the paired t-test to determine significance, different benchmarks were set for each mean variable difference. Because of the pilot, exploratory nature of this study, no clear benchmarks were available in the literature for significant changes in each of the variables of interest. However, based on previous studies as well as the intuition of the researchers, the following benchmarks were used: 5% difference in PFOS [29], 20 mm in toe clearance [30] and step width [31], 5 degrees for maximum knee flexion [32] and anterior pelvic tilt [33], and 2 steps/min for cadence. These values are based upon similar studies that investigated changes in movement patterns while walking up stairs, but none involved virtual reality and many were clinical studies in which small differences are more significant. Therefore the values in literature were used as a starting point, then the researchers' understanding of the tasks and intuition were used to set the final benchmark values.

CHAPTER FOUR

Results

Variables of interest addressed in this section are toe clearance, percent of foot on step (PFOS), cadence, step width, maximum knee flexion, and maximum anterior pelvic tilt. For toe clearance, PFOS, and knee flexion, all calculations were performed using the data from the lead foot for each subject. The first set of data analyzed is the learning effect trials which were the first 10 virtual reality trials held for every subject. Next comparisons were done between four sets of data: the second non-VR and first non-VR trials (Post- and Pre-VR stairclimbing), virtual environments and the real environment, between virtual environments, and between the same virtual environment with different visual representations of the subject's body.

Learning Effect

In the learning effect trials, subjects were placed in the most realistic virtual environment and tasked with walking up the stairs ten times. Then the results from each of the trial was graphed to determine if any changes occurred as the subject adjusted to the virtual reality system. Figure 4.1 shows the logarithmic trend lines of the subjects' cadence trials, which indicate a slight increase in cadence over time. Notably, most subjects are seen to increase for 6-8 trials before leveling off. This is the only variable that showed significance change for a few subjects, with a maximum increase of 15.7

steps/min by any of the subjects between the first and last trial. In Figure 4.2, the trend lines and data points for two subjects are plotted. From these plots, it can be seen that the actual cadence values do not follow a clean pattern, instead having some random variation between trials. However, the trend line can be shown to be fairly accurate for the subjects with a large variation over time, such as subject 5 (R^2 = 0.6845). For subjects that saw a smaller change over time such as subject 3, the logarithmic trend line does not fit the data as well (R^2 = 0.3367) but it is still better than a linear or exponential trend line.

Step width varied the most of the six variables analyzed between subjects, with some subjects decreasing slightly over time while others increasing (Figure 4.3). However, each subject did appear to become consistent in their step width after 5-6 trials. Percent of foot on step behaved similarly, with all subjects but one changing less than 10%. Pelvic tilt had virtually no change over the course of the trials, with no subject changing by more than 4 degrees. Changes in toe clearance over time leveled out quickly for most subjects. However, one subject started at a very high toe clearance (153.4 mm over the step) and decreased steadily with each trial into the 90 mm range. Because of the large change they made, the curve had not finished leveling off when the learning effect trials ended.

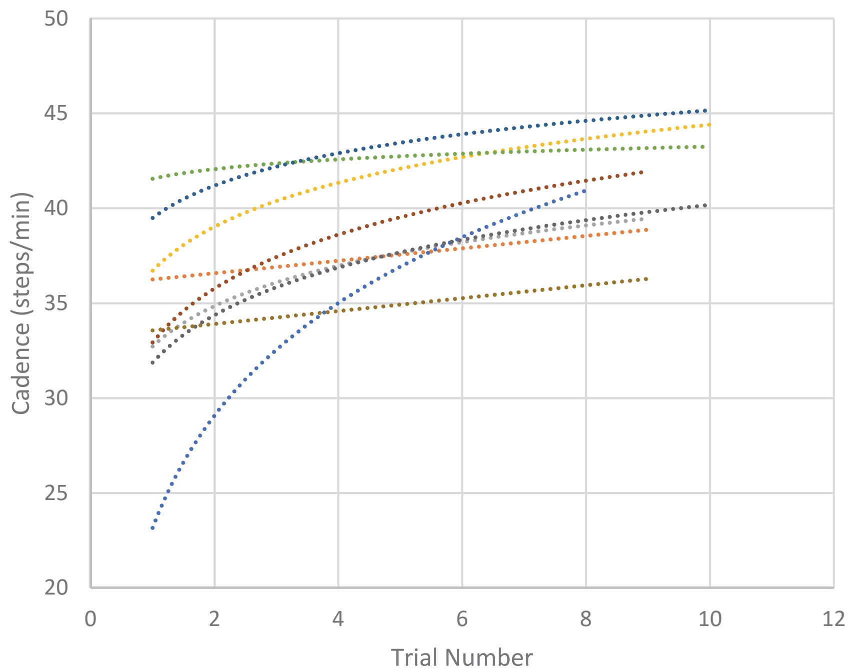

Figure 4.1: Logarithmic trend lines of cadence over time for all subjects in initial reality trials

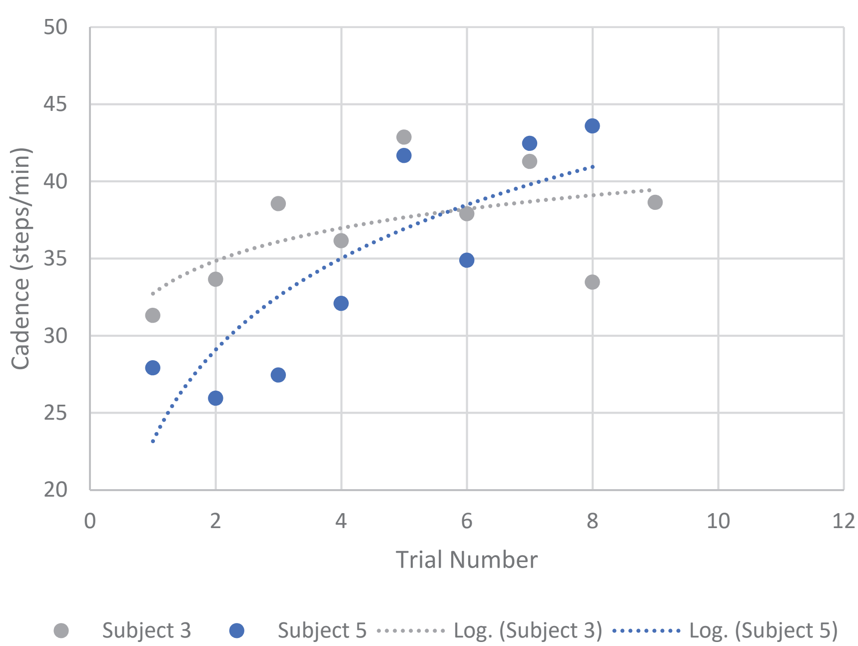

Figure 4.2: Cadence over time for 2 subjects with logarithmic trend lines

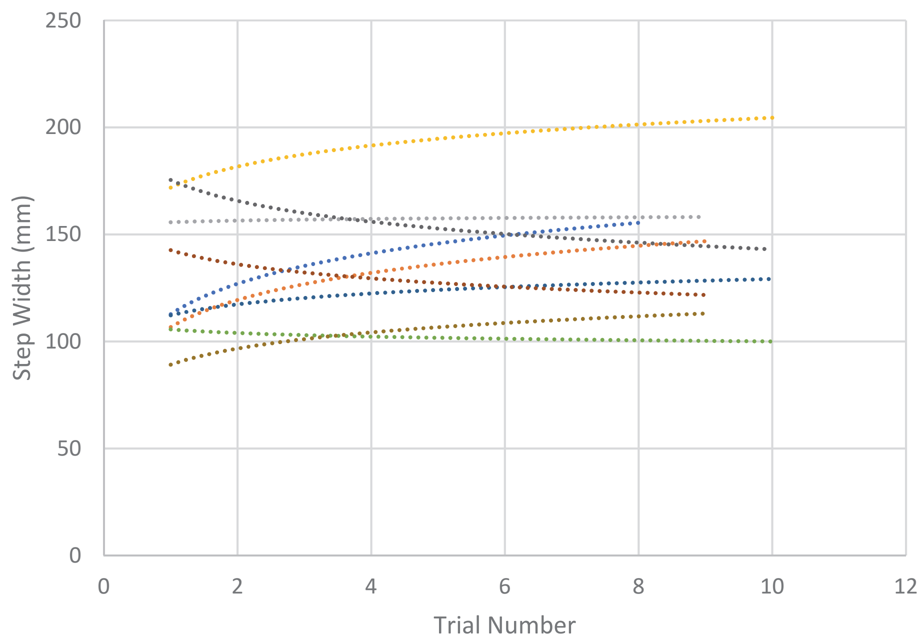

Figure 4.3: Logarithmic trend lines of Step Width over time for all subjects in initial virtual reality trials

Changes from Pre- to Post-VR Trials

In addition to these initial trials, the learning effect of virtual reality on stair climbing mechanics after removing the HMD was tested by comparing the initial non-VR data with the second set of non-VR data that was randomized in the series of trials in the final phase of the experiment. The difference between each of the variables of interest in the Post-VR trials and Pre-VR trials was calculated for each subject and averaged. The average differences across all subjects are shown in figure 4.3. The largest change is in step width, which saw an increase of 6.9 mm with a standard error of 3.4 mm. Though this is the most extreme difference of all of the variables, the p-value is 0.077, which implies the changes are not significant. Because step width ranged from approximately 110-180 mm, a 6.9 mm change is not drastic. Similarly, the subject's PFOS decreased by 5.4 ± 2.9%, the second largest change, but has a p-value of 0.095 which is not significant.

Toe clearance decreased in the post-VR trials by 4.3 mm ± 1.6 mm, which is significant with a p-value of 0.028. This value is small, less than 1 cm, but a notable trend appeared and is shown in figure 4.4. Of the nine subjects that had post-VR trial data collected, seven had decreased toe clearance that ranged from 4 to 13 mm while the two that increased did so only by 1-3 mm. The primary takeaway from this trend is that the people tested were more likely to significantly decrease their toe clearance than increase it much at all.

Table 4.1: Differenced data between post- and pre-VR trials

NoVR2-1	Average	Standard Error	Absolute Average	P-value
TC (mm)	-4.3	1.6	5.2	0.0279
PFOS (%)	-5.4	2.9	6.1	0.0945
Knee Flex (deg)	2.6	1.5	4.7	0.1291
Cadence (steps/min)	4.1	0.7	4.1	0.0004
Step Width (mm)	6.9	3.4	9.2	0.0774
Pelvic Tilt (deg)	-1.3	0.6	1.8	0.0552

Cadence also saw a consistent change, as all nine subjects increased their step frequency by an average of 4.1 ± 0.7 steps/min, both a significant increase and a very low standard error. This is the most dramatic change of all six variables because all subjects behaved similarly. Finally, the changes in knee angle and pelvic tilt were not large, with average differences of 2.6 ± 1.5 degrees and -1.3 ± 0.6 degrees, respectively. Neither change is significant due to large p-values and being less than 5 degrees change with error included [34].

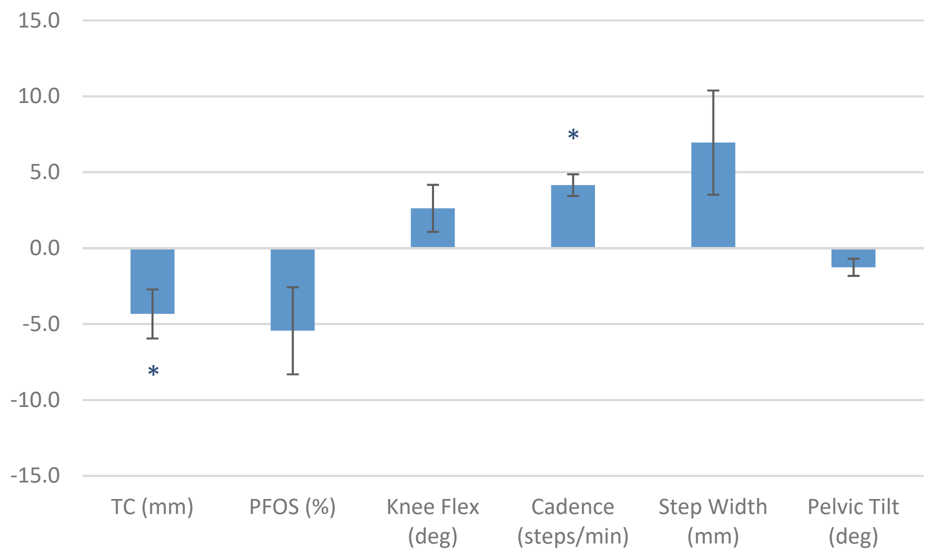

Figure 4.4: Difference in variables of interest between the second non-VR trials and the initial non-VR trials. * indicates significance with $p < 0.05$

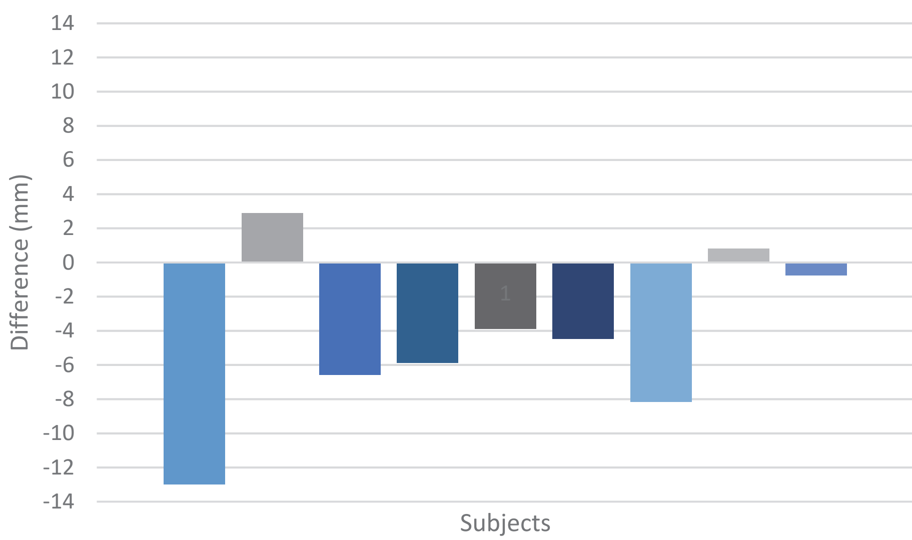

Figure 4.5: Difference in toe clearance between Post-VR and Pre-VR stairclimbing for all subjects

Difference between Real World and Virtual Environment

Similar to the previous set of results, the difference between two sets of virtual reality-based data were compared to the initial non-VR tests. The conditions used for this comparison were the forest with full body representation (FFB) and room with full body representation (RFB). These two were chosen to compare the impact being in virtual reality had on user's motion regardless of environment with the most realistic body representation. The differenced data for both sets is presented in graphically in Figure 4.5 and numerically in Tables 4.2 and 4.3.

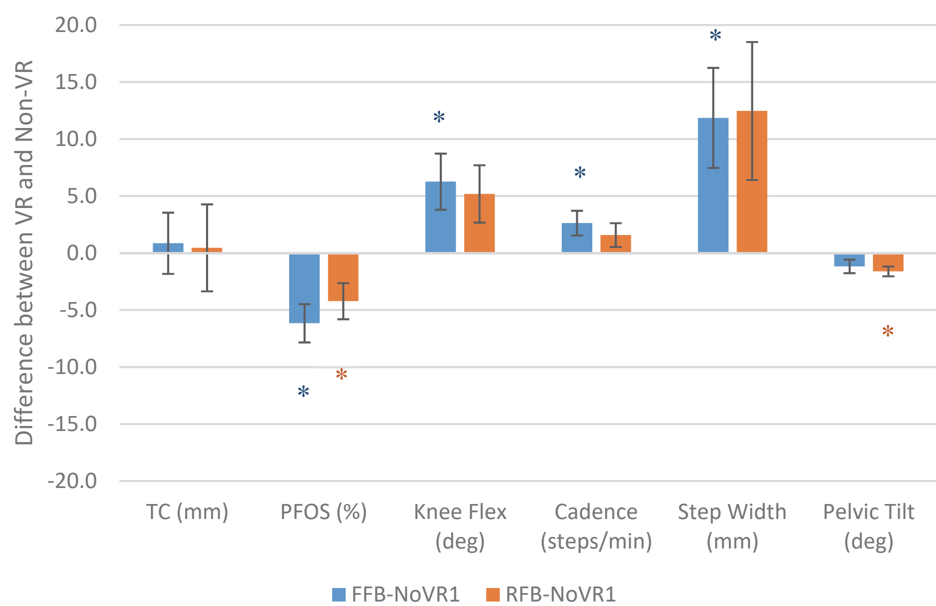

Figure 4.6: Difference in variables of interest between virtual reality trials and non-VR trials. * indicates significance, p<0.05

One common trend shown in this figure is that the difference between VR based and real world based trials is similar in both virtual environments for all variables. The average difference is either positive for both forest and virtual room environments or negative for both, which indicates there is a consistent effect from the virtual reality. The most extreme difference is in step width, which increased by an average of 11.9 ± 4.4 mm in the forest environment and 12.5 ± 6.0 mm in the room environment. The absolute averages were even larger, at 15.1 mm and 18.4 mm, respectively. This indicates that while some people decreased their step width, the vast majority of people increased it in virtual reality. One interesting difference, however, is the p-values for the two scenarios. For the FFB condition, the p-value was 0.024, which is significant. However the RFB p-value was 0.343, which is not significant. This could be attributed to the low sample size and the larger variation in the difference between RFB and non-VR step width. Another area of increase is the maximum knee flexion, which increased by 6.3 ± 2.5 degrees and 5.2 ± 2.5 degrees for the RFB and FFB conditions, respectively. Both of these values are greater than 5 degrees, which is often the benchmark for significant knee flexion changes.

Table 4.2: Differenced data between FFB and initial non-VR trials

FFB-NVR1	Average	Standard Error	Absolute Average	P-value
TC (mm)	0.9	2.7	7.1	0.757
PFOS (%)	-6.2	1.7	6.4	0.005
Knee Flex (deg)	6.3	2.5	7.6	0.032
Cadence (steps/min)	2.6	1.1	3.4	0.039
Step Width (mm)	11.9	4.4	15.1	0.024
Pelvic Tilt (deg)	-1.2	0.6	2.0	0.080

Table 4.3: Differenced data between RFB and initial non-VR trials

RFB-NVR1	Average	Standard Error	Absolute Average	P-value
TC (mm)	0.5	3.8	9.4	0.916
PFOS (%)	-4.2	1.6	5.3	0.026
Knee Flex (deg)	5.2	2.5	6.1	0.070
Cadence (steps/min)	1.6	1.0	2.9	0.167
Step Width (mm)	12.5	6.0	18.4	0.343
Pelvic Tilt (deg)	-1.6	0.4	1.9	0.004

The final variable that showed significant change was PFOS for both conditions. Both the FFB and RFB trials saw a decrease in PFOS when compared to the initial non-

VR trials, with changes of -6.2 ± 1.7% and -4.2 ± 1.6%, respectively. While these values do not appear to be large, when considering that most subjects were already not placing their entire foot on the step, a decrease of between 3-8% of their foot on a step could be significant. The p-values support this idea at 0.0005 and 0.026 for the FFB and RFB trials, respectively, while also implying that the forest environment caused a larger decrease than the virtual room.

From Figure 4.5, it can be seen that the average change in toe clearance is very low for both conditions, less than 1 mm. However, the absolute average difference gives more valuable information, with a change of 7.1 mm in FFB and 9.4 mm in RFB. This indicates that changes in toe clearance occur between virtual environments and the real world, but are not consistent between subjects, which is shown for the RFB trials in Figure 4.6 and FFB in Figure 4.7. One important trend that these two graphs reveal is the consistency of change for most subjects between the two virtual environments. Of the ten subjects, six were consistent in either increasing or decreasing their toe clearance, while the other four switched. The four that switched between environments, however, did not change their toe clearance much from the non-VR trials to either virtual environment, with a maximum change of 12.3 mm in either condition. Compared to the maximum changes for the six who were consistent, 24.6 mm, a clear difference is present between these two groups of subjects. This is a phenomenon that could be studied more closely in future studies.

Both cadence and maximum pelvic tilt did not change much from the real world to virtual world. Cadence increased by 2.6 ± 1.1 steps/min in the FFB condition compared to non-VR and 1.6 ± 1.0 steps/min in the RFB environment. Anterior pelvic tilt decreased by 1.2 ± 0.6 degrees and 1.6 ± 0.4 degrees, respectively. While none of these values are particularly large increases, the change in cadence had a p-value of 0.039 in the FFB environment while the change in pelvic tilt p-value was 0.004, both of which are significant.

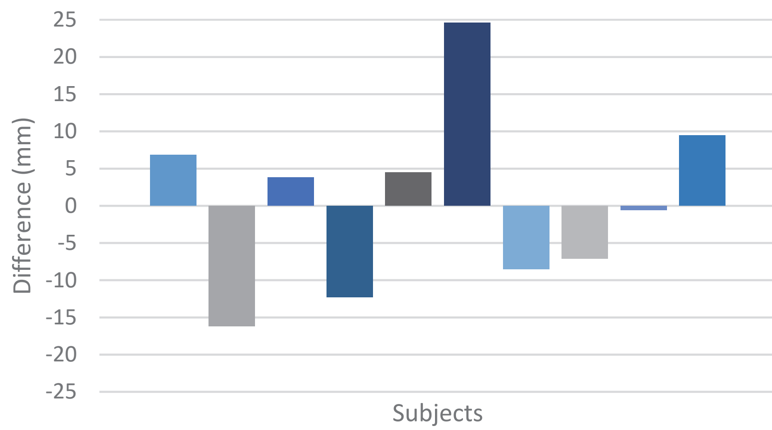

Figure 4.7: Difference in toe clearance between RFB and the initial non-VR trials for all subjects

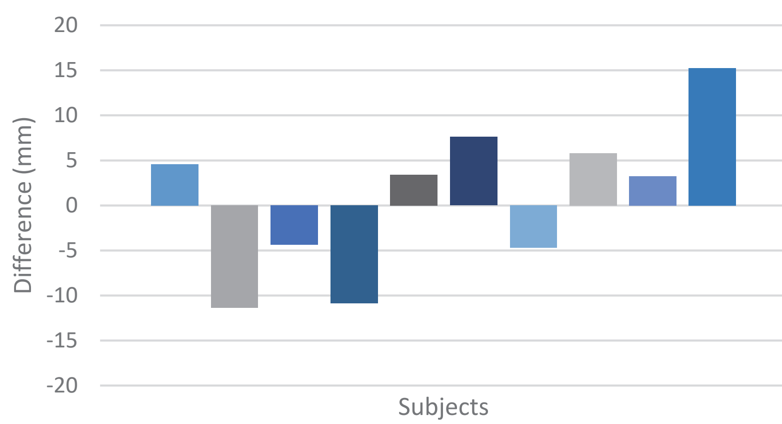

Figure 4.8: Difference in toe clearance between FFB and the initial non-VR trials for all subjects

Overall, the differences in the subjects' movements between virtual reality and the real world were consistent between the virtual environments and some were significantly large differences.

Difference between Virtual Environments

Another comparison that must be made is how different environments impact human motion in virtual reality. This is important because it helps indicate if an unrealistic environment causes significant changes in behavior compared to a more realistic environment that is natural for the activity being perform (stairclimbing in this study). Figure 4.8 shows the difference between each variable in the RFB and FFB environments and RF and FF environments, with Tables 4.4 and 4.5 giving the numeric data. If the value is negative, then then value was larger in the forest environment, while a positive value indicates a larger value in the virtual room.

Table 4.4: Differenced data between virtual room and forest trials with the full body model

RFB-FFB	Average	Standard Error	Absolute Average	P-value
TC (mm)	-0.4	2.6	6.1	0.869
PFOS (%)	1.9	2.1	4.4	0.375
Knee Flex (deg)	-1.1	1.5	3.9	0.500
Cadence (steps/min)	-1.0	1.0	2.6	0.341
Step Width (mm)	0.6	3.1	6.8	0.343
Pelvic Tilt (deg)	-0.4	0.3	0.7	0.155

Table 4.5: Differenced data between virtual room and forest trials with the feet only model

RF-FF	Average	Standard Error	Absolute Average	P-value
TC (mm)	-0.5	1.7	3.7	0.750
PFOS (%)	-1.8	1.5	3.8	0.271
Knee Flex (deg)	-0.2	1.8	3.9	0.905
Cadence (steps/min)	-0.9	1.2	2.7	0.482
Step Width (mm)	-6.1	4.3	11.9	0.190
Pelvic Tilt (deg)	-0.1	0.4	0.8	0.861

Two major differences stand out from this set of data: PFOS and step width. In the full body trials, both of these variables had a positive difference whereas in the just feet trials both variables had a negative difference. This indicates that while the environment had some impact on how the user responded, it was not the only factor. Step width is also the variable that saw the biggest difference in either set of conditions, with a -6.1 ± 4.3 mm difference from RF to FF environments with an absolute average of 11.9 mm. The average difference between RFB and FFB values is much smaller, 0.6 ± 3.1 mm with an absolute average of 6.8 mm. While still small, the absolute average being much greater than the average indicates that change is occurring differently for each subject in the two environments. It should be noted that while the step width values are the largest overall, the average difference is still less than 1 cm and therefore not significantly different.

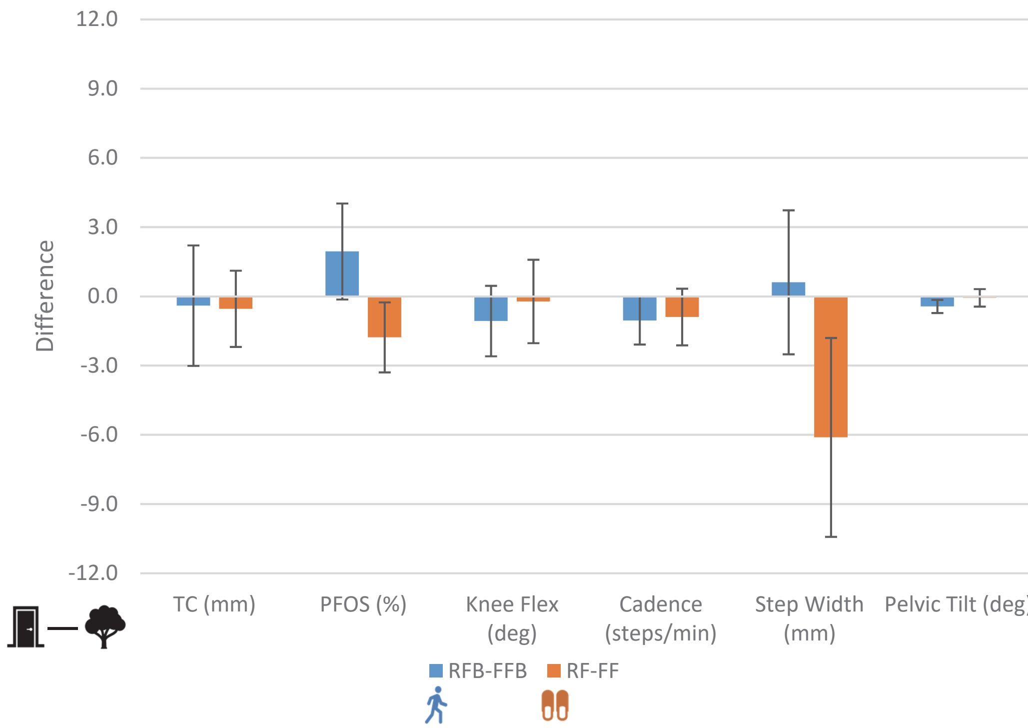

Figure 4.9: Difference in variables of interest between virtual room and forest environments. * indicates $p<0.05$

Similarly, the PFOS is more varied than the other variables in these conditions, but remains small. The difference in PFOS between RFB and FFB trials is 1.9 ± 2.1% and the difference between RF and FF is -1.8 ± 1.5%. These numbers are very similar in magnitude and small, with a range of 0-4% change between the environments. However, the most interesting aspect is the direction of change. Both sets have a magnitude of change around 2%, but the room environment had a larger PFOS in the full body scenario whereas the forest environment was larger in the feet scenario. This again indicates that the environment is not the only factor in a user changing their walking mechanics or that the differences are negligible.

All other comparisons made between the virtual environments show little difference. The difference in toe clearance between the room and forest environments was 0.4 ± 2.6 mm and -0.5 ± 1.7 mm for the full body and feet conditions, respectively. Maximum knee flexion was -1.1 ± 1.5 degrees less for RFB than FFB trials and -0.2 ± 1.8 degrees less for the RF than the FF conditions. Cadence decreased by -1.0 ± 1.0 steps/min. and -0.9 ± 1.2 steps/min., respectively. Maximum anterior pelvic tilt decreased by -0.4 ± 0.3 degrees and -0.1 ± 0.4 degrees for the two environments. These small changes for each variable, with some being very similar between the full body and just feet conditions, show little significant changes between virtual environments. Many of these values contains 0 within its error bounds, supporting the idea that the differences are negligible. Furthermore, all of the p-values for both the full body and feet only conditions were not significant, ranging from 0.155-0.905.

Differences based on Virtual Body Representation

The final comparison is how the visual representation of the subject's body impacted their movements. Differences between the RFB and the RF variables were calculated so that a positive value mean the RFB value is larger while a negative value means the RF value was larger. The same method was used to compare the FFB and FF conditions. These differences are shown in Figure 4.9.

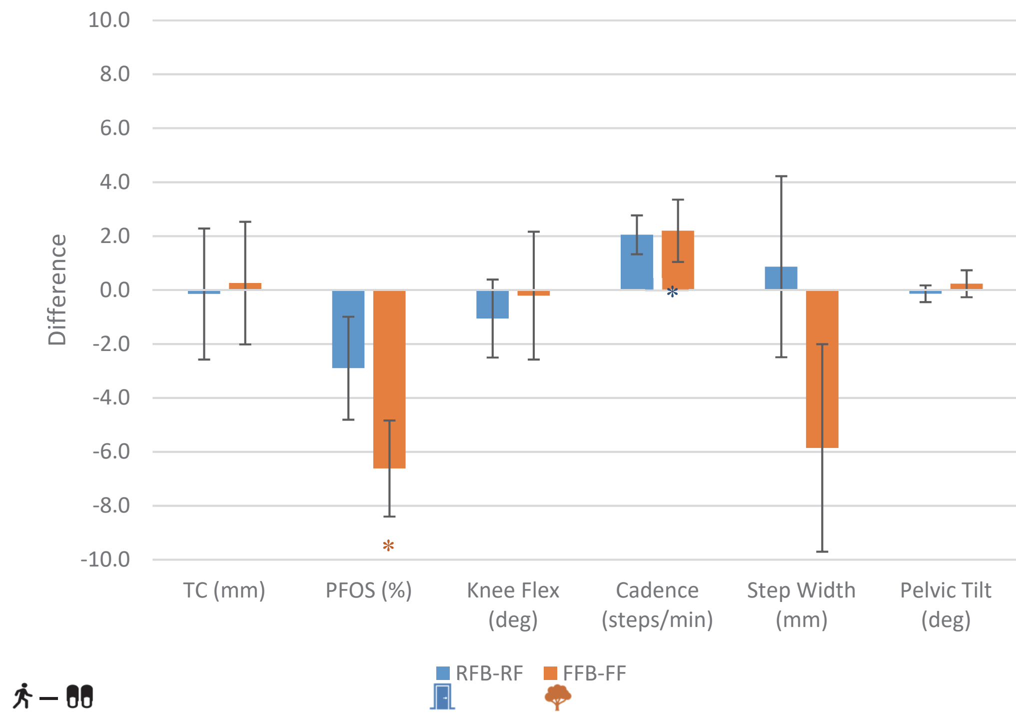

Figure 4.10: Difference in variables of interest between full body and feet only models in the same environment. * indicates p<0.05

As has been seen in other circumstances, the variables with the largest differences are PFOS and step width, primarily for the forest virtual environment. In this environment, the difference in PFOS was -6.6 ± 1.8%, a significantly large percent of a person's foot that resulted in a p-value of 0.005, shown in Table 4.6. The difference in PFOS for the virtual room environment was much lower, at -2.9 ± 1.9% and had an insignificant p-value of 0.163, shown in Table 4.7. Similarly, the average difference in step width in the forest environment is much greater in magnitude than that of the virtual room, and in an opposite direction. The step width difference in the virtual forest was -5.9 ± 3.8 mm and 0.9 ± 4.6 mm in the virtual room. Both of these values have large standard errors, indicating that there is little consistency between subjects. Furthermore, the absolute average difference in step width for the forest and room environments are 9.7

and 8.3 mm, respectively. So, it becomes clear that in both conditions the total amount of variation is consistent, but the direction that subjects changed varied between environments.

Table 4.6: Difference data between full body and just feet models in the virtual forest environment

FFB-FF	Average	Standard Error	Absolute Average	P-value
TC (mm)	0.3	2.3	5.6	0.885
PFOS (%)	-6.6	1.8	6.7	0.005
Knee Flex (deg)	-0.2	2.4	5.4	0.932
Cadence (steps/min)	2.2	1.2	3.5	0.090
Step Width (mm)	-5.9	3.8	9.7	0.162
Pelvic Tilt (deg)	0.2	0.5	1.2	0.651

Table 4.7: Difference data between full body and just feel models in the virtual room environment

RFB-RF	Average	Standard Error	Absolute Average	P-value
TC (mm)	-0.1	2.4	5.5	0.941
PFOS (%)	-2.9	1.9	5.2	0.163
Knee Flex (deg)	-1.1	1.4	3.2	0.483
Cadence (steps/min)	2.0	0.7	2.4	0.019
Step Width (mm)	0.9	3.4	8.3	0.343
Pelvic Tilt (deg)	-0.1	0.3	0.9	0.667

In both environments with the full body model, the subjects had a faster cadence by approximately 2 steps/min when compared to the same environment with just the virtual sneakers as virtual representations of their feet. A slightly larger difference in maximum knee flexion was seen in the room environment, -1.1 ± 1.4 degrees, compared to the forest, -0.2 ± 2.4 degrees, neither of which shows much significance. However, the absolute average difference in knee flexion for the forest environment is 5.4 degrees, much larger and above the 5-degree benchmark that has been used to signify a significant change. This discrepancy between the average and absolute average is caused by a few subjects that had much larger differences (greater than 10 degrees in magnitude), with one such subject in the virtual room trials and three in the forest trials.

Similarly, the average difference in toe clearance is very small for both the virtual room and forest environments, at -0.1 ± 2.4 mm and 0.3 ± 2.3 mm, respectively, but the absolute average is much greater. In the room environment, the absolute average difference is 5.5 mm compared to 5.6 mm in the forest environment. This is again due to some subjects having larger toe clearance differences that are similar in magnitude but in opposite directions that balance each other to make the average close to zero. While this does show there is some variation occurring between the full body and feet only representation trials, the values are small enough that no significant difference is seen, as told by p-values of 0.941 and 0.885 for the room and forest environments, respectively.

Finally, the differences in anterior pelvic tilt are again minimal, with a difference of -0.1 ± 0.3 degrees in the room environment and 0.2 ± 0.5 degrees in the forest. Neither of these changes is significant according to their p-values.

Effect of No Virtual Representation of Feet

As previously mentioned, an optional set of trials was performed on a few subjects in which no visual representation was given of their feet in either virtual environment. For these tasks the only part of their body that was represented were the controllers in their hands. This meant they had to rely entirely on their ability to know where their feet were in space without seeing them. Only three subjects performed this task in both the virtual room and forest environments, therefore not many significant observations can be made. However, it can still be useful to compare how these subjects behaved with no visual feet versus the benchmark full body model, shown in Figure 4.10.

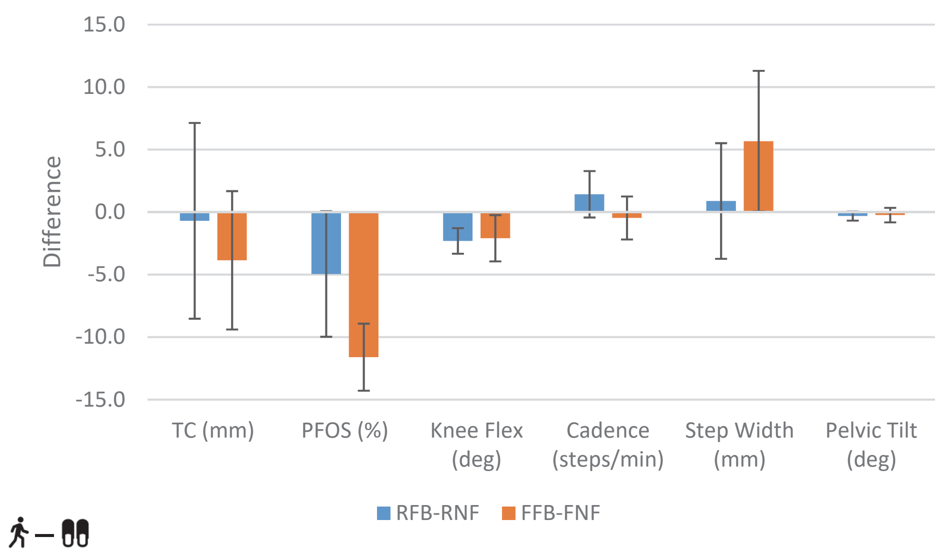

Figure 4.11: Difference data between full body model and no body model in both virtual environments. * indicates p<0.05

The most drastic difference seen is in PFOS, where the subjects had an average decrease of -11.6 ± 2.7% in the forest. The difference in PFOS in the room was much smaller at -5.0 ± 5.0%. Due to the extremely small sample sizes, the standard error for all variables is large, but if both of these values tended towards the higher magnitude end of their error bars, it implies an increase of at least 10% of PFOS without any visible feet.

The only other variable that shows much change in these conditions is the step width, which was greater with the full body model by 5.7 ± 5.6 mm in the virtual forest. While under 1 mm, it still indicates there is some change occurring between the best- and worst -case scenarios of body visualization in virtual reality. The difference between the two environments is also notable, as the forest tended to produce larger differences than the virtual room.

Overall, the no feet condition tests would be greatly benefitted by more data points because they currently have too large of error to be useful in determining any true patterns.

CHAPTER FIVE

Discussion

This thesis investigated the impact that virtual reality has on human lower body kinematics while interacting with a physical staircase. Different virtual environments were designed to test the user's response along with three different methods of representing the user's body in the virtual space.

Aim 0: To Determine the Movement Tracking Capability of Current, Off-the-Shelf Virtual Reality Systems that would be Capable of Implementing VR Training

While not a primary objective of this study, the first step towards making this project a reality was testing the accuracy and precision of the Oculus Rift S. Even though this VR system was not the one used in the final version of the study, it provided valuable information about the tracking capabilities of the current generation of VR systems. Most previous studies investigated the previous generation, such as the Oculus Rift and HTC Vive and found these systems were accurate within a few millimeters in translation and a few degrees in rotation [13],[14],[35]. Because systems in the second generation of modern VR systems such as the Oculus Rift S primarily built on the existing hardware from the first generation, the accuracy and precision should be at least as good. However, the results from this preliminary study found that the Oculus Rift S had a lower accuracy and precision than the HTC Vive. The Rift S' accuracy is likely still acceptable because the error is less than 5 mm in translation and less than 2 degrees rotation, but the slight increase in error from the Vive indicated that the lack of base stations for the Rift S may have introduced more error in positional tracking. Due to this, the second generation VR headset that was more similar to the HTC Vive by utilizing outside-in tracking, the Valve Index, was chosen for this study. It is a hope that the accuracy of this system will be tested in the near future.

Aim 1: Investigate if there is a Difference in Human Movement during a Single, Every-day Task that Requires Full-body Dynamic Engagement when Interacting with a Physical Object in the Real World vs. a Virtual Environment

The primary objective of this study was to determine if there was any difference in human movement while walking up the stairs in virtual reality compared to the real world. This is important because it will help determine if virtual reality is a viable medium for immersive training in fields such as firefighting and police work, and for proper physical therapy. In order to best track these changes, the VR trials in both environments with the full body model were compared to the initial real world stairclimbing trials. Differences for each variable of interest in both the virtual forest and room environments were shown previously in Figure 4.5. One immediate observation is the consistency between different environments. This implies that, regardless of the look of the virtual environment, at least for the environments used in this study, a similar change will occur when a user interacts with a physical object in VR compared to reality. There is a possibility that the environment could have a larger impact if it is more refined than the ones used in this study and more factors such as lighting and shadows are taken in to account. The large increase in step width in the virtual reality trials indicate the need for increased stability in the subjects while climbing the stairs [36]-[37], as expanding their step width provides a wider base of support and ensures their center of mass remains between their feet. An increase in maximum knee flexion was also seen in both virtual environments, which would allow for the subjects to be sure they are clearing the steps before setting their foot down. While toe clearance did not show any significant changes to support this finding, this is likely due to the definition of toe clearance used in this study, which would not account for an increased toe height prior to reaching the step that would result in the subject stepping down on the step earlier than in the real world. Along with the change in knee flexion was a decrease in the percent of their foot that the subjects placed on the step, meaning they were stepping down closer to the edge of the step in VR than in the real world. This value was small but still significant in both environments because a decrease in 5% of their PFOS can have serious impacts in how much people can rest on the steps without increasing their risk of falling.

Taking these three changes together, it appears that most subjects were attempting to be more cautious in the VR trials than the real world by spending less time with their feet off of the stairs. This is further supported by the slight increase in cadence in both virtual environments that results from the decrease in PFOS. By placing their foot down on the step sooner, subjects were able to increase speed overall despite the wider steps. This does present a risk in doing similar virtual studies if the subjects do in fact change their walking behavior. However, the differences are relatively small and no subject felt unsafe or uncomfortable during the virtual trials, so it is worth investigating more to determine if there is a severe enough change in mechanics to prevent the use of VR in this way, or if the changes are small enough as to not have any impact, as is hypothesized here. Furthermore, these small differences would likely not be impactful in a training simulation scenario in which the primary goal is to allow the user to train in an environment rather than precisely track their movements and any changes seen. The area of greater risk would be in a clinical setting, in which using the virtual stairs as a quantitative assessment of changes to natural stair climbing motions may not be able to detect small changes in motion due to the influence of the VR on the subjects.

One unexpected result was a lack of change in average vertical toe clearance between the virtual and real worlds. The likely cause of this is that there was change, but not consistent increases or decreases across subjects, as shown previously in Figures 4.5 and 4.6. As a result, the average difference is near zero despite changes. However, the absolute average difference is less than 1 cm, indicating that while there may be some change, it is not enough to substantially affect the subject's movement. Another potential reason for this lack of difference is due to how toe clearance was calculated for this study. While some studies choose to calculate it as the maximum distance from the front of the step to the subject's toe in both the anterior and vertical directions [38], this study focused solely on the vertical height between the toe and stair step at the moment the toe cleared the front of the step [39]. If the subject had their toe higher prior to reaching the step, then stepped down closer to the edge of the step as is often seen in the results, this increase in toe height prior to clearing the step would not be seen. Investigating a broader definition of toe clearance could provide insightful information beyond what was found in this study.

Aim 2: Investigate the Learning Behavior of Virtual Reality Users over Time

With the adoption of any new technology or method, it is expected that there will be an adjustment period as people learn how to interact with the system. The same is expected of using virtual reality [40],[41], especially when doing something as novel as interacting with a physical object in a virtual environment.

Initial Learning Effect

To attempt to see this learning effect, a series of 10 stairclimbing trials were performed as the first VR trials and the variables of interest were calculated. The logarithmic trend line for each subject in step width and cadence were previously displayed in Figure 4.1 and 4.2, respectively. Both graphs show a clear change in the first 5-8 trials compared to the last few. In the step width trials, each subject had a different direction of change, either starting wide and narrowing their step over time, or starting narrow and widening their step. Four of the subjects appear to reach a consistent step width after just 4 trials and five others appear to become more consistent after 8 trials. One subject continued to increase step width through all 10 trials, indicating that not all people can fully adjust in 10 trials.

Unlike step width, the cadence learning curve is very consistent across all subjects. Some increase more than others but all appear to reach a consistent cadence around 8-9 trials into the study. This is encouraging because it implies that having the subject perform 10 stairclimbing trials prior to beginning the main portion of the study likely reduced the variation and error present due to subjects learning the system for the first time. All other variables either show similar trends, changing in the first few trials then leveling off, or changes very little over time for all subjects (pelvic tilt).

How Post-VR Movement compared to Pre-VR Movement in the Real World

Another important area of learning effect that must be considered is how human movement is impacted in the real world after using a VR system. To examine this potential change, the difference in all variables was calculated between the second and first non-VR trials, shown previously in Figure 4.3. Similar to the comparison between

VR and non-VR trials, the largest difference is in step width, which increases in the second non-VR trials. This increase is less than that of the VR trials, but four of the nine subjects included in this section increased by at least 15 mm. While still less than the 2 cm benchmark set and not quite significant, it still shows a notable change between experiences outside of VR. The PFOS of subjects also decreased in the second non-VR trials like it did in the VR environments, with large significant decrease from the first set of trials. Changes in these two variables imply that there is some left over effect from the VR experience after the user is removed from it. This could be a concern for clinicians or trainers as they attempt to use VR to treat/teach a patient but alter their mechanics at least for a short time.

One major difference between the post-VR trials and the VR trials is the change in toe clearance from the initial non-VR trials. In the virtual environments, subjects changed their toe clearance in seemingly random fashion, with some changing drastically while other didn't, some increasing while others decreased. In the post-VR trials, however, seven of the nine subjects decreased their toe clearance by at least 4 mm, while the only two that increased doing so by less than 3 mm. This overall trend towards decreasing toe clearance is likely due to the subjects becoming more confident with their stair climbing ability once they are able to see the stairs and their feet again after relying on a virtual representation of both for at least five trials. Again, this leads towards the idea that while there is a learning effect when beginning VR use, there is also some lingering impact on human motion after they are removed from the virtual environment.

Aim 3: Investigate if the Look of a Virtual Environment Influences the User's Perception and Movement

While it has been seen that there are slight changes in human movement when interacting with a physical object in VR compared to interacting with the same object in the real world, the impact that the appearance of the virtual environment still needs to be investigated. For this section of the study, the impact of the room and of the visual representation of the subject's body were investigated separately.

Investigating if the Look of a Virtual Environment being Realistic Influences User's Perception and Movement

Figure 4.8 illustrates the difference between the virtual room and forest environments for both the full body and feet only virtual models. From these results, it is clear that few variables see a clear difference. The largest difference is in step width, with a slightly smaller width in the virtual room than the forest. However, the difference is less than 2 cm, which is not a significant difference. Overall, very little difference was observed between the two environments. No variable has a difference of more than 3 units in magnitude for either set of virtual body models besides the change in step width. This is an interesting result based on some comments made by the subjects, who felt more comfortable overall in the virtual room due to the textures on the floor compared to the forest's matte, depthless appearance. In addition, according to the survey given to the subject at the end of each session, the average subject felt slightly safer in the virtual room compared to the forest, at 9/10 and 8/10, respectively. These values are not very different, and both indicate that subjects felt safe in the VR space in general, but it was expected that some difference would be seen in the movement between these two environments.

Investigating if the Look of a Virtual Body Model Influences User's Perception and Movement

Unlike the comparison between environments, the comparison between virtual models used to portray to user's body in VR displays some significant differences. For the forest condition, changes in PFOS has the most significant difference. With the full body model, the subjects had much less of their foot on the step than with the feet only model. This is likely due to the subject being more confident in their ability to know where their body is in space in relation to the stairs when they are able to see some representation of their full body, rather than just their feet, leading to them needing less of their foot on the step to feel stable while walking. Additionally, the step width is also much lower for full body model trials in the forest than the feet only model trials, with only one subject showing a larger step width with the full body model. This further supports the need for more stability with just the feet models that was indicated by the difference in PFOS. The difference is not as severe in the room environment, but the majority of subjects still had narrower steps with the full body model.

While the differences are small, the difference in cadence in both environments is shown to be significant with the paired t-test and both are greater with the full body model. This correlates well with the decreased need for stability with the full body model because they were able to move faster by not setting their feet down as securely on the steps and keeping a narrow step. Therefore, while the difference is not large, the difference reflects the different walking patterns of a person with the two different models.

As with many other conditions, there is very little difference in average pelvic tilt, toe clearance, and maximum knee flexion. However, some of these have large individual differences that should be investigated. Three subjects showed large differences in knee flexion in both environments upwards of 10 degrees, which is a very significant difference. While the overall subject group did not have large differences, these three subjects show that some people will respond more extremely than others and should be accounted for in future uses of VR. Such a large difference in knee angle also suggests that one of these models is better than the other.

When comparing these two models, it becomes apparent that there is a significant difference in how the subjects walk with each one. This is likely due in general to the amount of information the subject has to work with to understand their physical location in the virtual world. With only feet models, the subjects have to rely more on their understanding of where their legs and upper body are in space in relation to their feet then any visual cues. This makes people more uncertain about how to best step forward and therefore more careful when climbing up the stairs than they are in the real world. By giving these subjects a full virtual body which approximates the locations of their body parts, they are more comfortable in interacting with a physical object in the virtual world. Therefore, the better model of the two is likely the full body model because it gives them more information to navigate through the virtual environment.

Result's Impact on Virtual Reality Training and Rehabilitation

The results presented hold significance for the future of virtual reality use in both training and physical rehabilitation applications. The small amount of variation between how humans interacted with the staircase gives hope to the possibility of using such techniques in these areas.

Impacts on the Future of Virtual Training

Many of the current virtual reality training regimens rely on a 3rd person, non-immersive setups that allow the user to see the events they are being trained for, but not to react physically in response. Instead, the trainees use a controller while stationary to maneuver their character to respond to actions in the simulation [15],[35]. However, these types of trainings could prove more effective if the user is able to physically interact with some of the objects they are supposed to be using, whether it be a fire hose, replica gun, or climbing steps. By interacting with these important objects, the trainee would have a better sense of how they are supposed to respond physically as well as mentally without the need for an entire training site. While there is some indication that changes occur in the user's movement patterns, the changes are small enough that it would not necessarily outweigh the cost of either not having an immersive training exercise or not needing a full facility to host traditional trainings.

Impacts on the Future of Physical Rehabilitation

Potential impacts to physical therapy based on this work are more uncertain than in the field of virtual training. Because there is evidence that virtual reality can change a user's movement while interacting with a physical object, clinicians and therapists should be hesitant to proceed with any treatment of this type until further research is done. If the desire for this type of therapy does increase, the virtual environment should be as detailed as possible, such as the virtual room with the full body model used in this study. Having more details both in the room and representing the user's body appeared to decrease the amount of change seen while using the VR system.

If clinics do begin to use this type of set-up, it opens new possibilities in how they may approach some physical therapy. In some stroke rehabilitation studies, patients have been asked to walk on a treadmill and respond to virtual obstacles that they see, but are not actually present [18]. This could be improved upon by introducing physical objects for these patients to step over or off of at certain points in the experiment so that they are able to experience hitting the obstacle if they do not lift their leg high enough or changing elevation if they are stepping off of an object. These types of improvement could greatly change the way physical rehabilitation is performed. Additionally, by introducing virtual reality in general there is a gamification of the therapy that can make patients more likely to follow the treatment protocol than they would with regular treatments. Combining these two factors could make virtual reality with physical objects an effective method of performing physical therapy.

Limitations

As with any study, there were multiple limitations in this study that could be improved upon. While the experiment was performed under the best conditions available in the Baylor Biomotion Lab, there were a few limitations that could be improved upon in future studies.

Interference

As was mentioned previously in chapter 2, there were many issues with the Vicon motion capture cameras emitting infrared light at a similar frequency as the SteamVR base stations. This created an issue of balance that had to be achieved; the maximum amount of IR that could be emitted from the Vicon cameras without restricting the ability of the base stations to track the Vive Trackers had to be found. While it was discovered that decreasing the strobe intensity to 14% avoided the interference issue the majority of the time, it caused issues in the ability of the motion capture system to accurately track the passive markers placed on the subjects. With only 14% of their maximum potential, gaps in the motion capture data were more frequent than in most studies. While these could be filled using the methods detailed previously, the ability to fill gaps depended on the quality of the data on either side of the gap in the individual trials. If the data was too inconsistent, it had to be removed from the subject's dataset, reducing the effectiveness of the experiment.

Another area of interference that should be avoided in future studies was the positioning of the spotter that walked alongside each subject as they walked up the stairs. While it was important to have this spotter, their positioning was often close to at least one motion capture camera's center field of view due to the need to be near the subject. This crated another form of interference, albeit a more avoidable one. To best avoid this in the future, more cameras should be focused around where the spotter could be to make up for their presence blocking the view of some cameras, or the spotter should be made to purposefully avoid the cameras' fields of view.

Lack of Subjects

Due to the pilot nature of this study, having ten subjects worth of data was satisfactory to investigate initial trends and prove the feasibility of incorporating physical objects into a virtual reality experiment. However, increasing this sample size for future studies would give a broader picture into how people respond in the VR environment and could account for responders better.

Technical Limitations

While the positional and rotational data from the Valve Index was not reported in this thesis, it was collected during each trial for the two Knuckles controllers, HMD, and two Vive Trackers placed on the subjects' feet. This was done with a custom Python script that extracted the data from SteamVR through Unity then saved each component's position and rotation in separate .csv files. While this could provide valuable data for future use, the amount of files it created caused the program to slow down over time during each data collection session. Additionally, when the stop recording button was pressed in the Unity game and the files were created, the game would pause and go to a black loading screen in the HMD. At first this was not an issue but as the number of trials completed increased, the length of this pause also increased. By the end of the session it would often be up to 3-4 seconds. Besides slowing down the progress of the collection, this pausing caused issues by making many subjects momentarily dizzy due to the rapidly changing colors and brightness in the HMD screens. This dizziness occurred only between trials and no subjects needed a break from the system due to feeling dizzy. If not for this issue, no subjects reported they experienced any issues with motion sickness caused by using VR. However, it is difficult to know for certain if their dizziness or motion sickness solely came from this pause without testing how they felt with and without the pause, which was beyond the scope of this study.

Future Work

Based on the work of this thesis, there is great promise in using VR with physical objects. However, there are still a few concerns that remain about potential impacts on human motion based on the findings of this study. To address these, a similar experiment should be conducted with a larger sample size to help provide better clarity into how people movement changes.

Testing Human Interaction with Other Physical Objects in Virtual Environments

While the stair climbing study is an important first step, as there are no other studies similar to it in current literature, it represents only one activity that people perform on a daily basis. Expanding on this idea into other potential activities is a crucial next step to determining if using VR with physical objects is an appropriate method of performing training or physical therapy. Some examples of other activities that could be tested would be descending stairs, stepping over an object, and getting up from a chair. These would all test different movements involving the lower body and expand the knowledge of how the body responds to a virtual environment.

Another area that should be addressed is how upper body motion changes in virtual reality with a physical object. This could be accomplished by moving items between shelves, which is in the process of being tested by Arlati et. al. [20], throwing an object, or simply picking up an object. Any of these experiments would contribute to better understanding how the full body responds in VR instead of just the lower body. A task that uses both the upper and lower body would be ideal to see how one subject performs overall, rather than having separate sets of subjects for each part of the body.

Virtual Models

Based on the results of this thesis, it is clear that having an accurate full body model of the user in VR creates a less drastic change in the user's movement. The model that was used in this study could be improved upon though, in two different ways:

appearance and accuracy. By creating a few different models that represent male and female users of different skin tones, the user would be able to imagine it is their body more easily compared to the generic military pilot used in this study. Changing the model to match the user may create a smaller difference in movement between the virtual and real worlds.

A method of improving the accuracy of the model would be to strap additional Vive Trackers to the user's legs, one on each thigh and calf. By doing this, along with the Trackers already present on the waist and feet, a model that bends according to how the subject moves could be improved substantially. In the model used in this study, all joint motion was determined by estimated the ankle and knee angles based solely on the waist and feet trackers which can introduce errors. Fixing this issue could create a more comfortable environment for the users and make their change in movements less severe. Another method of addressing any issues with the accuracy of the model would be to remove potential interference from the motion capture cameras by only using the VR system to record the motion of the user. While this was mostly accounted for in the set-up of this experiment, eliminating the risk altogether may increase the accuracy even further.

Significance

This study quantitatively analyzed the changes in human movement during a single every-day task performed in virtual reality when compared to the same task performed in the real world. For clinical use, this study showed that there is not much significant change in step motion between the virtual and real world trials, meaning that it could be possible to utilize VR in physical therapy to enhance existing methods. Similarly, training programs could attempt to implement VR to improve the effectiveness of their program using 1st

person, immersive VR experiences with physical interactions based on the information about the small changes in human motion presented here.

APPENDICES

APPENDIX A

Survey

Investigating the Impact of Interacting with Real World Objects in Virtual Environments
Survey:

1. Have you ever used a virtual reality system in the past?

2. Did you experience any dizziness or nausea while wearing the virtual reality headset?

3. On a scale of 1-10, with 1 being not very safe and 10 being completely safe, how safe did you feel when walking up the stairs while wearing the virtual reality helmet at the beginning of the experiment?

   With just the feet?

   In the room environment?

   In the forest environment?

   At the end of the experiment?

4. On a scale of 1-10, with 1 being not comfortable at all and 10 being completely comfortable, how comfortable did you feel wearing the virtual reality setup, including the headset, controllers, and feet and hip trackers?

APPENDIX B

Consent Form

Baylor University

Mechanical Engineering Department

Consent Form for Research

PROTOCOL TITLE:	**Investigating the Impact of Interacting with Real World Objects in Virtual Environments**
PRINCIPAL INVESTIGATOR:	Jonathan Rylander, Ph.D.
SUPPORTED BY:	**Baylor University**

Invitation to be Part of a Research Study

You are invited to be part of a research study. This consent form will help you choose whether or not to participate in the study. Feel free to ask if anything is not clear in this consent form.

Important Information about this Research Study

Things you should know:

- The purpose of the study is to compare how people move in normal, everyday tasks to performing tasks in virtual reality.
- In order to participate, you must:
  - Be at least 18 years of age
  - Have a BMI under 30
  - Be able to maintain moderate, intermittent physical activity for an extended period of time
  - Not be pregnant
  - Not have any condition or prior injury which would potentially alter normal motion (such as an ACL tear, stroke, lower back injury, neuromuscular disorder, etc.)
  - Not experience motion sickness from virtual reality
- If you choose to participate, you will be asked to perform ordinary tasks such as stair climbing and object avoidance while using the HTC Vive, as well as perform these

actions normally. During both parts, motion capture will be used to evaluate your movement. These activities will take place at Baylor University's Biomotion Lab located at the Baylor Research and Innovation Collaborative (BRIC). This will take 2 to 3 hours.

- Risks or discomforts from this research include possibly experiencing motion sickness from using the virtual reality headset and tripping if experiencing disorientation.
- There is no direct benefit for participating in this study.
- Taking part in this research study is voluntary. You do not have to participate, and you can stop at any time.

More detailed information may be described later in this form. Please take time to read this entire form and ask questions before deciding whether to take part in this research study.

Why is this study being done?

The purpose of this study is to compare performance of people when completing tasks in a virtual reality environment and completing ordinary tasks. Additionally, we will monitor how people adjust to a virtual environment.

What will happen if I take part in this research study?

If you agree to take part in this study, you will be asked to complete a single visit that will follow a procedure and take at most three hours. You will be asked to perform ordinary tasks such as stair climbing and object avoidance while using the HTC Vive, as well as perform these actions normally. During both parts, motion capture will be used to evaluate your movement.

During the study visit, you will be asked to do the following procedures:

- A motion capture session, which consists of having reflective markers placed on your body
    - During this, you will perform typical tasks such as walking and stair climbing normally.
    - You will play VR games before performing tasks in VR to acclimate to a virtual environment.
    - You will perform the same tasks in a virtual environment.
- During any task which combines a virtual environment with a real world object, a spotter will follow you to attempt to prevent you from falling.

Motion Capture: You will be in minimal clothing (males: short shorts, females: short shorts and a sports bra). A researcher will then place reflective markers on your body according to their procedure. Once all of the markers are placed, then the researchers will talk you through the different activities you are to complete. Your motions will be tracked and the data will be collected by our motion capture system. The reflective markers will then be removed.
We would like to make a video recording and take photographs of you during this study so that marker movement data collected via the motion capture system can be compared to visual data. Video recording and photography are both optional for this study. They are separate in that if you consent to one you do not have to consent to the other. Additionally, if you do not want to be recorded, you can still be a part of the study. There are three sets of cameras, one for the motion capture (which records the motion of the reflective markers only), one for video

recording, and one for EMG tracking. Thus, the video recordings do not have to be saved and stored for data analysis to occur. Having the video to compare allows us to better understand the data, especially in the cases of abnormalities, but you will be in minimal clothing and are free to opt out of being video recorded. You will indicate your decision concerning both at the end of this form.

How long will I be in this study and how many people will be in the study?

Participation in this study will last 2 to 3 hours. About 40 of subjects will take part in this research study.

What are the risks of taking part in this research study?

There are some risks you might experience from being in this study. They are:

- Experiencing motion sickness from virtual reality
- Not adjusting properly to the virtual environment, potentially causing you to trip and fall
    - A spotter will spot you whenever you are in a virtual environment interacting with real world object
- Becoming tired while doing the motions, or your muscles may get tired or sore
- Mild discomfort from removal of the motion capture markers, similar to removing a band-aid

You can stop or rest at any time, especially if you are feeling nausea, pain, or discomfort.

Are there any benefits from being in this research study?

Although you will not directly benefit from being in this study, others might benefit because this research may help develop a greater understanding of interactions with virtual reality.

How Will You Protect my Information?

A risk of taking part in this study is the possibility of a loss of confidentiality. Loss of confidentiality includes having your personal information shared with someone who is not on the study team and was not supposed to see or know about your information. The researcher plans to protect your confidentiality.
We will keep the records of this study confidential by only using de-identified information away from the secure collection computer. We will make every effort to keep your records confidential. However, there are times when federal or state law requires the disclosure of your records.

The following people or groups may review your study records for purposes such as quality control or safety:

- Representatives of Baylor University and the BU Institutional Review Board
- Federal and state agencies that oversee or review research (such as the HHS Office of Human Research Protection or the Food and Drug Administration)

The results of this study may also be used for teaching, publications, or presentations at professional meetings. If your individual results are discussed, your identity will be protected by using a code number or pseudonym rather than your name or other identifying information.

Will information you collect about me be used for future research studies?

Information collected from you as part of this research may be shared with the research community at large to advance science and health. We will remove or code any personal information that could identify you before the information are shared with other researchers to ensure that, by current scientific standards and known methods, no one will be able to identify you from what is shared.

What happens if I am hurt by participating in this research study?

If you become ill or injured as a result of your participation in the study, you should seek medical treatment from your doctor or treatment center of choice. You should promptly tell the researcher about any illness or injury.

There are no plans for Baylor University to pay you or give you other compensation for your injury or illness. You do not give up any of your legal rights to seek compensation by signing this form.

Your Participation in this Study is Voluntary

Taking part in this study is your choice. You are free not to take part or to withdraw at any time for any reason. No matter what you decide, there will be no penalty or loss of benefit to which you are entitled. If you decide to withdraw from this study, the information that you have already provided will be kept confidential. You cannot withdraw information collected prior to your withdrawal.

If you are a Baylor student or faculty/staff member, you may choose not to be in the study or to stop being in the study before it is over at any time. This will not affect your grades or job status at Baylor University. You will not be offered or receive any special consideration if you take part in this research study.

Contact Information for the Study Team and Questions about the Research

If you have any questions about this research, you may contact:
Jonathan Rylander
Phone: (254) 710-4193
Email: jonathan_rylander@baylor.edu

Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the following:

Baylor University Institutional Review Board
Office of Research Compliance
Phone: 254-710-3708
Email: irb@baylor.edu

Your Consent

SIGNATURE OF SUBJECT:

By signing this document, you are agreeing to be in this study. We will give you a copy of this document for your records. We will keep a copy with the study records. If you have any questions about the study after you sign this document, you can contact the study team using the information provided above.

I understand what the study is about and my questions so far have been answered. I agree to take part in this study.

_______________________________________ _____________________

Signature of Subject Date

Optional

Consent to be video recorded
I agree to be video recorded.

YES_________ NO_________ Initials ________

Consent to be photographed
I agree to be photographed for this study.

YES_________ NO_________ Initials ________

Consent to be Contacted for Participation in Future Research
I give the researchers permission to keep my contact information and to contact me for future research projects.

YES_________ NO_________ Initials ________

APPENDIX C

Learning Effect Plots

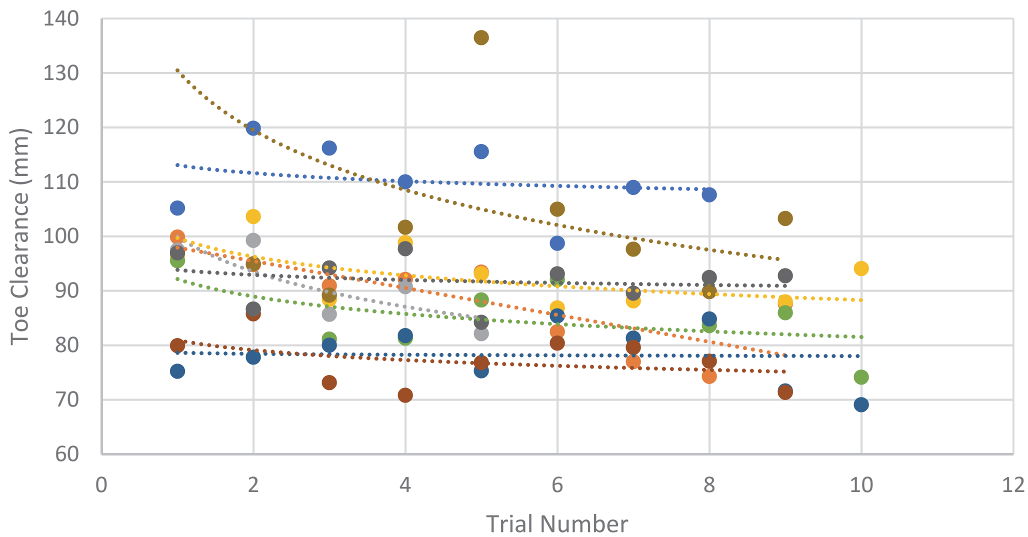

Figure C.1: Toe clearance over time during the learning effect trials with logarithmic trend lines

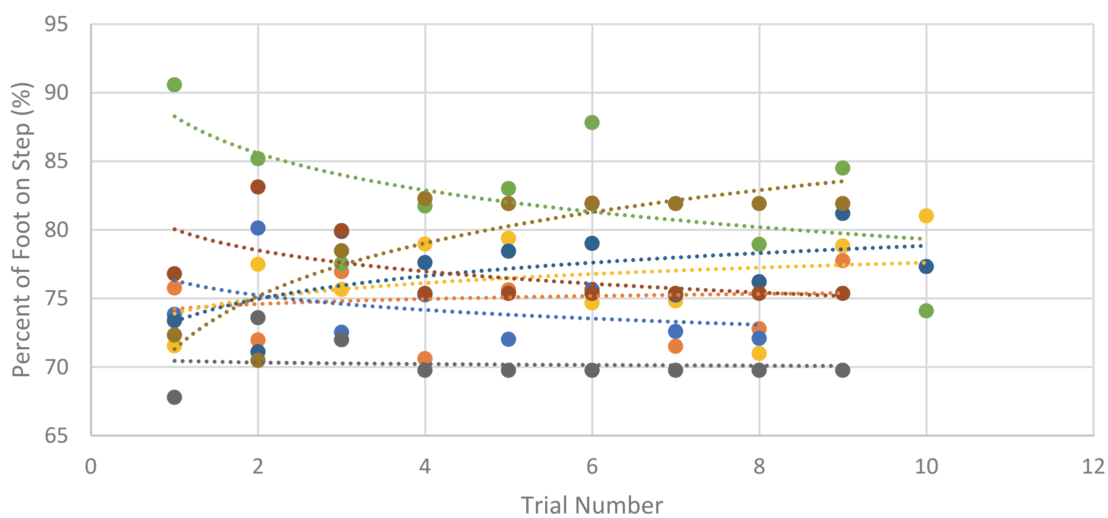

Figure C.2: PFOS over time during the learning effect trials with logarithmic trend lines

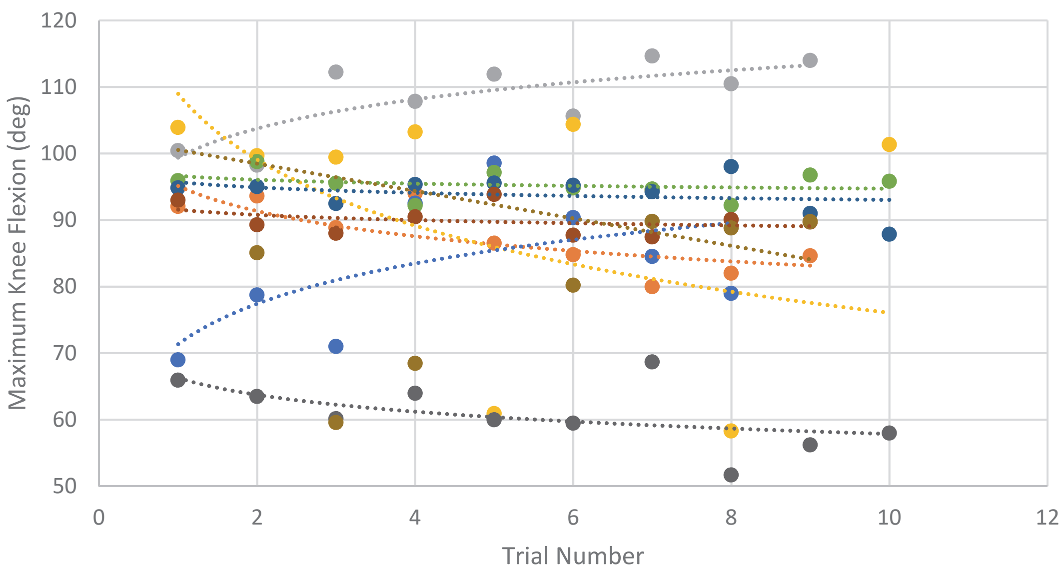

Figure C.3: Maximum knee flexion over time during the learning effect trials with logarithmic trend lines

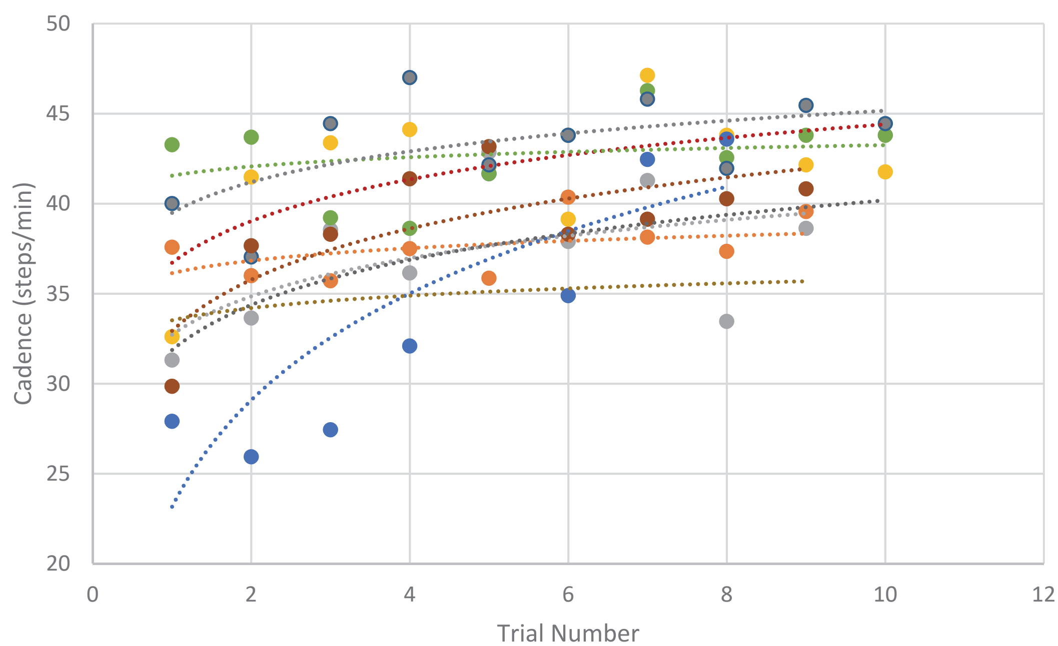

Figure C.4: Cadence over time during the learning effect trials with logarithmic trend lines

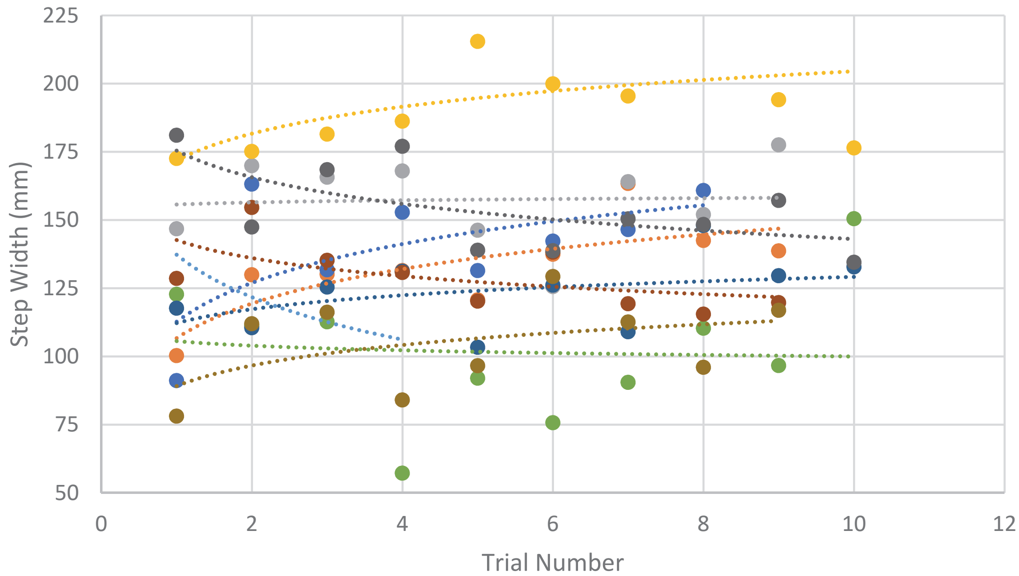

Figure C.5: Step width over time during the learning effect trials with logarithmic trend lines

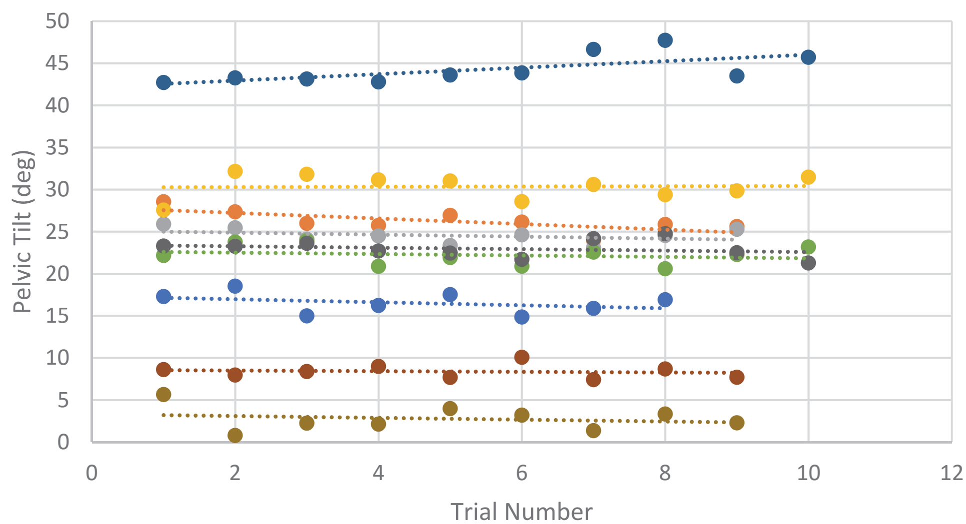

Figure C.6: Pelvic tilt over time during the learning effect trials with linear trend lines

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