Spring Stepper: A Makerspace Controller for Seated Hands-Free Locomotion in Virtual Reality

by

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Chair of Examining Committee	Dr. Faisal Qureshi
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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

Abstract

Natural locomotion is crucial for improving presence in a virtual environment (VE), while also reducing simulator sickness. While research in various areas of virtual reality (VR), such as head-mounted displays (HMD) and optical tracking, has been advancing at an unprecedented rate, there is currently a lack of suitable hands-free locomotion devices for VR, with most existing locomotion solutions involving complex, high-cost systems. This thesis presents the Spring Stepper, a hands-free, consumer-level seated VR locomotion controller. The presented system is created with open-source readily available development tools, commonly known as ”makerspace” tools, such as 3D printing and Arduino, an open electronics platform. The full design and development process of the system is discussed, including analyzing existing literature to gather requirements, and the iterative design process to create the prototype. Finally, the prototype was validated through user testing by comparing it to existing consumer-level seated VR locomotion devices for speed, ability to allow accurate hand interactions, and usability.

Keywords: virtual reality; locomotion; makerspace

Author's Declaration

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Christopher Carmichael

Statement of Contributions

Part of the work described in Chapter 3 has been published as:

M. Valdez Balderas, C. Carmichael, B. Ko, A. Nova, A. Tabafunda, and A. Uribe-Quevedo, "A Makerspace Foot Pedal and Shoe Add-On for Seated Virtual Reality Locomotion," in 2019 IEEE 9th International Conference on Consumer Electronics (ICCE-Berlin), 2019.

I worked on the design of the shoe add-on, designed and developed the experiment and the test simulation, and wrote part of the manuscript for the above paper.

I hereby certify that I am the sole author of the rest of the content of this thesis. I have used standard referencing practices to acknowledge ideas, research techniques, or other materials that belong to others.

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Abbreviations

ANOVA analysis of variance.

DOF degrees of freedom.

FSR force-sensitive resistors.

HMD head-mounted displays.

IDE integrated development environment.

IMU inertial measurement unit.

LDTM look-down-to-move.

PBI Phidgets Bridge Interface.

PLA polylactic acid.

PTT point-to-teleport.

SMRE subjective rating of mental effort.

SRT simple reaction time.

SUS System Usability Scale.

TTC time-to-completion.

UES User Engagement Scale.

VE virtual environment.

VR virtual reality.

WFBB Wii Fit Balance Board.

Chapter 1

Introduction

Locomotion in VR is crucial for user immersion, but its development has been lagging behind in comparison to other areas of VR such as HMDs and hand controllers [2,6]. This master's thesis reports on the design of a novel seated locomotion device for VR, and its evaluation through a user study. The device was iteratively developed over the course of the master's degree. The goal of the user study was to compare it to two existing consumer-level seated locomotion techniques for VR. In the following sections, some brief context of locomotion in VR is provided, followed by the problem statement, justification, and research questions of this thesis. Then, the objectives of this thesis are outlined, followed by a brief summary of the methodology used.

1.1 Context

Burdea and Coiffet define VR as "a high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels." [9]. This definition stipulates that VR must be a high-end interface. However, with recent advances in VR technology, it has become more accessible to consumers than ever before [2]. Steuer instead defines VR as the experience of a VE by means of telepresence [49]. In order to understand this definition, one must first know what a VE is, and one must also understand telepresence, and consequently presence. A VE is any computer simulation of an environment [49]. Presence is defined as feeling as though one is within a particular environment [49]. This relates not to how the environment actually is, but rather how it is perceived to be by the user [16]. Telepresence is the experience of presence via a communication medium, such as a HMD [49]. Therefore, VR is the presentation of a computer simulated environment through any communication technology so that the user feels as though they are actually within that environment. On the other hand, immersion is defined as a system's ability to deliver realistic sensory information to a user [46]. This can include some or all sensory channels, such as vision, audio, taste, haptics, or smell [49]. Given these definitions, it can be surmised that the goal of VR is to maximize immersion, and therefore a user's sense of presence in a VE. However, immersion can be achieved with different levels of interaction fidelity, which is defined as the degree of realism of interactions in a VE [1,32].

VR is constantly evolving and improving thanks to recent technological advances related to miniaturization of electronic components and improvements in graphics processing [43]. HMDs, haptic devices, and optical tracking have all been improving at unprecedented speeds, with visuals and audio being the most progressive [2]. However, natural locomotion in VR has seen comparatively slower progress than other fields. Locomotion is defined as self-propelled travel [3], and natural locomotion techniques are those that allow the user to use gait movements as input, such as steps, leg or arm swinging, and hip movement [31]. Locomotion in VEs is considered crucial for most VR applications [6,37], and natural locomotion has been shown to reduce the occurrence of simulator sickness [48]. Early locomotion techniques involved mechanical systems that used treadmills [12], mobile robotics [23], and sliding based surfaces [22]. However, such techniques are typically unsuitable for consumer use due to high cost and space requirements. For example, the Virtuix Omni, a common sliding-based surface device, costs \$6,500 [1] at the time of writing this thesis, takes up 2 m^2 of floorspace, and weighs over 100 kg in total [2]. The the high cost of such devices has led to the development of locomotion techniques employing readily available hardware and software solutions such as the current standard point-to-teleport (PTT) and gamepad locomotion techniques [6], which are significantly more accessible. However, since these are hand-based locomotion techniques, the user is required to manipulate objects in the environment as well as control locomotion with their hands. Redistributing this control load to allow foot-based locomotion would increase usability, thus improving task performance and user experience [32].

In order to understand the requirements of a VR locomotion device, one must first understand human gait. A gait cycle is the interval between consecutive steps of the same foot when walking [33]. There are two phases in gait, when the foot is touching the ground, known as stance, and when the foot is off the ground and moving forward, known as swing [33]. The gait cycle begins when the heel of one foot touches the ground, that leg is then in the stance phase and the person's body weight is transferred to that foot [33]. The other leg, meanwhile, is in swing, and moves forward while off the ground [33]. The movement is then mirrored, beginning with the heel of this leg hitting the ground and the foot of the first leg lifting off the ground, after which the cycle is repeated [33]. There is a brief period of time when both feet are touching the ground, which is referred to as double-limb support, and when only one foot is touching the ground it is referred to as single-limb support [33].

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[1] https://www.macevl.com/omni-packages

[2] https://www.virtuix.com/wp-content/uploads/2019/01/Virtuix%20Omni%20-%20Product%20Specs.pdf

1.2 Problem Statement

While technologies such as HMDs and hand controllers have been progressing rapidly in recent years, there is a lack of suitable hands-free locomotion devices for seated VR. This thesis develops a low-cost, hands-free consumer-level seated device that would fill this gap. Through user testing, the proposed device will be compared to existing devices to understand how it affects users' speed, ability to allow accurate hand interactions, and usability.

1.3 Justification

Development in various areas of VR, such as HMDs and optical tracking, has been improving at unprecedented speeds in recent years [2]. However, while locomotion in VR has been found to be very important for user experience, its progress has been comparatively slow [6, 37]. Given the wide range of fields employing VR, such as video games [42], training and education [39], healthcare [18], psychology [55], and rehabilitation [28], natural locomotion has become a subject of growing research for enhancing task completion [32]. Therefore, it follows that a usable, effective, and intuitive locomotion device would improve the results of a wide range of VR applications. Furthermore, a low-cost, lightweight, and compact device would make it more accessible to more users.

1.4 Research Questions

What are the effects on performance in VR when employing the system proposed in this thesis, in comparison to consumer software and hardware locomotion techniques? How does the Spring Stepper compare with the PTT technique and the 3D Rudder in terms of locomotion speed? How does the Spring Stepper compare with the PTT technique and the 3D Rudder in terms of allowing users the ability to accurately manipulate objects with their hands while locomoting? How does the Spring Stepper compare to the PTT technique and the 3D Rudder in terms of usability?

1.5 Objective

The objective of this thesis is to create a novel hands-free locomotion controller for seated VR and compare its efficacy and usability to existing consumer-level seated VR locomotion techniques. In order to complete this objective, the existing literature must first be analyzed to determine requirements for the prototype. Next, the prototype must be iteratively designed to produce a device that satisfies the requirements. Finally, the prototype must be validated in a user study, which will compare it to the standard PTT technique and the 3DRudder, which are both existing consumer-level seated VR locomotion techniques.

1.6 Methodology

Approximately one year of research was required to gather requirements and compare existing VR locomotion techniques. A wide range of existing types of locomotion techniques were analyzed and compared in order to determine which ones best address the problems that are trying to be solved. The taxonomy proposed by Nabiyouni and Bowman [31] was used as a basis for categorizing locomotion techniques. These categories were used to group similar techniques together so that they could be compared. The results of this research can be found in Chapter 2 of this thesis.

Following the requirement gathering phase, a nine month period of iterative design was undertaken to create a series of prototypes that improved on previous designs, while satisfying the requirements that were determined in phase one. Four different prototypes were made in all, ranging from the simplest being a 2”x4” piece of wood affixed with load cells, to the final prototype that used an Arduino and 3D-printed parts. More information about this process can be found in Chapter 3.

User testing was employed to determine the performance and usability of the later prototypes as compared to existing consumer-level devices and techniques. This required the creation of a VE where participants were tasked with following a path from start to end while completing objectives along the way. Such objectives required the participants to use their hands to interact with objects in the scene in order to test their ability to do so while also moving with the locomotion technique. Metrics such as completion time, position and orientation of the user’s head and body, and objective-related metrics such as how often the objectives were dropped, were gathered and analyzed to determine the performance of the locomotion technique. In addition, the user’s impression of the usability of each device was determined using the SUS [8], which asks the user questions using Likert scales to determine their overall impression of the ease of use of each device.

1.7 Document Structure

- **Chapter 2: Related Works** presents previous work in the field of VR locomotion.
- **Chapter 3: Development** describes the iterative design process used in prototyping the seated locomotion device. It presents each iteration of the prototype in depth, split into sections for both the hardware and software, and includes relevant pictures, blueprints, flowcharts, and pseudocode. It also presents the

third-party tools that were used during the design process and in the final design of each prototype.

- **Chapter 4: Experiment Design** describes the design and execution of the experiment used to test the efficacy and usability of the final prototype in comparison to existing devices and techniques.
- **Chapter 5: Results** presents and analyzes the results of the experiment presented in Chapter 4.
- **Chapter 6: Conclusions** presents a summary of the research, including impact and limitations.

Chapter 2

Related Works

This chapter reviews previous work in the area of VR locomotion techniques. It has been broken down into sections based on the category of technique. These categories are single-directional treadmills, omni-directional treadmills, walking in place, sliding-based surfaces, and stepping systems, with a final section reserved for miscellaneous systems that do not fall into the other categories.

2.1 Single-Directional Treadmills

A single-directional treadmill consists of a belt that circulates infinitely underneath the user while the user walks forward [34]. This type of locomotion device only requires tracking the movement speed of the belt [26]. It also does not require the user to wear any obstructing sensors or mechanical devices, which could reduce the user's sense of presence [34]. However, the main drawbacks of this type of device are that it is not capable of realistically simulating turning while walking, and it typically only allows movement on a flat surface or slope [26]. It is also difficult to control the speed of the belt to match the walking speed of the user [34], although recent work has made improvements in this regard [35].

Noma et al. [34] developed a Ground Surface Simulator that combines a single-directional treadmill with a terrain surface simulator. This device uses magnetic position sensors to track the positions of each of the user's feet, thereby allowing the system to estimate the user's walking speed. This was done by comparing the foot position to the current belt speed to detect what phase of walking the user was currently in, timing the stance phase, and using that duration to calculate walking speed. It also uses a series of rollers underneath the belt to simulate bumps in the terrain up to 6 cm high. These rollers are also capable of simulating up to a 5% incline. Based on the information provided by Noma et al., it is unclear whether the system allows the user to turn while walking. Their previous work utilized a three-axis motion platform underneath the treadmill to rotate the entire treadmill when it detected that a user was trying to turn while walking [34]. However, there is no mention of such functionality in their newer Ground Surface Simulator system. There is also no mention of whether this system is capable of simulating surfaces such as stairs. It seems that the system does not allow sidestepping, but it is unclear whether it allows backward walking. Due to the lack of information and studies, it is difficult to assess the suitability of this devices for VR applications.

Fung et al. [15] developed a single-directional treadmill system that is mounted on a six-degrees of freedom (DOF) platform for use in rehabilitation training for stroke victims. In this system, a potentiometer is tethered to the user in order to measure the user's distance and velocity in real-time. This allows the speed of the treadmill to be controlled based on the walking speed of the user. The platform utilized hydraulic actuators to rotate the treadmill at a rate of up to 30°/s and translate at a rate of up to 0.25 m/s in any direction. The system also included handrails to allow the simulated use of a cane. The author concludes that post-stroke patients are able to improve their gait by using the system, since they were able to successfully adapt to walking on the treadmill within 15 minutes of using the system. While the system is sufficient for its purpose, it has several drawbacks that make it unsuitable for other applications. First, it is unclear whether the system allows the user to turn in any direction they want, as the paper mentions obstacle avoidance but not how the system determines if the user is trying to turn. In addition, the system does not allow the user to run or back-step, and while it can simulate sloped terrain, it cannot simulate bumpy/uneven terrain or stairs.

2.2 Omni-Directional Treadmills

An omni-directional treadmill utilizes two or more treadmills that rotate in such a way as to allow unlimited travel in any direction [12, 21]. Darken et al. [12] devised the earliest omni-directional treadmill, which involves two perpendicular treadmills, with one surrounding the other. It also uses an arm mounted on an overhead boom to track the user's position and orientation. The belts of each treadmill are composed of rollers, with the rollers of one belt being perpendicular to the rollers of the other. When the user walks in the direction parallel to the outer treadmill, it behaves like a regular treadmill would, rotating so that the belt moves in the opposite direction to the user's travel. However, when the user walks in the direction parallel to the inner treadmill, the inner treadmill moves in the same direction, causing the outer rollers to roll in the opposite direction of motion, thereby cancelling the user's movement. This system has several benefits. It allows unlimited natural walking in a 2D plane with several possible gaits, such as back-stepping and side-stepping. This is achieved by having the user wear a harness, which pulls the overhead boom to track the direction the user is walking. The user can also turn naturally in any direction they wish.

However, there are also several drawbacks to this system. In the authors' own words, "Skill level plays too important a role in determining the usability of the system" [12]. This means that the system requires significant familiarization in order to be able to use the system proficiently, although specifics were not provided with regard to how much time is required. The system suffers from controls that do not respond quickly enough to user actions, resulting in situations that cause the user to stumble, although specific measures of this were not provided in the paper. An example of such a situation is when user is trying to come to a stop, but the system has not stopped yet, causing them to lose balance and stumble. This makes sidestepping particularly difficult with the system. The system also only supports movement in a 2D plane and does not simulate movement up or down slopes or stairs, or over bumpy terrain. Additionally, the system is extremely loud when in operation, which would impact immersion in the VE and could disturb those who are nearby. The user is also required to wear a harness that is attached to the overhead boom, which could be uncomfortable and cumbersome. Overall, the system is quite large, and unsuitable for consumer use.

Iwata [21] describes another omni-directional treadmill that is called the Torus Treadmill. This device is composed of twelve single-directional treadmills that are arranged on a larger single-directional treadmill, perpendicular to the larger treadmill. Essentially, the twelve treadmills form the 'belt' of the larger treadmill. When the user wants to walk parallel to the axis of the larger treadmill, the smaller treadmills function normally to cancel out the user's movement. When the user wants to walk perpendicularly to the axis of the larger treadmill, the smaller treadmills are rotated around the axis of the larger treadmill, oppositely to the direction of the user's travel. The user's feet and head are tracked using magnetic sensors, thereby allowing the system to calculate the position of the user. This system also includes a neutral area, where it only tries to re-center the user when they leave that area, thus eliminating any jitter from small movements that could cause the user to stumble. This system allows the user to walk and turn freely in a 2D plane with multiple gaits. It does not require the user to wear a harness, but it does require them to wear several sensors. There are several drawbacks of this system. First, it only allows movement in a 2D plane, and it does not allow movement on slopes or stairs. It also does not simulate uneven or bumpy terrain. The mechanical limitations of the system limit the walking speed of a user to slower than natural walking, however the author states that this did not affect the stability of the users while walking. The system is also quite large and complex [23], and would probably not be suitable for consumer use.

2.3 Walking in Place

This type of system uses sensors to detect when a person is walking in place, and uses that information to determine how they should move in a VE [21]. Slater et al. [47] were the first to devise such a system. It uses only a HMD with six-DOF electromagnetic tracking, and feeds the position information from it to a neural network. That neural network analyzes the position data to determine whether the user is walking in place. Whenever they are walking in place, the system moves the user through the VE in the direction of their headset orientation, which is also measured by the HMD. This system benefits from being an inexpensive solution to allowing users to locomote infinitely in a 2D plane, in that the only equipment required is a HMD. However, the system only allows forward walking, and does not simulate anything other than a flat surface.

Bouguila et al. [5] proposed a system where the user stands atop a turntable and wears infrared markers. An infrared camera tracks the user's orientation, and the turntable rotates whenever the user turns in order to keep the user facing forward. This allows the system to use a large, static display in front of the user instead of requiring the user to wear a HMD. The user is then able to naturally turn their body when they want to change their orientation in the VE. Sensors under the turntable allow the system to determine when the user is walking in place, and consequently moves them forward in the VE. This system allows the user to walk infinitely in a 2D plane and to turn naturally, and it benefits from not requiring the user to wear any equipment aside from the infrared markers. The turntable is quiet and is able to rotate smoothly at a maximum speed of 50°/s, so that the user does not lose their stability or become disoriented. However, if the user turns faster than the maximum speed, the turntable is unable to keep up and the user may experience some inconsistency in the system. Another limitation of the system is that it is only capable of simulating a flat surface.

Bouguila et al. [4] proposed another system called the Walking-Pad. This system is a more portable version of the above that uses switches embedded in a pad that the user walks in place on. The switches measure the placement and step frequency of the user's feet to determine the direction the user is facing and how fast they are trying to walk. A large screen is used to display the VE instead of a HMD. If the system detects that the user is not facing the screen, it continuously turns them in the VE in the direction they are facing until they return to facing forward in the real world. The system allows the user to move infinitely in a 2D plane, and allows somewhat natural turning and walking action, with the user being able to control their walking speed. It also does not require the user to wear any equipment at all, and since it has a USB interface, it is simple to set up and use. It is also quite compact and portable. However, it suffers from the same design limitations as its predecessors. It is unable to simulate anything but a flat surface, and only allows a single gait.

Yan and Allison [56] used four sensors mounted on the user's body to track when they are walking in place in a CAVE-like environment. A CAVE (cave automatic virtual environment) is a VR environment that uses projectors to project images of the VE onto the walls of a room-sized cube. InterSense IS-900 Precision Motion Trackers are mounted on the user's head, waist, and left- and right-leg, just below the back of the knee. These sensors are capable of tracking six-DOF position and orientation. The head tracker is used to control the user's viewport, the waist tracker is used to determine the user's walking direction, and the two leg sensors are used to determine when the user is walking in place. The system determines that the user takes a step when the upward speed of a leg is above a certain threshold, which is not specified in the paper. The user's locomotion speed is also determined by the upward speed of the leg. The system allows the user to walk infinitely in a 2D plane, but it does not simulate uneven or sloped terrain. It is only usable with a CAVE-like environment, which is uncommon for consumer use. Another drawback is that it requires users to wear several wired sensors, which can be obstructive and reduce the user's experience.

Tregillus and Folmer [52] proposed a system called VR-STEP for mobile VR. VR-STEP uses only the inertial measurement unit (IMU) of the smartphone being used as the mobile HMD, which has a three-DOF accelerometer and three-DOF gyroscope, to capture the stepping motions of the user. Those stepping motions, along with the head orientation, are then used to control locomotion in the VE. They also dynamically calculated locomotion speed based on the time between steps, so that a user could move faster in the VE by stepping faster in real life. The authors compared VR-STEP to a look-down-to-move (LDTM) locomotion technique, where a user would have to look at their feet briefly in order to toggle movement on or off. They had users complete two navigation tasks, one where the user had to walk on a straight trajectory, and another with obstacle avoidance. They found that users perceived LDTM to be a more reliable and efficient locomotion technique, but VR-STEP was a more intuitive and immersive one.

2.4 Sliding-Based Surfaces

Sliding-based devices utilize low-friction surfaces to allow the user's feet to slide as they walk, thereby cancelling the walking motion passively [34]. Iwata and Fujii [22] developed such a system, named the Virtual Perambulator. The Virtuix Omni is another system that is nearly identical to the Virtual Perambulator [54]. The user stands on a round platform and wears specialized shoes that have a low-friction film in the middle of the sole, and high-friction rubber on the tip of the sole. The rubber adds friction to the foot, which helps the user to brake and increases their stability [21]. The device also has a hoop that goes around the user, which gives novice users something to grab onto. It also prevents users from falling off the platform. The user is able to freely turn in any direction as they are walking. Magnetic sensors track the position and orientation of the user's feet and head, which the system uses to determine the speed and direction of travel. There are also touch sensors underneath each shoe to determine if the shoe is touching the ground or not, but the specific kind of touch sensor is not specified. The first benefit of this system is that it allows unlimited travel in a 2D plane, with multiple possible gaits. Users are able to freely turn around and continue walking in any direction they wish. The hoop also lends stability to the user, making them less likely to stumble while walking. However, the system is not capable of simulating sloped surfaces or uneven terrain. The user is also required to wear several sensors and specialized shoes, which could be bothersome. Finally, the walking motion is not completely natural because humans do not slide their feet while walking, and there is some familiarization required to use the system proficiently. Cakmak and Hager [10] described the Cyberith Virtualizer, which is a system that is very similar to the Virtual Perambulator, except that the sensors are located within the structure of the device, and not on the body of the user. This is less cumbersome for the user, but the user is still required to wear specialized shoes so that they can slide their feet on the walking surface.

Two other systems are described by Hsu et al. [19] and Huang [20] that are nearly identical to each other. These systems are similar to the Virtual Perambulator, except that instead of wearing specialized shoes and walking on a regular surface, the user instead walks on a specialized surface that is made of an array of ball bearings. These ball bearings rotate when the user slides their foot over them, cancelling out the walking motion. The bearings also have sensors embedded in them that are capable of tracking the positions of each of the user's feet. In this way, the user is not required to wear any sensors. The system also uses a hoop like the Virtual Perambulator to give the user stability and provide a surface that they can push against in order to slide backward. The main benefit of this system over the Virtual Perambulator is that the user is not required to wear any specialized gear other than a HMD when they use this locomotion system. However, like the Virtual Perambulator, users needed a period of familiarization to learn how to walk proficiently on the device.

Swapp et al. [51] proposed a device called the Wizdish which is used in conjunction with CAVE-like environments. The user wears low-friction footwear and slides their feet on a dish while making a walking-like motion. The position and orientation of the feet are tracked using a Vicon motion tracking system. Their setup also utilizes a redirected walking system to turn the user towards the middle screen of their three-screen CAVE environment. The motion that the user must take using this device is not particularly similar to natural walking, as the user slides their feet back and forth conversely, without their feet ever leaving the ground. The author notes that it takes some time for users to get used to this motion, and therefore is not particularly intuitive. There is also no frame around the device, and is therefore somewhat unsafe if the user were to slip and fall.

2.5 Stepping Systems

Stepping systems utilize actuators that are attached to the user's foot in some way, so that they can actively reposition each individual foot as needed. In this way, they are able to cancel out walking movements by repositioning the feet back to their starting positions.

Iwata et al. [24] describes the Gait Master, a stepping system that employs two six-DOF motion platforms mounted on a turntable. The user stands on top of these motion platforms. The system tracks the position of the user's feet using strings connecting the foot and the motion platform. The motion platforms follow the positions of each foot, subsequently returning the foot to its original position. The turntable rotates the entire upper mechanism when the system detects that the user has changed their direction, so that the mechanism is always facing the same direction as the user. This enables the user to turn freely and walk in any direction. The system is not only capable of unlimited travel in a 2D plane, but is also capable of simulating sloped and uneven terrain. This is accomplished by connecting three linear actuators to each footpad via a yaw joint. The maximum load of each motion platform is 150 kg. This system thus satisfies all of the requirements of the optimal VR locomotion system. It allows for natural walking, and it also allows for more than one gait. However, the authors have found that the tracking performance of the system is lacking, noting that there is a 0.3 s time delay, causing an offset between the foot and the platform that could lead to the user stepping off the platform. A safety strap was implemented to prevent this from happening.

Shiozawa et al. [45] developed a Virtual Walkway System that has two foot plates that the user stands on. The user wears specialized shoes equipped with two LEDs and a pressure sensor in the sole. A camera tracks the positions of the LEDs, and in combination with the pressure sensors, monitors the walking speed and direction of the user. The XZ-position of each foot plate is controlled via three rack-geared arms with three AC motors. The Y-position of each foot plate is controlled via a hydraulic cylinder mechanism. This allows users not only to walk infinitely on a flat surface, but also on sloped surfaces and uneven terrain, such as stairs. However, the author notes that the system is unable to keep up with a change of gait, such has transitioning from standing to walking or vice-versa, and a prediction model is required to predict the change in gait before it happens.

Yoon and Ryu [57] describe a system that uses planar parallel robots. The user stands on two platforms, one foot on each platform. The platforms have three arms attached to each of them, which are composed of three joints each. Only the first joint of these arms uses an actuator, and the other two joints rotate freely. These arms are capable of three-DOF planar movement (x, y for translation, and yaw for orientation). The actuators are fixed to the base of the structure, so that the platforms remain lightweight. However, since the device does not use a turntable, the maximum turning angle is limited to 20° in order to prevent collisions between the two platforms. The platforms that the user stands on have pneumatic actuators that also give them three-DOF motion (pitch, roll, and z). This allows the system to simulate slopes, stairs, and other forms of uneven terrains. However, one limitation of this device is that it supports a maximum weight of 100 kg, which could exclude a significant consumer base. Additionally, its maximum planar speed is only 1.2 m/s and its maximum vertical speed is only 0.2 m/s.

Iwata et al. [25] proposed a system called Powered Shoes that uses footwear similar to roller skates to reposition the feet after a step. A flexible shaft drives the rollers, and the shaft is driven by motors that are worn in a backpack. The position of each foot is tracked via optical sensors, and when a foot moves, the skate moves in the opposite direction. The goal of this device was to enable unlimited walking in any direction while eliminating the need for bulky treadmills or extreme sensor accuracy. The shoes themselves are lightweight, since the motors are not mounted on them directly. However, having to wear a backpack to use this device is not ideal, especially when it contains heavy motors and batteries.

Iwata et al. [26] developed a novel locomotion system called the String Walker. This system employs eight strings that connect the user's shoes to motor-pulley mechanisms. These mechanisms are capable of measuring the position and orientation of each shoe. As the user walks, the motors pull the shoes back toward the centre of the device, thus cancelling out the user's movement and simulating unlimited walking. The entire mechanism is mounted on a turntable, which allows the user to turn without limitation. The system also allows several gaits, such as sidestepping and back-stepping. However, this system only allows planar movement, and is not capable of simulating uneven or sloping terrain.

2.6 Miscellaneous

This section describes miscellaneous systems that do not fall into any of the above categories. There are subsections for spherical systems, robotic tiles, redirected walking, hand-based locomotion techniques, and locomotion techniques specifically for seated VR.

2.6.1 Spherical Systems

Spherical systems, also known as human-sized hamster balls [31], are systems that allow the user to walk inside of a large sphere. Fernandes et al. [13] describes such a system, which they call the Cybersphere. This system consists of a translucent sphere that is 3.5 m in diameter, which sits upon a smaller sphere. As the user walks inside of the larger sphere, the sphere rotates, transferring the movement to the smaller sphere. Sensors measure the rotation of the smaller sphere in order to determine how much the user has moved, and in which direction. Five projectors, one on the ceiling and one on each wall of the room that the Cybersphere is in, project images of the VE onto the sphere from each direction. In this way, the user is fully immersed in the VE without needing to wear a HMD. The benefits of this system are that it allows unlimited natural locomotion in a 2D plane and it allows any gait, including sidestepping and crawling. One drawback of this system is that it does not simulate sloped surfaces or stairs. The system is also massive, requiring an entire room just to itself, making it impractical for consumer use.

2.6.2 Robotic Tiles

Robotic tile systems consist of tiles that move and rearrange themselves as the user walks over them to cancel out the user's movement and simulate infinite floor. Iwata et al. [23] developed the only known example of this type of system, which is named the CirculaFloor. There are sensors on each tile and on each of the user's legs to track the position and orientation of each. This information is passed to a computer which determines the direction and speed of the user, which in-turn informs the pattern of movement that the tiles should use to rearrange themselves. The system allows the user to move infinitely in a 2D plane, and also allows natural turning. However, the main problem with the system is that it is too complicated to allow a high enough walking speed for the walking to feel natural [26]. The system is also not capable of simulating uneven or sloping terrain.

2.6.3 Redirected Walking

Redirected walking is a technique which tricks the user into thinking they are walking straight, when in reality they are walking in circles [37]. While not a locomotion device per se, it does allow unlimited walking within a confined space. According to Field and Vamplew [14], this algorithm works by imperceptibly rotating the user's orientation within the VE. When this is done, the user subconsciously turns their body to correct the rotation. This causes the user turn in a large circle, but they think they are still walking straight because of what they see in their HMD. However, the author concludes that the tracking space needs to be on the order of 3600 m^2 in order to allow a user to feel as though they are infinitely walking in a straight line. Nevertheless, this requirement could be reduced depending on what the user is expected to be doing in the VE. For example, any pauses in movement or fast turning could be taken advantage of to redirect the user appropriately.

2.6.4 Hand-Based Techniques

The point-and-teleport technique is the current standard for consumer VR locomotion [7]. The user points their controller where they want to go, presses a button on the controller, and the system instantly teleports their viewport to the new position. This technique can be used either seated or standing, and it can be used with any VR system that uses tracked controllers. This locomotion technique has been shown to reduce simulator sickness in users due to the fact that movement between points is instantateous, not interpolated [6]. However, this technique can also reduce spatial awareness and orientation [40]. In addition, since this technique uses hand-held controllers, the burden of control is placed on the hands instead of the feet.

Gamepad-based locomotion is still a common locomotion technique in VR, despite it being significantly lower fidelity than other techniques [32]. Avatar controls are typically mapped according to convention in non-VR games, which is arbitrary for VR applications [11]. However, because of this, people who are familiar with such control schemes are more easily able to use gamepads for locomotion in VR because they do not have to learn it [11]. This typically leads to better performance when compared to other low- and mid-fidelity locomotion techniques, even though immersion also tends to be lower [11, 32].

Arm swinging is another hand-based locomotion technique where the orientation of the user's arms is tracked in some way, such as the Myo armband [30]. The user swings their arms back and forth to move forward in a VE.

2.6.5 Locomotion Techniques for Seated VR

Ohshima et al. [36] propose a system called the Virtual Intuitive Striding Unit that allows a user to locomote in virtual space while maintaining a seated position in real life. The device uses a cushion with two embedded pressure sensors which the user sits on. The user is then able to walk by moving their thighs, and the sensors detect the change in pressure. The faster a user moves their legs, the faster they will walk in the VE. The direction of movement is controlled by the user's head, i.e., they will move in the direction that they are looking. This device is not only suitable for average consumers, but it is also suitable for disabled users who may be amputees or are otherwise unable to stand/walk. It is also relatively cheap, since it only uses pressure sensors. It is also very safe, since there is little or no risk of the user falling, since they are already in a seated position. One downside of this system is that it uses the user's head orientation to determine their walking direction, and thus they are unable to look around while walking in a specific direction at the same time.

Kitson et al. [27] study the effects of user-powered motion cueing on spatial updating. Spatial updating is a user's ability to maintain an accurate mental model of a 3D environment relative to themselves as they move based on sensory input. This sensory input not only includes visual information, but also proprioceptive and vestibular cues. Motion cueing is a type of haptic feedback where accelerations are applied to a user's body to make them feel as though they are moving in a particular way. In user-powered motion cueing, these accelerations are the result of the user leaning or turning their body. Kitson et al. [27] developed a locomotion interface to capture these inputs, called the NaviChair. The NaviChair allowed the user to lean forward to move, and to rotate the chair to turn. They compared this interface to a stationary chair with a joystick used to control locomotion. Unfortunately, they found there was no significant difference in either interface's ability to help orient users in a VE. However, during interviews users did report that they felt more immersed in the VE when using the NaviChair as opposed to the joystick, even though they felt that they had better control and accuracy with the joystick.

2.7 Summary

From the above literature review, several requirements for a new locomotion prototype can be established. The first requirement is that the user's hands should be free to interact with objects in the environment. Thus, the device should be controlled by the user's lower body rather than their upper body. This would also be closer to natural walking, and thus would be more immersive than hand-based locomotion.

The second requirement is that the device should be seated. Seated locomotion devices increase user safety by reducing the chance that the user will fall while using the device. In addition, the requirements of the devices would be lessened by not needing to support the full weight of the user. A seated device would also be more accessible for people who have special needs, such as not having full use of their legs or who become fatigued easily.

The third requirement is that the device should be made using low-cost and open-source “makerspace” materials and manufacturing techniques, such as 3D printing and open electronics platforms such as Arduino. This would make the device more accessible to more people, since it could be made and customized by anyone with minimum knowledge and investment.

The design and development process for the new locomotion device will be presented in Chapter 3, and its analysis will be presented and discussed in Chapters 4 and 5.

Chapter 3

Development

From the literature review, several requirements for a locomotion prototype were established. First, it was determined that the device should be controlled by the user's lower body. This would free the hands to interact with other parts of the simulation, and would also allow it to feel more immersive. Second, it was determined that a seated device was needed for several reasons. A seated device can increase user safety by reducing the chance of falling, which is a possibility if users lose their balance while standing. It would also lower the requirements of the device by not needing to support as much weight, and it would increase accessibility by allowing people who only have partial use of their legs and may not be able to stand for extended periods of time to still use the device [50]. Finally, it was decided that the prototype should make use of low-cost materials and manufacturing techniques, often referred to as makerspace technology. This would further increase the accessibility of the device, since users could make their own version of it given the designs, and they could even improve upon it if they were so inclined.

An iterative design approach was followed in order to arrive at a final prototype design that would satisfy the requirements laid out above. This meant designing a prototype, building it, evaluating it to determine its strengths and weaknesses, and subsequently refining the design, beginning the cycle once more. To restrict scope, only walking forward and turning were considered as features for the prototype designs. Starting with the earliest iteration of the design, this chapter will describe each iteration in depth, with sections on hardware, software, and any additional third party tools. All relevant pictures, blueprints, flowcharts, and pseudocode are included.

3.1 Plank Device

As stated above, it was determined that one of the requirements of the prototype was that it should be used while seated. To explore whether a seated locomotion device could still feel natural, a simple prototype was created that could fulfill the most basic requirement, simply moving forward in a VE. To this end, a plank of wood was fitted with pressure sensors, which would be placed in front of a chair. The user would sit on the chair and place their feet on the plank, and when the user alternately stepped on the plank, it would move their avatar forward in the VE. This prototype is shown in Figure 3.1.

3.1.1 Hardware

This prototype consisted of a 50 mm x 100 mm x 450 mm plank of wood, with a Phidgets S-Type Load Cell attached to each end of the plank. These load cells are capable of measuring loads between 0 kg and 100 kg. The load cells were connected to a Phidgets Bridge Interface (PBI) as shown in Figure 3.2, which was then connected to a computer via a USB cable.

Figure 3.1: The first design iteration.

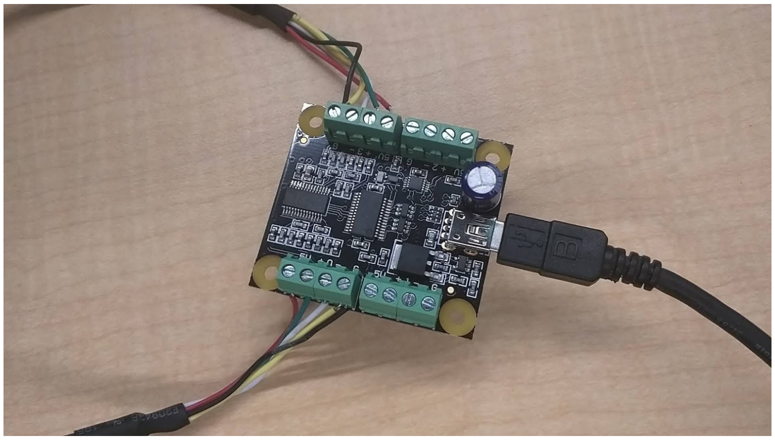

Figure 3.2: Phidgets Bridge Interface that is required to connect the Phidgets Load Cells to a computer.

3.1.2 Software

All the software for this prototype was written in C# in Unity. A script was created called PhidgetComponent that handled all logic required for taking input from the load cells and translating it into movement for the avatar. The input was a single floating point value from each of the load cells every time the Unity simulation updates, which is variable frequency that is tied to the rendering loop.

The load cells needed to be calibrated at the beginning of the simulation to account for variances in leg weight. For the first five seconds of the simulation, the user was asked to keep their feet on the board without moving their legs at all. The values that were obtained from the load cells each update for those five seconds were summed, and at the end of the calibration phase the sum was divided by the number of updates that occurred. This gave a baseline calibration value for each of the load cells.

After the calibration phase, each new value read from a load cell was subtracted from the relevant calibration value. This gave an absolute value which represented the difference between the leg at rest and the leg at the current point in time. It was necessary to only move the avatar forward if the user was alternating their steps, so a delta was determined by subtracting the absolute load value of each leg. If the absolute value of this delta was greater than a certain threshold, then a step had occurred. The sign of this delta value would determine which leg was currently stepping, and if it was the opposite of the last step, then the avatar could be moved forward.

The pseudocode for the PhidgetComponent script is included in appendix A.1.

3.1.3 Analysis & Conclusion

The Unity game engine was used in conjunction with this locomotion device. A simple scene was created with a plane for the user to walk on that was textured to look like grass. As stated above, a C# script was created to handle input from the device and control an avatar. The standard FPSController prefab was modified to accept motion input from the PhidgetComponent script.

A Phidgets plugin, Phidget21.NET.dll, needed to be added to the Unity project, and was used to read the load cell values from the PBI. In addition, the Phidget Control Panel needed to be installed on the computer and a Phidget web service needed to be running in order to feed sensor values to the Phidgets plugin. A full install guide and list of downloads can be found at `https://www.phidgets.com/`

`docs21/OS_-_Windows`.

The Unity scene was run on a computer with a standard desktop monitor, with a first-person view mode. To turn, the user would simply use a mouse to rotate their avatar. No VR was used with this device.

Through analysis of this device, it was found that alternately stepping with one's feet while seated works well to move in a VE. It was also determined that turning would be a vital contributor to immersion, however, and therefore the prototype would need to be able to turn as the user turns.

3.2 Seat Controller

Through analysis of the Plank Device, it was determined that the prototype needed to allow the user to turn to provide adequate locomotion, and the most natural way to turn is to turn with one's own body. Therefore, it was decided that a new prototype would be designed that used a swivel chair instead of a regular chair, which would allow the user to turn naturally. This meant that the device needed to be able to turn with the user. The first iteration of this was to implant pressure sensors onto the seat of the swivel chair. Hypothetically, this would allow the device to sense the user shifting their weight on the chair from left to right, while also allowing them to turn the chair, thus allowing the user to both walk and turn in a VE.

3.2.1 Hardware

An adjustable swivel chair was used for this prototype, which would allow the user to adjust to their preferred height. The seat of the chair was affixed with two custom-made pressure sensors, one for the left leg and one for the right leg. The pressure sensors were made with conductive foam approximately 80 mm by 80 mm, with copper wire spread out on either side of the foam, and electrical tape wrapping it. When the foam is compressed, its resistance drops, thus lowering the voltage drop across it. These sensors were connected to an Arduino Uno in a basic configuration to read the voltage drop across the sensors. The circuit diagram for this can be found in appendix B.1. An HTC Vive Tracker[1] was attached to the back of the chair in order to track the chair's orientation.

Figure 3.3: Full SeatController prototype with custom made pressure sensors affixed to the seat.

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[1] https://www.vive.com/ca/vive-tracker/

3.2.2 Software

Code was written for the Arduino Uno that would read the voltage value as a number between 0 and 1024 from the appropriate analog pin and determine if a step had occurred. This was done by comparing the newly read value for a sensor to the previous value, and if the difference was over a particular threshold, then a step had occurred on that side of the seat. The threshold was determined empirically by measuring the value without pressure, then measuring it with pressure, and determining the minimum threshold that could be used to activate the sensor. A bit field was outputted from Arduino by printing it to the serial output. A value of 01 (output 1) indicated that just the left sensor was activated, 10 (output 2) indicated that just the right sensor was activated, and a value of 11 (output 3) indicated that both sensors had been activated for that update loop. The pseudocode for this program can be found in appendix A.2.

A Unity C# script was written called ArduinoComponent to read the value outputted from the Arduino at every frame, resulting in VR walking. This was done by reading the bit field as a line from a SerialPort every update. If the bit field indicated that only a left step had occurred and the previous step was right, or vice versa, then the avatar was made to move in the direction indicated by the Vive tracker for a set amount of time, which could be customized. Any input indicating that both sensors had been activated at the same time was ignored, because this indicated that the user was not shifting their weight, but rather just sitting still. The pseudocode for this script can be found in appendix A.3.

3.2.3 Analysis & Conclusion

The Unity game engine was used to test this device. A simulated medical laboratory environment, created by a previous student named Rob Shewaga [44], was used. The user was able to walk around the scene and interact with various objects in the scene. This scene is shown in Figure 3.4.

Figure 3.4: Simulated medical laboratory environment that was modified and used to test the SeatController prototype. This scene was originally created by Rob Shewaga.

Since the Arduino Uno was connected to the computer via USB port, the SerialPort class in the System.IO.Ports C# library was used to communicate between the Arduino and the Unity simulation. This required knowing which specific port the Arduino was connected to, which could be found using the Arduino integrated development environment (IDE), and setting it manually in the Unity inspector.

The SteamVR plugin was used to implement VR in the Unity scene, with an HTC Vive used for the VR HMD and controllers. In addition, a Vive Tracker was mounted on the back of the swivel chair and was used to track its orientation. This was subsequently used in a Unity script to determine the direction that the user's avatar should move in.

The SeatController prototype was demonstrated at Lakeridge Health Centre. Several health professionals were introduced to the prototype and orally gave their feedback. Several of them reported that they did not understand the interaction that was required to move the avatar forward. It was therefore inferred that the interaction was not intuitive enough to warrant pursuing in a final prototype.

It was also found that the custom-made pressure sensors were difficult to use due to the fact that they did not instantly depress once weight had been removed from them. If the user shifted their weight rapidly from side to side, the sensors would constantly be activated and the software would not be able to tell if they were activating the sensors or just remaining still on them.

3.3 Home Hiker

The next iteration of the device prototype was developed as a group project for the course CSCI 5540G: User Interface Technology, which was a joint graduate/undergraduate course with INFR 3380U: Industrial Design for Game Hardware. The other group members for this project were Bill Ko, Atiya Nova, and Angela Tabafunda. They helped to brainstorm ideas for the next iteration of the device, design it on paper, and model it in Autodesk Fusion 360.

Through brainstorming, over 200 ideas were generated and subsequently filtered down to the top 20 most valid ideas. Finally, it was decided that the system should be a type of VR sandal, which the user can put on their feet and step in place to move. It would still be seated, and still use the turning method that employed the Vive Tracker.

The Home Hiker, as the device was later named, was designed to be strapped onto the bottom of the user's shoe with adjustable velcro, to fit varying foot sizes. It was designed to have a front and back sole, which would be used for forward and backward movement, respectively. By alternately tapping the left and right sole, the user could move forward or backward appropriately. A drawing of the Home Hiker can be seen in Figure 3.5. Due to time constraints, only the front sole was actually created and tested.

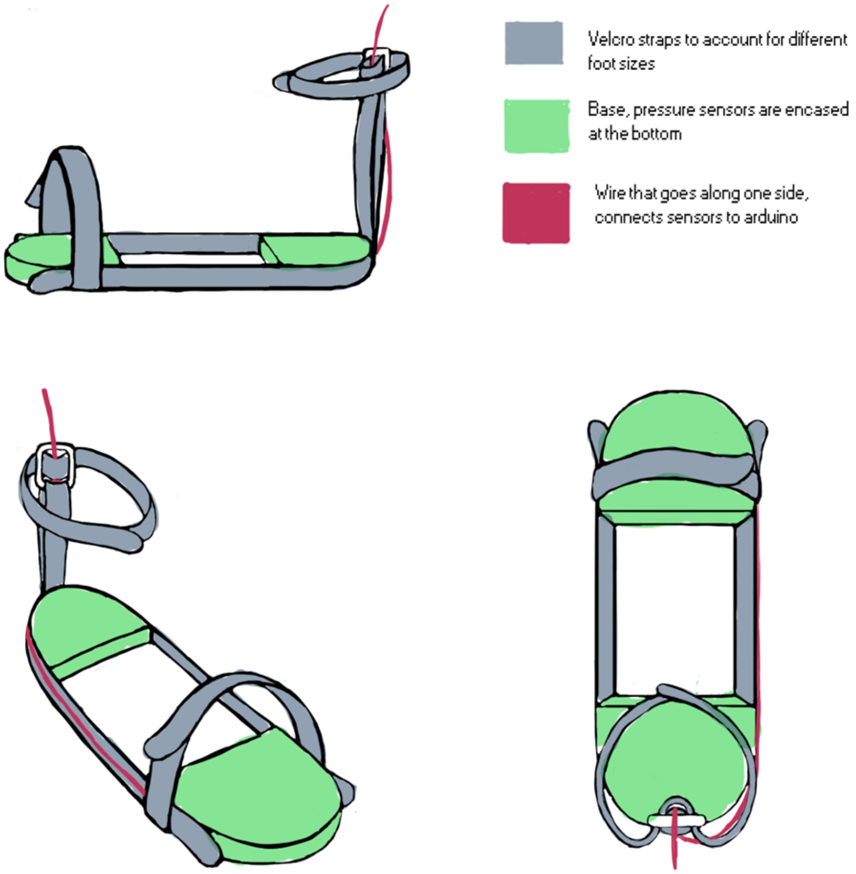

Figure 3.5: Concept art of the Home Hiker prototype.

3.3.1 Hardware

The soles were modelled in Autodesk Fusion 360 and 3D printed using a Creality Ender 3 printer with 1.75 mm polylactic acid (PLA) filament. The blueprints for these soles are shown in appendix C.1. Round force-sensitive resistors (FSR) measuring 12.7 mm in diameter were embedded into each sole (see Figure 3.6). These FSRs were connected to the Arduino Uno in the same configuration as the custom pressure sensors from the Seat Controller, as seen in appendix B.1. The device was also used with a swivel chair that had a Vive Tracker attached to the back to track its orientation.

Figure 3.6: Force-sensitive resistor used with the Home Hiker prototype.

3.3.2 Software

Since the Home Hiker's circuit configuration was the same as the SeatController's, the latter's Arduino code was used as a basis for the Home Hiker's code, slightly modifying how the sensor input was compared to the threshold values. Instead of comparing the difference in sensor values from one frame to the next with a threshold value, the flat sensor value was directly compared to the threshold (see appendix A.4). Since the output format from the Arduino code had not changed, the same

Unity C# script, ArduinoComponent, could still be used in Unity for testing (see appendix A.3). The flowchart for the system can be seen in Figure 3.7.

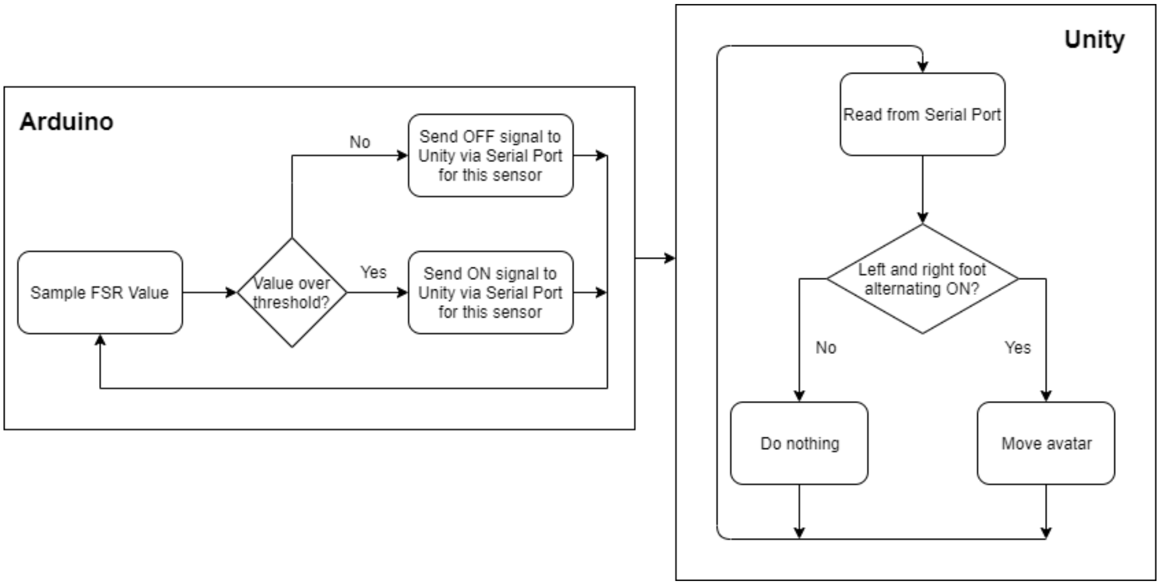

Figure 3.7: Flowchart showing the flow of logic for the Home Hiker, combining the programs running on both the Arduino and in Unity.

3.3.3 Preliminary Study

A preliminary study was conducted that compared the Home Hiker to existing VR locomotion techniques for efficacy as well as usability. To this end, a new test environment was created in Unity. It used Unity's Viking Village demo scene[2] as a base, which was modified according to the test requirements. Participants were required to walk through the VE using various VR locomotion techniques, following a path that was clearly marked with yellow animated arrows on the ground so they would not get lost. At two points along the path, the participants were required to pick up an object; first a yellow sphere, and second a yellow cube. The participants were required to bring both objects to the end of the level in order to complete the test.

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[2] https://assetstore.unity.com/packages/essentials/tutorial-projects/viking-village-29140

This would test both their ability to use the locomotion device, as well as their ability to interact with objects in the scene while walking.

Figure 3.8: Map showing the route that participants were required to follow in the Viking Village VE for the Home Hiker preliminary study.

This was a between-subjects study; eleven participants (seven male, four female) were split into two groups. The first group traversed the VE using the PTT technique, a Wii Fit Balance Board (WFBB), and a 3dRudder. These devices were chosen because they are all consumer-level seated locomotion devices. The WFBB is a device created by Nintendo that is cable of sensing weight distribution on the board. In this study, the user would sit in a chair in front of the WFBB and place their feet on it, using it similarly to a joystick. Putting pressure on the front or back end of the board would move their avatars forward or backward, respectively, while putting pressure on the sides would turn their avatar. The 3dRudder is a device made by a company of the same name[3], which is capable of sensing tilt. The controls for this device were similar to that of the WFBB, except that the user would tilt the device instead of putting pressure on it with their feet.

The second group traversed the VE using the PTT technique, the Home Hiker, and another prototype device called the Foot Pedals, created by an Ontario Tech student named Marco Valdez Balderas. The Foot Pedal system was another makerspace device that was created using 3D printing, and was shaped like a car accelerator pedal. It incorporated an Arduino Uno and an IMU to sense how far the pedal had been depressed. It used the orientation of the user's head to turn; when the user turned their head further than 30°from the centre, their avatar would begin turning in that direction.

To avoid carryover effects, users were assigned a device usage order such that each usage order had an approximately equal number of users. This would reduce the likelihood of the overall results being skewed due to users becoming familiar with the simulation after the first or second use.

Participants were first asked to fill out a demographics survey (appendix D.3) before beginning the study. They were then given a brief description of what they were required to do, and were instructed to reach the exit of the map as quickly as possible. Before using each locomotion technique, participants were given a short explanation on how to use the technique. After using each technique, the participants were asked to complete an SUS survey. The metrics collected during the test were TTC and objective drop count.

The full study design, results, and analysis can be found in [53].

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[3] https://www.3drudder.com

3.3.4 Conclusion

It was found that on average, the Home Hiker had the longest TTC of all the locomotion techniques in this study. It is hypothesized that this is due to the sensors in the device, which several participants commented that they were difficult to activate. However, the Home Hiker performed favourably with regards to objective drop count and SUS score. The objective drop count can be explained by the fact that users did not need to use their hands for anything other than interacting with the objectives, since locomotion was controlled by their feet. This is in contrast to the PTT technique, which performed much worse in this metric. Regarding the SUS score, several participants commented while using the Home Hiker that they enjoyed the motion of stepping their feet to move forward. They also commented that they enjoyed swivelling the chair to change their movement direction, and thought it was a very intuitive interaction.

3.4 Spring Stepper

With the results of the preliminary study in mind, a new prototype was designed that would improve upon the limitations of the Home Hiker. The FSR sensors were removed from the design, and it was determined that a simpler, on-off interaction was needed for activating the device, which would not require a threshold of any kind. This was due to difficulty that the participants had in activating the device depending on their individual strength and leg weight. Some were unable to reliably put enough pressure to active the device, while others would activate it accidentally with their leg weight alone. Therefore, a digital on-off interaction would eliminate this inconsistency by activating when the foot is down and deactivating when it is up.

It was originally considered to put a push-button in the sole of the device, but this was not pursued due to the possibility of users crushing the push-button when they stomp their feet. Therefore, the mechanism needed to be able to withstand significant force. To this end, a circuit-closing mechanism was designed where two leads would be attached to one side of the device with the other side having enough conductive material to close the circuit between them. When the user's foot stepped on the ground, the device would depress to close the circuit, thus activating it. The device needed to be able to reopen when the user lifts their foot, so a spring was included in the design.

The swivel chair with the Vive Tracker affixed to the back was used again in this design, which provided a very intuitive turning interaction in VR. The Arduino Uno was also used again to pass input from the device to the computer.

Figure 3.9: The Spring Stepper device when assembled and connected to the Arduino Uno, which is mounted on the back of the swivel chair.

3.4.1 Hardware

The device consists of two 3D printed parts, a top piece that would be strapped to the user's foot, and a bottom piece that would make contact with the ground (see appendix C.2). The two parts are essentially square pieces that have cylinders that protrude from one side. The cylinder on the bottom piece is slightly larger than the one on the top piece. These cylinders fit into each other in order to guide the pieces together when the foot depresses the device. There are smaller concentric cylinders inside the larger cylinder of each part, which hold each end of a spring. This spring constant was chosen such that it would allow the device to reopen when lifting the foot, but would not prevent the user from easily pressing the device down. The top piece includes holes for velcro straps to be attached to, which the user would be able to strap to their feet and adjust as needed.

Two copper wires are attached to the top piece with copper tape, which form the two leads on the device. Those wires are then connected to the Arduino Uno in a similar configuration as the Home Hiker (see appendix B.2), except that the input was connected to digital pins on the Arduino instead of analog pins, and resistors with higher resistance were used. The top rim of the cylinder on the bottom piece is lined with copper tape. When the device is depressed, the bottom piece's top rim completes the circuit between the two leads on the top piece, sending an ON signal to the Arduino's digital input pins.

3.4.2 Software

An Arduino program was written that reads the state of each digital pin, and checks if they are high or low. The output of this program is a bit field printed to the serial port, so if the right pin is high 01 (1) is printed, if the left pin is high 10 (2) is printed,

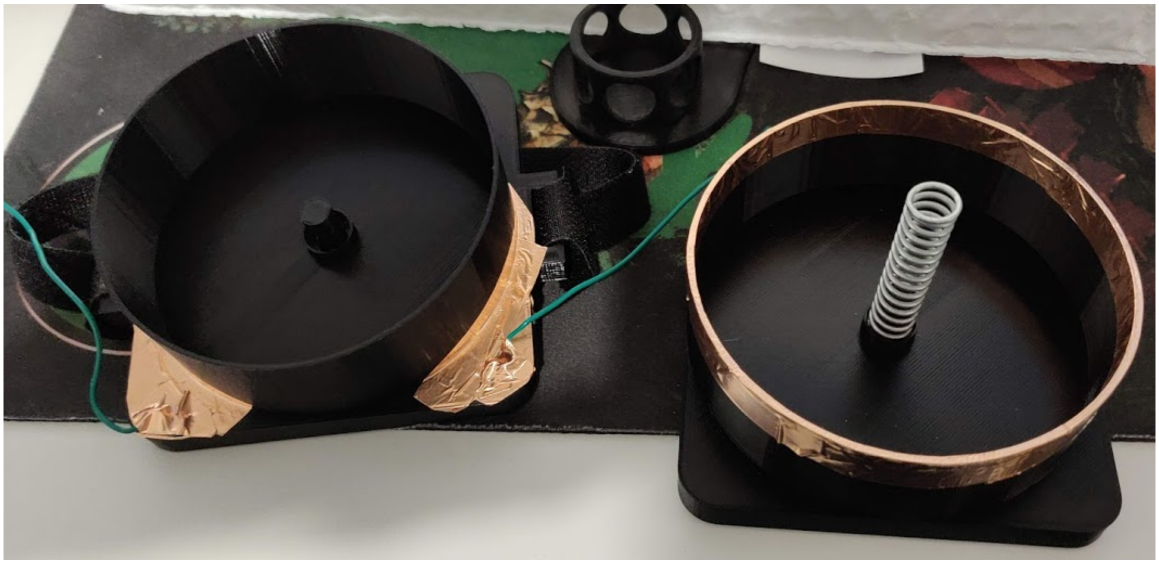

Figure 3.10: View of the Spring Stepper with its top (left) and bottom (right) half split apart to show its internals. The rim of copper tape on the bottom half completes the circuit between the two leads on the top half when the user's foot presses the device down. The spring inside the device then ensures that it opens again when the user lifts their foot.

and if both are high then 11 (3) is printed. Otherwise, 0 is printed. The pseudocode for this program is included in appendix A.5.

Since the output from the Arduino program was the same format as the one for the Home Hiker, the same C# script, ArduinoComponent, was used in Unity without any modifications.

The validation and results of the Spring Stepper prototype are presented in Chapters 4 and 5.

Chapter 4

Experiment Design

A user study was designed to test if the Spring Stepper was an improvement over existing consumer-level seated VR locomotion techniques for both efficacy and usability. The Spring Stepper was compared to the standard PTT technique and the 3D Rudder in a locomotion task that required both speed and the ability to manually interact accurately. This study was reviewed by the University of Ontario Institute of Technology Research Ethics Board (REB# 15314) and originally approved on May 28, 2019.

4.1 Research Questions and Hypotheses

Research Question 1: How does the Spring Stepper compare with the PTT technique and the 3D Rudder in terms of locomotion speed?

> **Hypothesis 1:** *The Spring Stepper will allow users to locomote faster than the PTT technique and 3D Rudder.*

Research Question 2: How does the Spring Stepper compare with the PTT technique and the 3D Rudder in terms of allowing users the ability to accurately manipulate objects with their hands while locomoting?

Hypothesis 2: *The Spring Stepper will allow users to more accurately manipulate objects with their hands while locomoting than the PTT technique and 3D Rudder will.*

Research Question 3: How does the Spring Stepper compare to the PTT technique and the 3D Rudder in terms of usability?

Hypothesis 3: *Users will find the Spring Stepper more usable than the PTT technique and the 3D Rudder.*

4.2 Participants

Thirty healthy participants (24 male, 5 female, 1 other) ages 19-34 (M = 23.3, sd = 3.37) volunteered to participate in this study. These participants were recruited from the Ontario Tech University community, and their backgrounds varied between game developers (programmers, designers, and artists), engineers, and IT specialists. Seventeen participants reported that they play video games every day, eight every other day, and five once per week. Eight participants reported that they use VR at least once per week, thirteen once per month, eight once per year, and one had reported never using VR. Eleven participants responded that they never get motion sick in VR, Thirteen said they rarely get motion sick in VR, five said they sometimes get motion sick in VR, and one reported that they often get motion sick in VR.

4.3 Setup

An HTC Vive VR system, complete with HMD and controllers, was used for this study. The Vive was chosen due to it being one of the most common VR systems, and also because of its many features such as accurate room-scale tracking and ease of use. It was set up in a dedicated space in the GAMER Lab, with a tracking area of 2.5 m × 2.6 m horizontally and 2.4 m vertically.

Unity was used to create the VE that would be used for the study, and the SteamVR plugin was used to integrate VR into it. A modified version of Unity's Viking Village demo scene was used in this study. It was modified to include a longbow and ten target dummies around the level. The participants were to follow a route through the level and shoot all the targets with the longbow, which would not only test their ability to locomote in the VE, but also their ability to accurately manipulate objects with their hands while doing so. The route they needed to follow was clearly marked with yellow animated arrows on the ground so that they would not get lost and erroneously increase the TTC.

The three locomotion techniques tested were the PTT technique, the 3D Rudder, and the Spring Stepper. No special setup was required to use the PTT technique, other than the modifications to the VE to make it compatible. The 3D Rudder required a special dashboard program to be installed on the computer and be running in the background while the 3D Rudder was in use. It was configured as a joystick, and this input was interpreted accordingly in Unity. The Spring Stepper just needed to be plugged into the computer for it to work, with no extra programs running in the background.

A single swivel chair was used for all devices, including the PTT technique to maintain consistency. Since the Spring Stepper could not be easily detached from the swivel chair, it was hung on the back of the chair when not in use. This did not adversely affect the usage of the other devices.

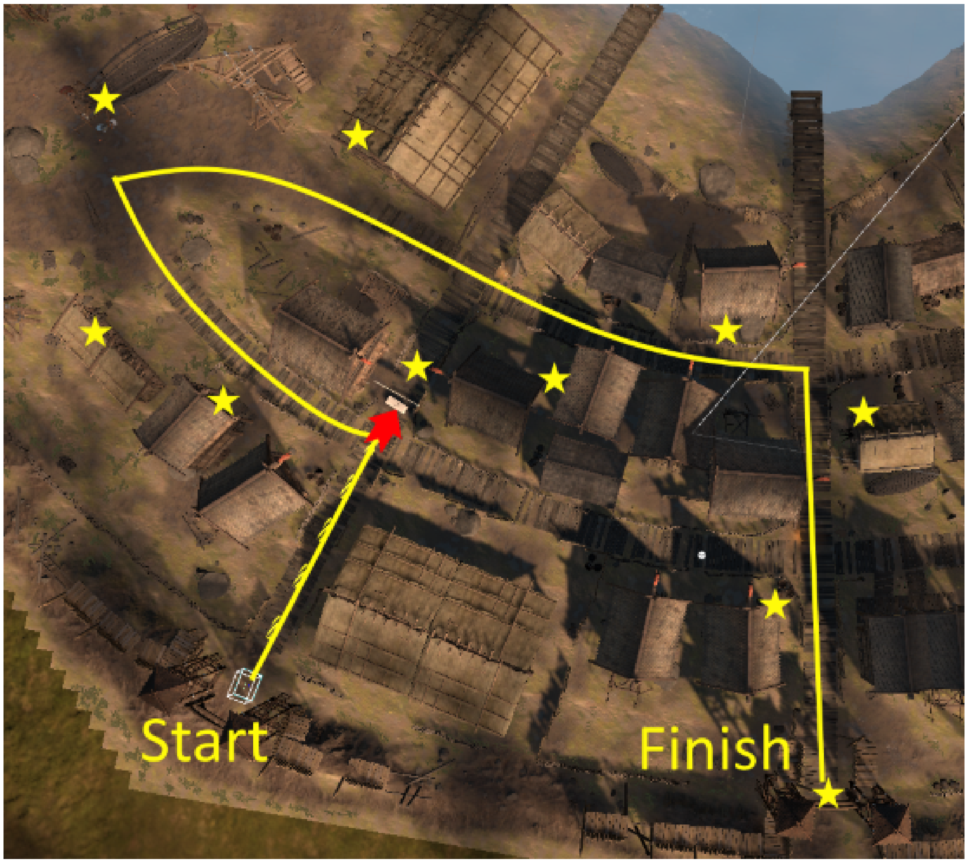

Figure 4.1: Map showing Viking Village VE used for the Spring Stepper study. The route that participants were required to follow is shown as a yellow line, while a target dummy is located at each yellow star. The longbow is located at the tip of the red arrow.

4.4 Procedure

When the participants first arrived at the lab, they were greeted and asked to read and sign a consent form (see appendix D.2). Next, they were asked to fill out a demographic survey (see appendix D.3). Once that was done, they were given a brief description of what their task would be, which was to walk through the level, following the yellow arrows, and shooting all the targets they see with a longbow. They were shown an aerial view of the VE and shown approximately where they would start and where they would need to go. Participants were asked to complete their task as quickly as possible, and that they would be timed. This was to prevent them from skewing the TTC results by exploring the VE or being distracted by the visuals or by the novelty of VR.

Next, they were assigned the order that they would use the three locomotion techniques. To avoid carryover effects, this assignment of usage order was done such that each permutation had an equal number of users. This would reduce the chance that the results would be skewed due to users learning the layout of the VE after the first or second use. Before using each locomotion technique, a short explanation was given to the participant on how to use the technique.

Once they had completed the task with a technique, they were asked to fill out an SUS survey. Once they had finished using all the techniques, they were thanked for participating in the study (see appendix D.5).

4.5 Data Collection

This was a within-subjects study, with each participant using all three locomotion techniques rather than having separate populations for each technique. Three main pieces of quantitative data were collected. The TTC measured the time it took for the participant to shoot all of the target dummies. A timer starts when the participant successfully shoots the first target dummy, and ends when they shoot the last one. This is so that the participant has time at the beginning of the course to familiarize themselves with the longbow, as not all participants would have experience with how to use it. The shot accuracy is another metric that was collected, which was a ratio of how many arrows the participant actually shot compared to the number of target dummies in the level. Each target dummy only needed to be hit by one arrow to be destroyed. The SUS score, which is a measure of system usability, was the last piece of quantitative data collected. This was done by using a questionnaire, which can be found in appendix D.4. The SUS score is calculated from the questionnaire by subtracting 1 from the answers for questions 1, 3, 5, 7, and 9, subtracting the answers for questions 2, 4, 6, 7, and 10 from the value 5, and summing all the resulting values up. The resulting sum is then multiplied by 2.5 to obtain a value that can range from 0 to 100. Qualitative data was also gathered in the form of observed behaviours and remarks, as well as written subjective feedback for each device. Data collection was not focused on immersion or simulator sickness since the focus for this experiment was the usability and efficacy of the device. However, if any of the participants reported simulator sickness, it would be noted.

Chapter 5

Results

This chapter describes the results of the experiment from Chapter 4. All quantitative data collected, namely the TTC, shot accuracy, and SUS scores are analyzed and discussed. Furthermore, qualitative data gathered through observation and informal interview are also discussed.

5.1 Analysis Method

The experiment was a within-subjects study, meaning that each participant used all three locomotion techniques, rather than having separate populations for each technique. Therefore, a one-way repeated measure analysis of variance (ANOVA) was used to analyze the collected data for statistical significance. This analysis method has five preconditions that the data must satisfy in order to be used. First, the dependent variable should be continuous, which is satisfied by all the dependent variables in this experiment. Second, the independent variable should consist of at least two categorical related groups. In this case, it is the three locomotion techniques being used by all participants, and therefore this requirement is satisfied. The third

Spring Stepper		3D Rudder		Teleporting	
W	p	W	p	W	p
0.93551	0.1049	0.94831	0.2116	0.9244	0.05707

Table 5.1: Results of Shapiro-Wilk test for normality of TTC data for each device. p-values lower than 0.05 would indicate that the data violated normality.

requirement is that there should be no significant outliers in the related groups. The fourth requirement is that the data should be approximately normally distributed, which is verified using the Shapiro-Wilk test of normality [41]. Finally, the sphericity of the data, or the condition of having the variances of the differences between all combinations of related groups being equal, must not be violated.

5.2 Time-To-Completion

5.2.1 ANOVA Precondition Tests

There were four significant outliers in the dataset for TTC, which were therefore removed. According to the Shapiro-Wilk test, the data did not violate normality for any of the devices (see Table 5.1). Mauchly's test [29] indicated that the assumption of sphericity had been violated, $W = 0.717$, $p < 0.05$, therefore the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.779$) [17].

5.2.2 Statistical Significance

There was a significant main effect of device on the TTC, $F(1.56,38.96) = 56.12$, $p < 0.0001$, $\eta_G^2 = 0.50$.

5.2.3 Results

It was found that the TTC for the Spring Stepper (M = 157.37, sd = 38.10) was higher than both the PTT technique (M = 81.21, sd = 27.34) and the 3D Rudder (M = 135.57, sd = 31.23). The TTC for the PTT technique was the lowest, and therefore it is the device that performed best, with the 3D Rudder performing slightly better than the Spring Stepper.

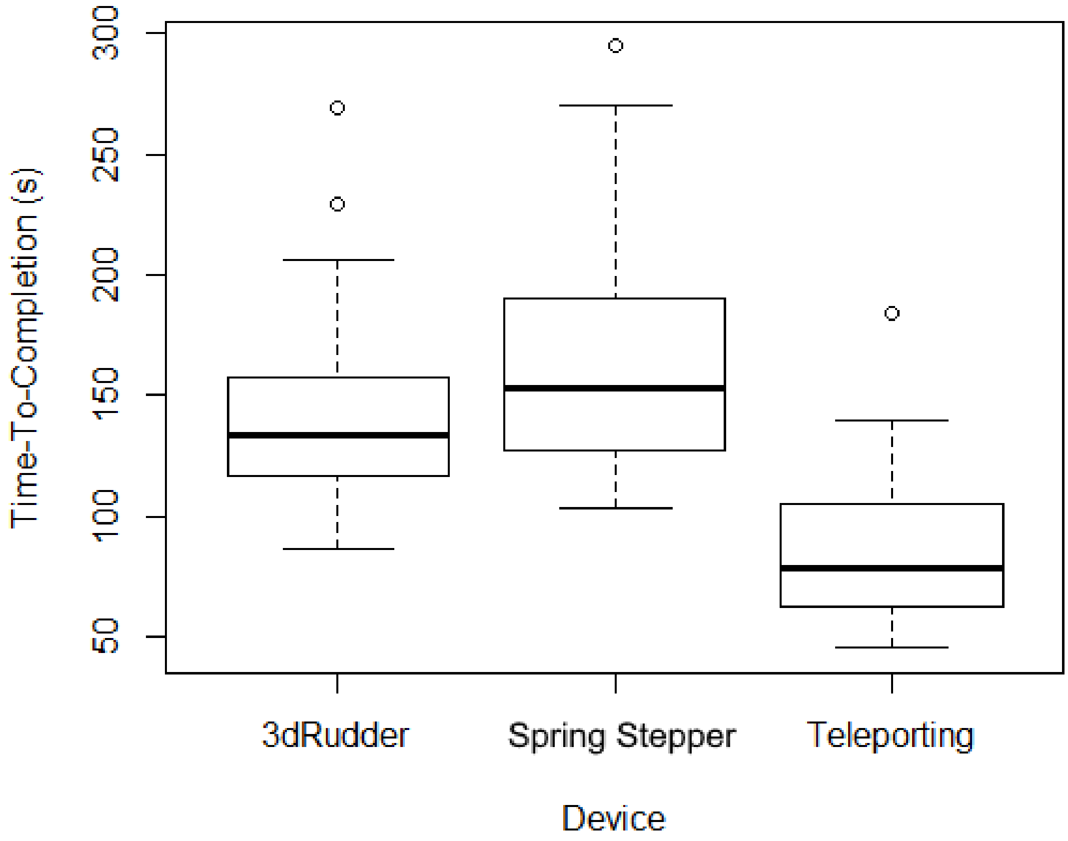

Figure 5.1: Box plot of TTC for each device. Significant outliers are shown in this plot, but were removed from the dataset for analysis.

Spring Stepper		3D Rudder		Teleporting	
W	p	W	p	W	p
0.93041	0.07927	0.96521	0.5042	0.96665	0.5388

Table 5.2: Results of Shapiro-Wilk test for normality of accuracy data for each device.

5.3 Shot Accuracy

5.3.1 ANOVA Precondition Tests

Four significant outliers were removed in the dataset for shot accuracy. The Shapiro-Wilk test showed that the data did not violate normality for any of the devices (see Table 5.2). Mauchly's test indicated that the assumption of sphericity had not been violated (W = 0.92, p = 0.38).

5.3.2 Statistical Significance

There was a significant main effect of device on the shot accuracy, F(2,50) = 7.25, $p < 0.002$, $\eta_G^2 = 0.13$.

5.3.3 Results

It was found that the shot accuracy for the Spring Stepper (M = 0.49, sd = 0.10) was the lowest of the three devices, performing slightly worse than the 3D Rudder (M = 0.53, sd = 0.14). The PTT technique (M = 0.61, sd = 0.18) performed the best of the three devices.

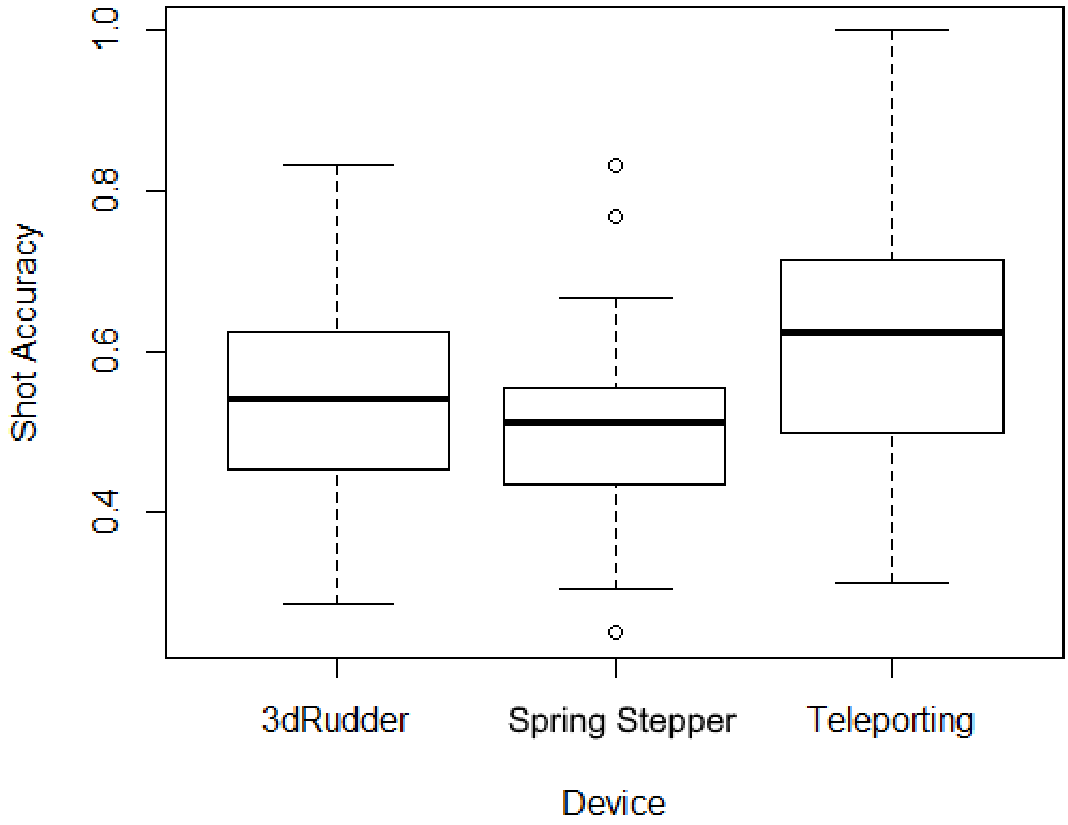

Figure 5.2: Box plot of shot accuracy for each device. Significant outliers are shown in this plot, but were removed from the dataset for analysis.

5.4 System Usability Scale

5.4.1 ANOVA Precondition Tests

One SUS score was a significant outlier, and was therefore removed from the dataset. The Shapiro-Wilk test showed that the data did not violate normality for any of the devices (see Table 5.3). Mauchly's test indicated that the assumption of sphericity had not been violated (W = 0.88, p = 0.18).

Spring Stepper		3D Rudder		Teleporting	
W	p	W	p	W	p
0.95138	0.1987	0.97834	0.7945	0.94009	0.1008

Table 5.3: Results of Shapiro-Wilk test for normality of SUS score data for each device.

5.4.2 Statistical Significance

There was a significant main effect of device on the SUS score, $F(2,56) = 61.73$, $p < 0.0001$, $\eta^2_G = 0.56$.

5.4.3 Results

It was found that the SUS score for the Spring Stepper ($M = 65.26$, $sd = 18.25$) was better than the 3D Rudder ($M = 45.52$, $sd = 15.14$), which scored the lowest. However, it performed worse than the PTT technique ($M = 86.03$, $sd = 9.79$), which was the highest scoring technique.

5.5 Qualitative Data

Through observation and collected feedback, several common remarks were expressed by participants. Eleven participants expressed that they felt the Spring Stepper was immersive or enjoyable to use, while nine participants expressed negative comments about its usability. Some of these negative comments were about how awkward it was to turn, since the device was so high that they did not have any part of their foot in contact with the ground, and therefore could not turn without activating the device. Four participants expressed that they felt the Spring Stepper was flimsy and were afraid of breaking the device. Seven participants expressed that the PTT technique was the easiest to use, but seven expressed that it was not immersive. Eighteen

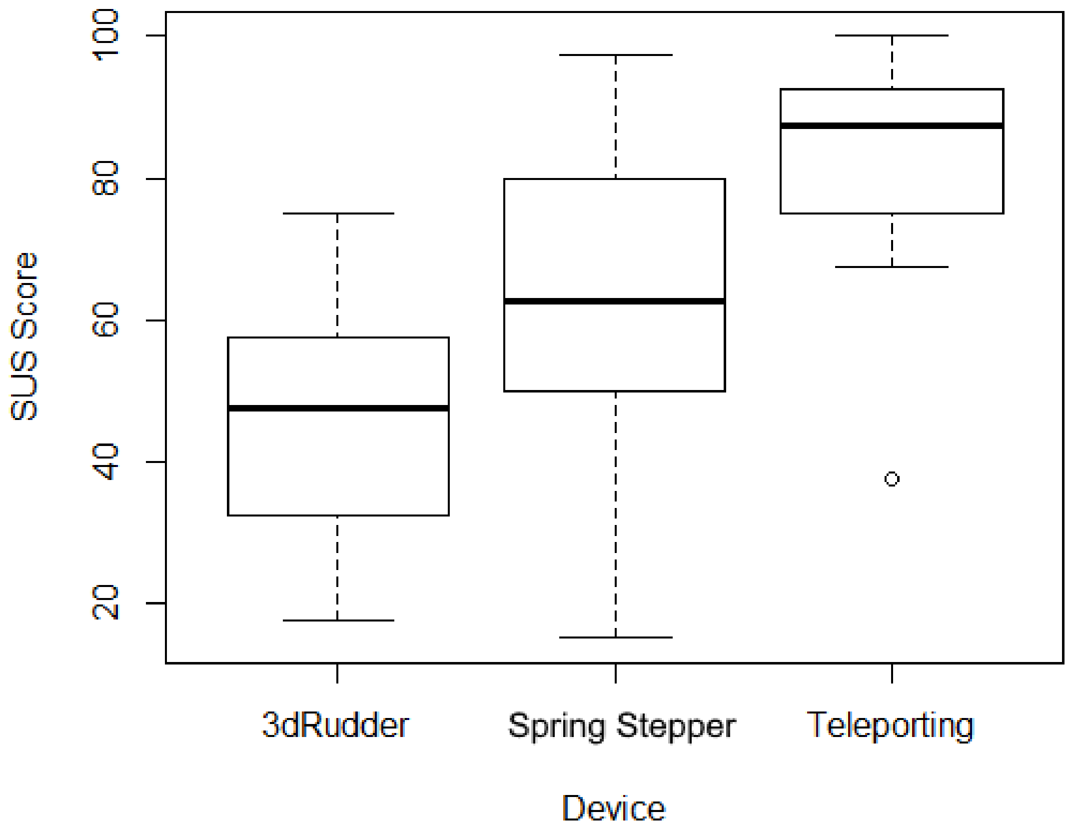

Figure 5.3: Box plot of SUS scores for each device. A significant outlier is shown in this plot, but was removed from the dataset for analysis.

participants expressed negative comments about the usability or enjoyment of using the 3D Rudder, mostly citing difficulty in turning. No participants reported any incidence of nausea with any of the devices.

5.6 Discussion

The mean TTC and shot accuracy for the Spring Stepper prototype was lower than both the PTT technique and the 3D Rudder, thus not supporting **Hypothesis 1**.

One possible explanation for why the TTC is higher for the Spring Stepper than for the PTT technique is that the interaction simply takes longer to do. If one was to compare walking in real life to teleporting around, teleporting would obviously be faster. However, it is interesting that the TTC for the 3D Rudder is slightly lower than that of the Spring Stepper. This could be explained by the fact that once the user has the 3D Rudder tilted forward, their avatar will continuously move forward until they lift their feet back. This is contrasted by the Spring Stepper, where continuous, active input is required to move the avatar. It is also possible to miss a step by not depressing the device far enough, which can cause movement to be more disjointed than the 3D Rudder.

Regarding shot accuracy, the higher accuracy for the PTT technique could be the result of its ease of use. When the user teleports, they are able to choose exactly where they want to appear, as long as the destination is within sight. This allows the user to be able to teleport directly in front of the target instantly and shoot it point-blank. This is contrasted by the Spring Stepper and 3D Rudder, where users are more likely to take long-shots at targets because it takes more time and effort to approach those objects.

The mean SUS score for the Spring Stepper is higher than that of the 3D Rudder, but lower than that of the PTT technique, thus partially supporting **Hypothesis 3**. This makes sense when considering the qualitative data that was gathered from participants. In addition, the qualitative data further supports **Hypothesis 3** because some users reported that they preferred the Spring Stepper over the other two techniques, even if the usability score they gave it was lower. Therefore one can surmise that usability is not necessarily a measure of preference of device, because a device can be less easy to use than another, but still more fun to use.

An additional observation that was made was regarding the build quality of the

3D printed housing of the device. Several participants commented that it felt flimsy and that they were afraid to break it. Furthermore, at the end of the study, the device was taken apart for inspection. It was discovered that there was significant structural damage to the 3D printed housing where the pieces had been rubbing together. In addition, due to the malleable nature of copper, the copper tape on the device had also been deformed and shifted where the two pieces made contact. At one point during the study, additional copper tape needed to be added to the device because it had shifted so much that the contacts were no longer being reliably bridged.

Chapter 6

Conclusion

This thesis reported on the development process and evaluation of a novel, low-cost, seated VR locomotion technique, the Spring Stepper. The objective was to analyze existing techniques to gather requirements, iteratively design a new one that satisfied the requirements, and verify the prototype by testing it against existing consumer-level locomotion techniques. It was compared to the standard PTT technique and the 3DRudder for locomotion speed, ability to allow users to accurately manipulate objects with their hands, and user-reported usability. While the Spring Stepper was found to perform more poorly than the other devices for speed and accuracy, it was found to have a higher usability score than the 3DRudder, an existing consumer-level device.

Below is presented the answers to the research questions introduced in chapter 1:

How does the Spring Stepper compare with the PTT technique and the 3D Rudder in terms of locomotion speed? It was found that the Spring Stepper performed worse than both the PTT technique and the 3DRudder for locomotion speed. It is hypothesized that the Spring Stepper under-performed because of the nature of the stepping action. Walking step-by-step is naturally slower than teleporting, and therefore it makes sense that the user would traverse the VE more slowly using the Spring Stepper. Similarly, when comparing the Spring Stepper to the 3D Rudder, there are periods of time between each step when the avatar stops moving. This is not the case with the 3DRudder, which keeps the avatar moving as long as the device is tilted.

How does the Spring Stepper compare with the PTT technique and the 3D Rudder in terms of allowing users the ability to accurately manipulate objects with their hands while locomoting? It was found that the Spring Stepper performed worse than the 3DRudder and the PTT for allowing the user to accurately manipulate objects with their hands. The difference between the Spring Stepper and the 3DRudder was very small, however, which is promising. It can be hypothesized that the Spring Stepper under-performed again due to the nature of the stepping action. The stepping action makes the user less steady than when using the other two techniques. Both the PTT technique and the 3DRudder allow the user to locomote without having to continually move their body, allowing them to be more steady when they take a shot with the bow. Given that the Spring Stepper is a makerspace device, its design could be improved to increase its performance in the future.

How does the Spring Stepper compare to the PTT technique and the 3D Rudder in terms of usability? The Spring Stepper was found to rate higher among users for usability than the 3DRudder, but lower than the PTT technique. These results make sense when considering the qualitative data that was gathered. The 3DRudder was considered the least user-friendly device of the three, and therefore had the lowest SUS score. Most participants felt that the PTT technique was the most usable one, even if it was not immersive, thus resulting in a high SUS score. Meanwhile, opinions were split regarding the usability of the Spring Stepper, even if several participants felt it was immersive, resulting in a lower SUS score than the PTT technique.

This work contributes to the body of research in VR locomotion in several ways. First, a survey and analysis of existing locomotion techniques was performed and reported on. Next, the analysis of those techniques was used to inform the iterative design of a novel, low-cost, seated VR locomotion device, the Spring Stepper. Finally, the performance and usability of several VR locomotion techniques, including the Spring Stepper, were compared in user studies and the results reported on.

6.1 Contributions

This thesis makes the following contributions in VR locomotion. A makerspace, cost-effective, seated VR locomotion device was created, and the entire process of iterative design taken to develop the device was documented and presented in this thesis. This makerspace approach is flexible enough that the design of the device can be further refined, and more features can be added to it. Furthermore, two user tests were completed and their results were presented in a published paper [53] and in this thesis.

6.2 Future Work

Given the results and feedback from the final study, the Spring Stepper prototype could be further refined and improved upon. The main part that would be changed is the structure of the housing. Rather than use a cylindrical design, it could be redesigned as a sort of miniature pedal that could still be affixed to the user's shoe. This would have a small spring attached to the pedal's hinge to allow it to open when the foot is up, but not strong enough for the user to feel like they need to apply force to press the pedal. The copper leads would be placed such that one is on the underside of the pedal, and one is on the piece that is in contact with the ground. This would make it such that when the pedal is depressed the two leads would make contact, and activate the circuit. This would improve the design in several ways. First, both the plastic parts and the copper tape would not rub against each other, which would improve the longevity of the device. In addition, the pedal design would allow the user's heel to rest on the ground, thus allowing them to be able to turn the swivel chair without activating the device. Another complaint about the Spring Stepper was that it could be difficult to know exactly which direction the chair was pointing in, and users were more inclined to use their upper torso as reference instead of their hips. In light of this, perhaps the Vive Tracker could be removed from the design. Instead, movement direction could be a function of controller position with respect to head position, thus attempting to estimate where the user wants to go based on body posture.

The scope of the device for this thesis was limited to walking forward and turning. In the future, it could be modified to include more interactions, such as back-pedaling and side-stepping. Furthermore, haptic feedback could be added in the form of vibration motors to indicate when the user has walked into an obstacle. Pressure sensors or accelerometers could be added to the design to sense the speed of stepping and the force with which the user steps. This could be used to track walking speed or how quietly the user is trying to walk.

It would also be interesting to directly explore the effects of locomotion technique on immersion and cognitive load. It would be useful to quantitatively measure user immersion using something like the User Engagement Scale (UES) [38]. This, paired with the SUS would give a deeper insight into not only how easy it is to use the device, but also how fun and enjoyable it is to use. Furthermore, cognitive load could be measured using subjective rating of mental effort (SMRE) and simple reaction time (SRT). This would provide information on how difficult it is to use each device while also using controllers to interact with the VE.

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Appendix A

Pseudocode

A.1 PhidgetsComponent

```
Update:
    if calibrationTimer < 5 seconds
        Increment calibrationCount
        loadCell1Sum += ReadValue1
        loadCell2Sum += ReadValue2
        Update calibrationTimer

        if calibrationTimer >= 5 seconds
            loadCell1Calibration =
                                    loadCell1Sum / calibrationCount
            loadCell2Calibration =
                                    loadCell2Sum / calibrationCount
    else
        loadCell1Value =
```

```
            Absolute(ReadValue1 - loadCell1Calibration)
        loadCell2Value =
            Absolute(ReadValue2 - loadCell2Calibration)

        delta = loadCell1Value - loadCell2Value

        if lastStep is Right AND delta < -stepThreshold
            lastStep = Left
            Move avatar forward
        else if lastStep is Left AND delta > stepThreshold
            lastStep = Right
            Move avatar forward
```

A.2 ArduinoPressureSensors

```
Loop:
    Read LeftSensorValue
    Read RightSensorValue
    Output = 0

    if Delta(PreviousLeftValue, LeftSensorValue) > Threshold
        Output +1
    if Delta(PreviousRightValue, RightSensorValue) > Threshold
        Output +2

    Print Output
```

A.3 ArduinoComponent

```
Update:
    Read ArduinoInput from SerialPort

    if ArduinoInput is 01 AND PreviousStep is Right
        PreviousStep = Left
        StepTimer = 0
    else if ArduinoInput is 10 AND PreviousStep is Left
        PreviousStep = Right
        StepTimer = 0

    if StepTimer < StepCooldownTime
        Update StepTimer
        Move Avatar in direction Vive Tracker is facing
```

A.4 HomeHikerArduino

```
Loop:
    Read LeftFSRValue
    Read RightFSRValue
    Output = 0

    if LeftFSRValue > Threshold
        Output +1
    if RightFSRValue > Threshold
```

```
        Output +2

    Print Output
```

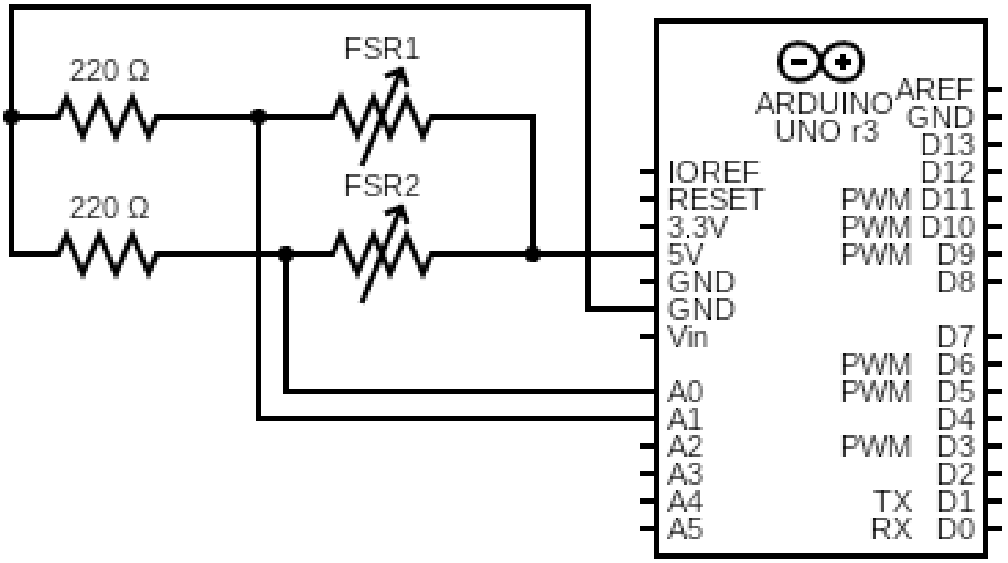
A.5 SpringStepperArduino

```
Loop:
    Read LeftPinState
    Read RightPinState
    Output = 0

    if LeftPinState is HIGH
        Output +1
    if RightPinState is HIGH
        Output +2

    Print Output
```

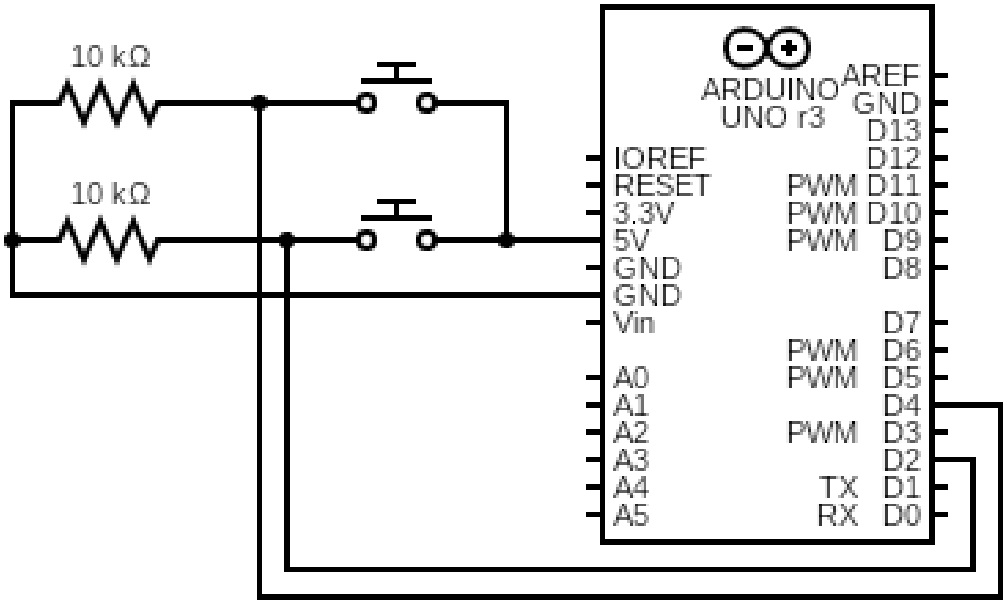
Appendix B

Circuit Diagrams

B.1 Seat Controller and Home Hiker Circuit



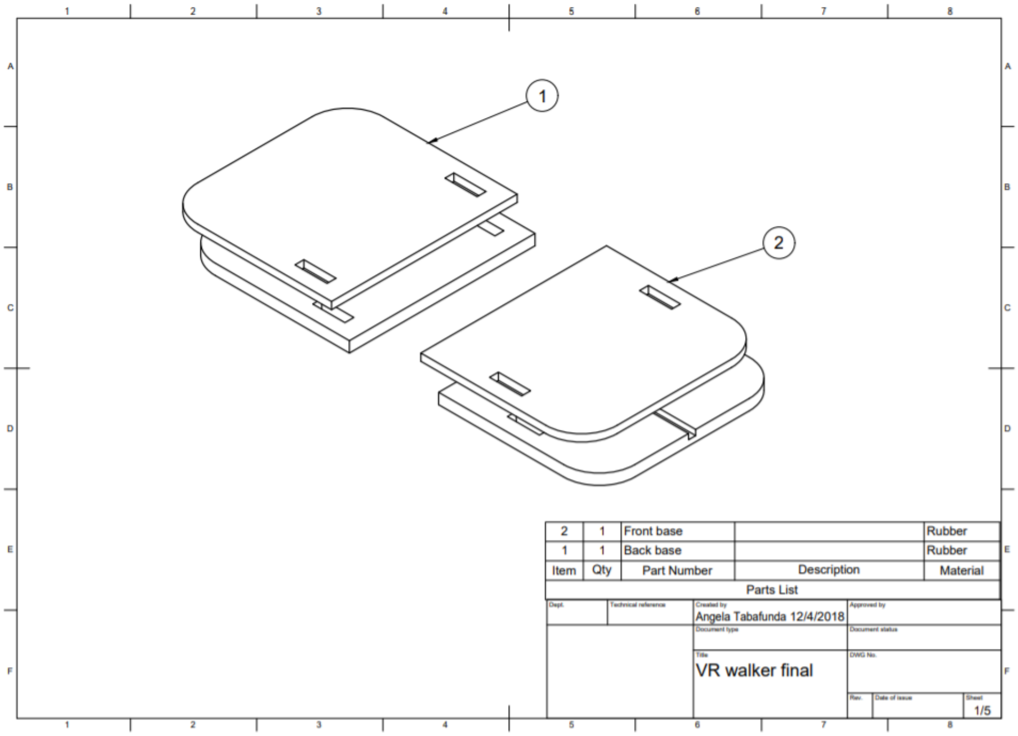
B.2 Spring Stepper Circuit



Appendix C

Blueprints

C.1 Home Hiker Blueprints



Item	Qty	Part Number	Description	Material
2	1	Front base		Rubber
1	1	Back base		Rubber

Parts List

Dept.
Technical reference
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Approved by
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Document status
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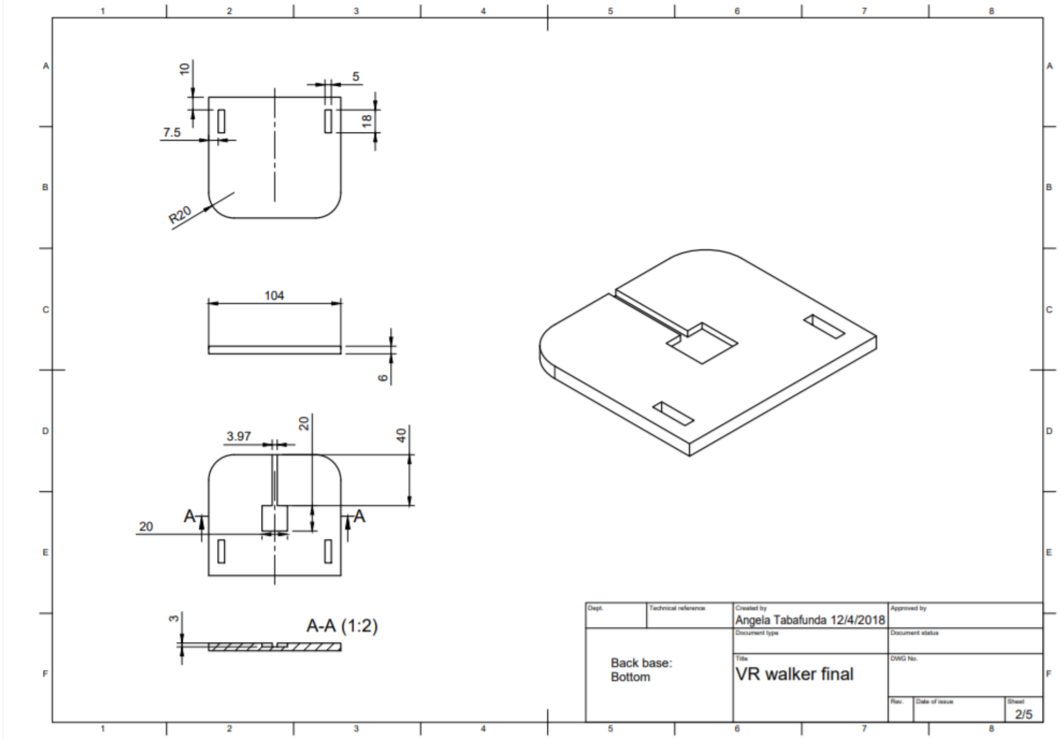
DWG No.
Rev.
Date of issue
Sheet: 1/5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Technical reference
Created by
Angela Tabafunda 12/4/2018
Approved by
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Document status
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Bottom
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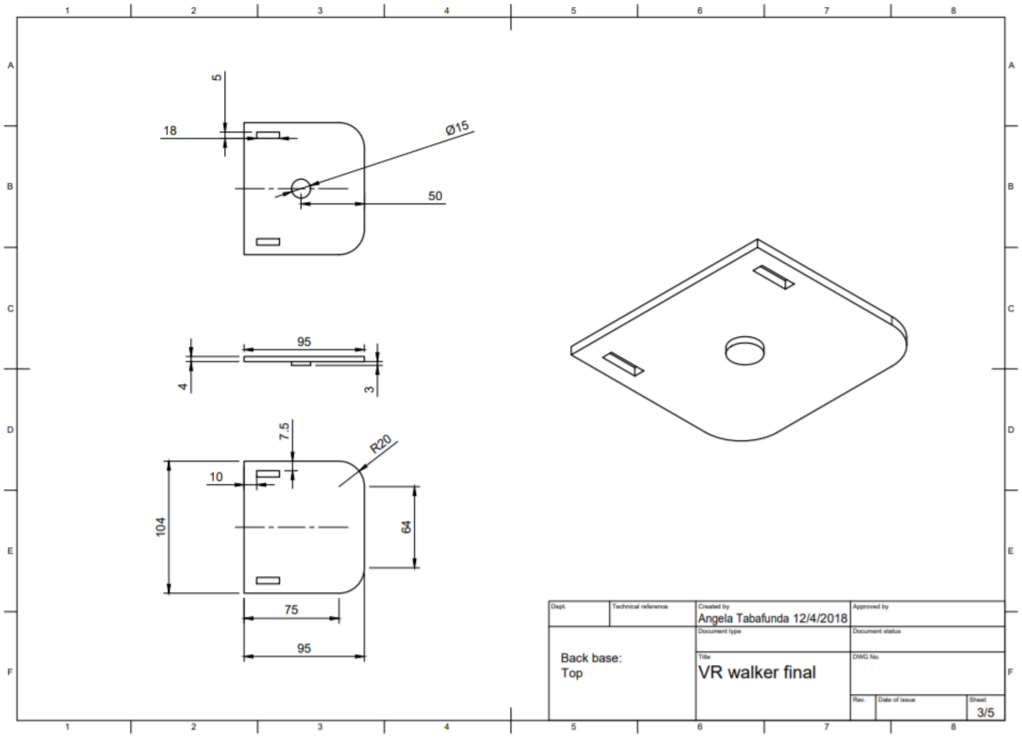
VR walker final
DWG No.
Rev.
Date of issue
Sheet
2/5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Angela Tabafunda 12/4/2018
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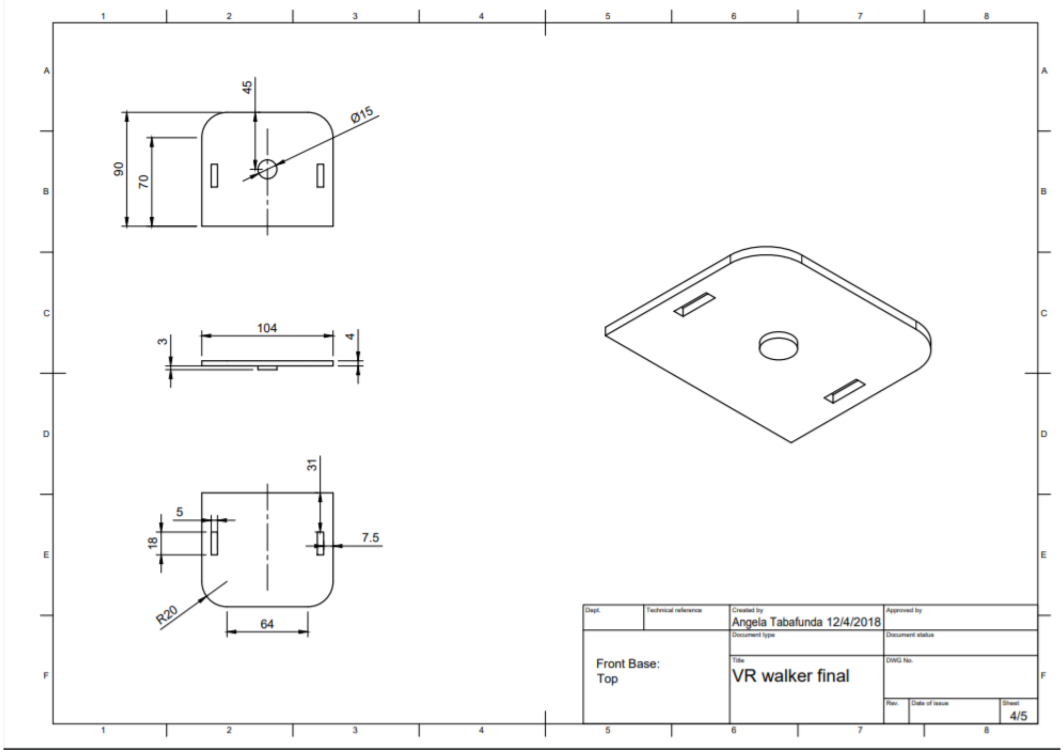
3/5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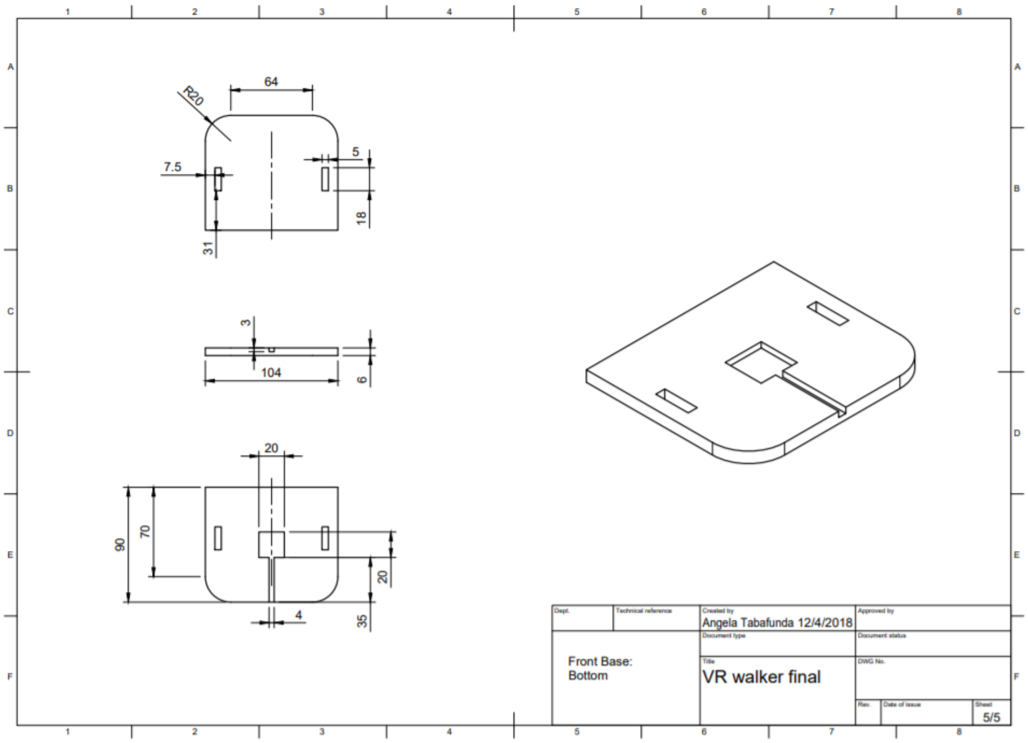
4/5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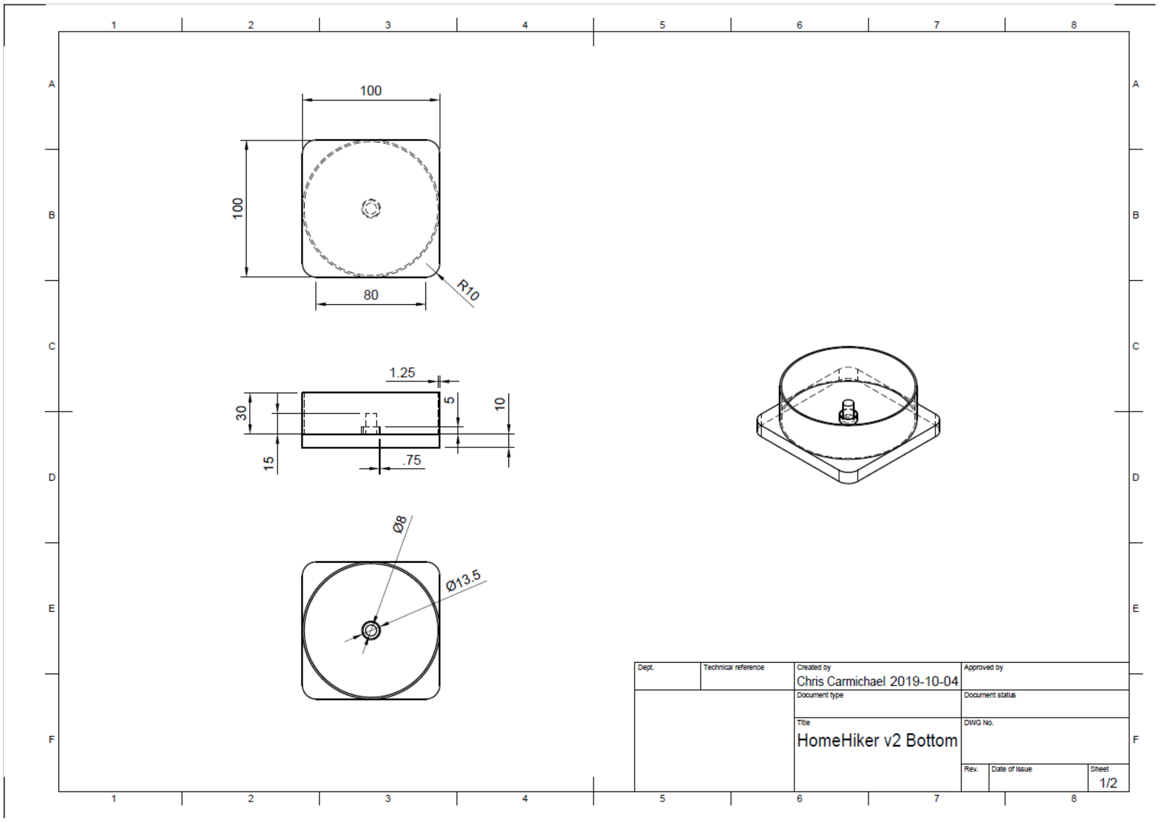
Angela Tabafunda 12/4/2018
Approved by
Document type
Document status
Front Base:
Bottom
Title
VR walker final
DWG No.
Rev.
Date of issue
Sheet
5/5

C.2 Spring Stepper Blueprints



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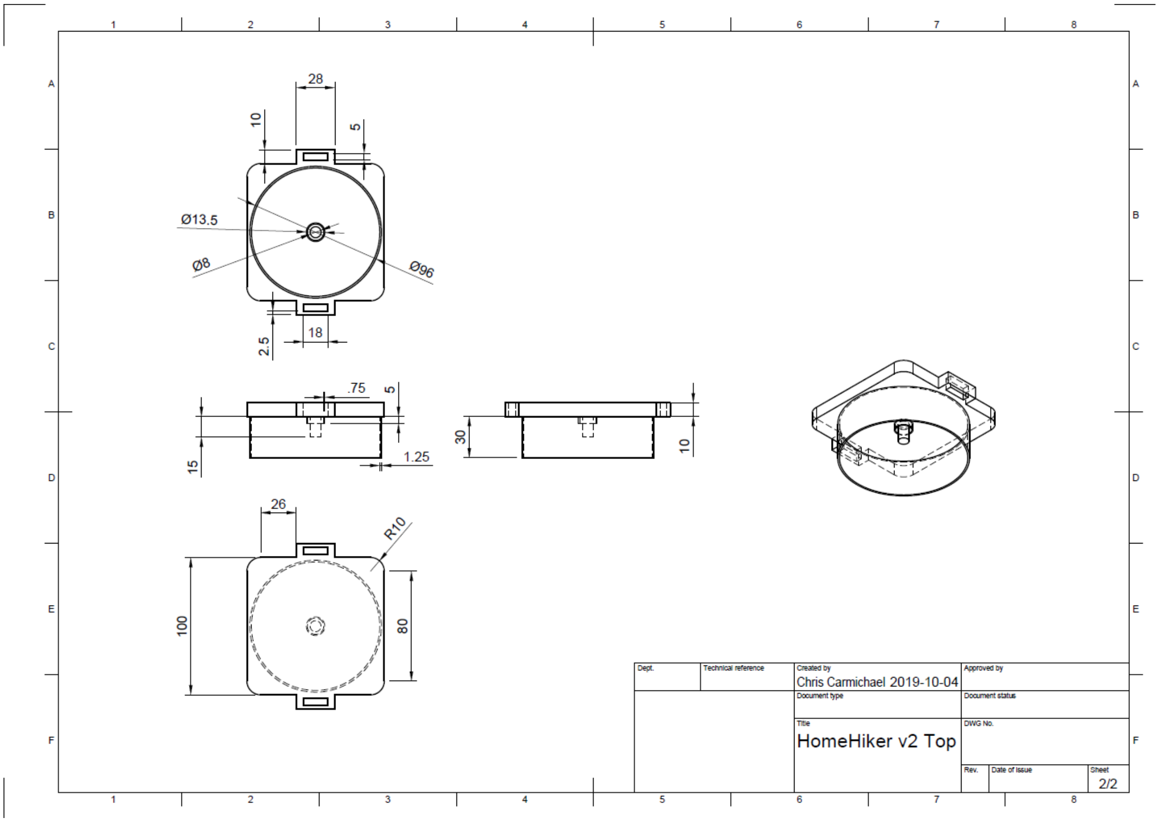
Rev.
Date of Issue
Sheet: 1/2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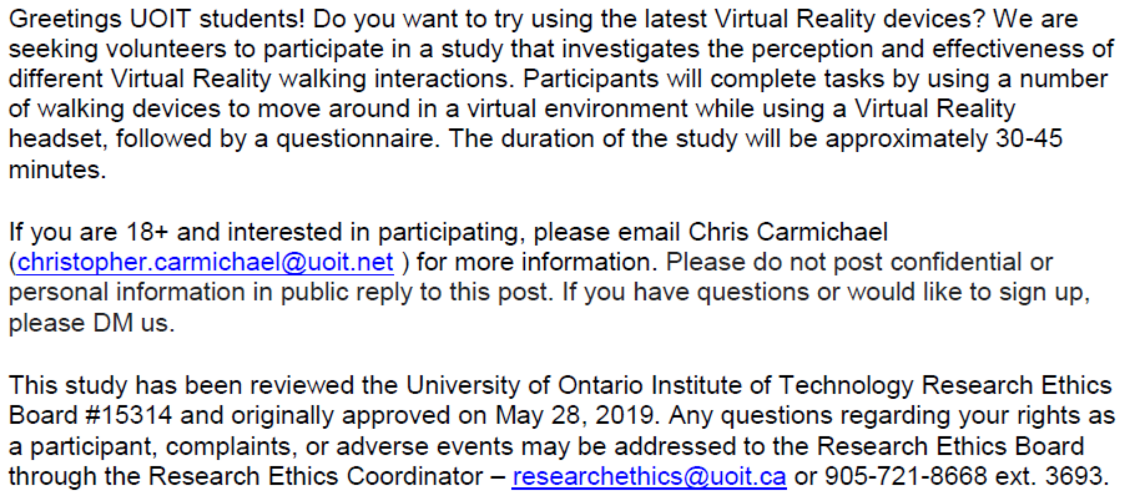
2/2

Appendix D

Study Materials

D.1 Recruitment Script

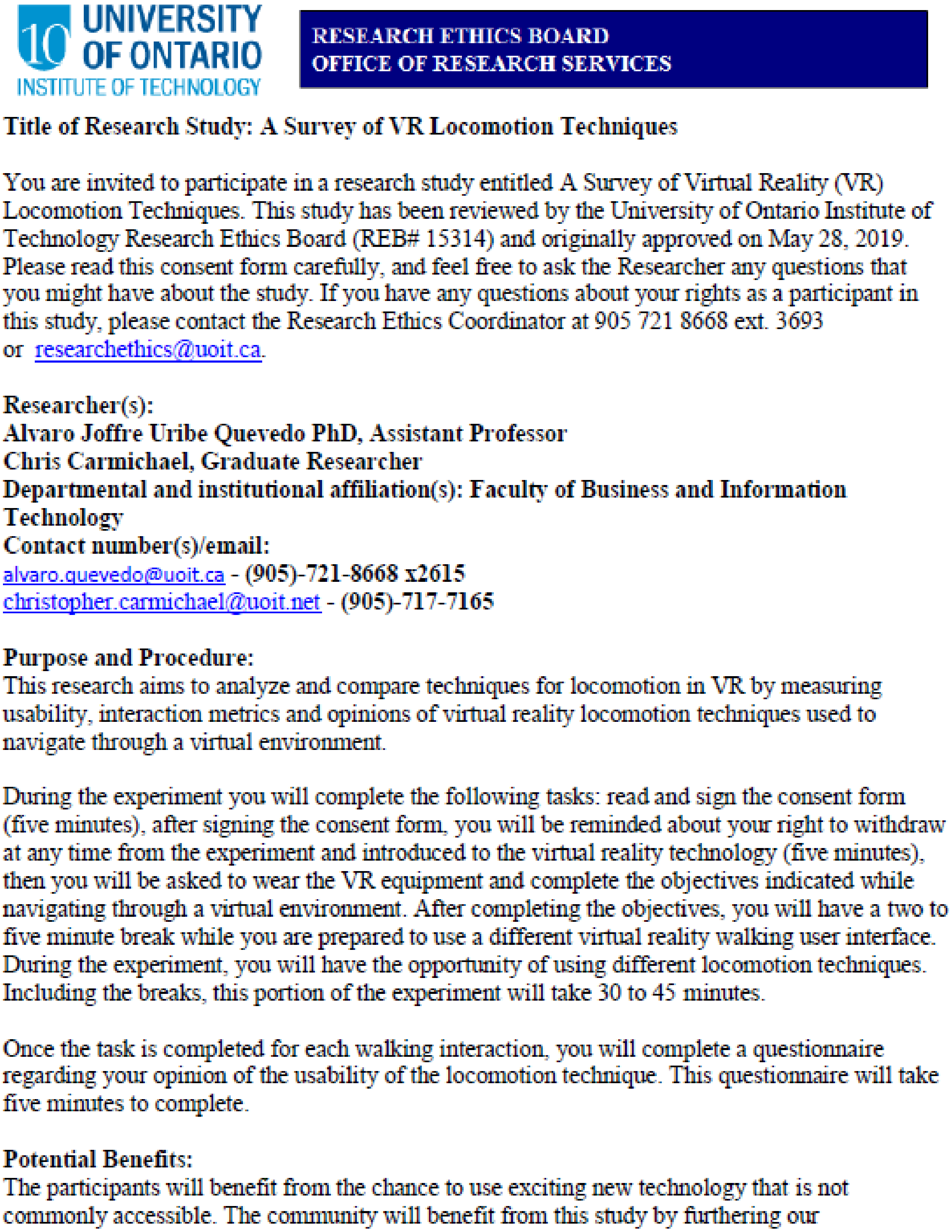


Greetings UOIT students! Do you want to try using the latest Virtual Reality devices? We are seeking volunteers to participate in a study that investigates the perception and effectiveness of different Virtual Reality walking interactions. Participants will complete tasks by using a number of walking devices to move around in a virtual environment while using a Virtual Reality headset, followed by a questionnaire. The duration of the study will be approximately 30-45 minutes.

If you are 18+ and interested in participating, please email Chris Carmichael (christopher.carmichael@uoit.net) for more information. Please do not post confidential or personal information in public reply to this post. If you have questions or would like to sign up, please DM us.

This study has been reviewed the University of Ontario Institute of Technology Research Ethics Board #15314 and originally approved on May 28, 2019. Any questions regarding your rights as a participant, complaints, or adverse events may be addressed to the Research Ethics Board through the Research Ethics Coordinator – researchethics@uoit.ca or 905-721-8668 ext. 3693.

D.2 Consent Form



UNIVERSITY OF ONTARIO INSTITUTE OF TECHNOLOGY

RESEARCH ETHICS BOARD
OFFICE OF RESEARCH SERVICES

Title of Research Study: A Survey of VR Locomotion Techniques

You are invited to participate in a research study entitled A Survey of Virtual Reality (VR) Locomotion Techniques. This study has been reviewed by the University of Ontario Institute of Technology Research Ethics Board (REB# 15314) and originally approved on May 28, 2019. Please read this consent form carefully, and feel free to ask the Researcher any questions that you might have about the study. If you have any questions about your rights as a participant in this study, please contact the Research Ethics Coordinator at 905 721 8668 ext. 3693 or researchethics@uoit.ca.

Researcher(s):
Alvaro Joffre Uribe Quevedo PhD, Assistant Professor
Chris Carmichael, Graduate Researcher
Departmental and institutional affiliation(s): Faculty of Business and Information Technology
Contact number(s)/email:
alvaro.quevedo@uoit.ca - **(905)-721-8668 x2615**
christopher.carmichael@uoit.net - **(905)-717-7165**

Purpose and Procedure:
This research aims to analyze and compare techniques for locomotion in VR by measuring usability, interaction metrics and opinions of virtual reality locomotion techniques used to navigate through a virtual environment.

During the experiment you will complete the following tasks: read and sign the consent form (five minutes), after signing the consent form, you will be reminded about your right to withdraw at any time from the experiment and introduced to the virtual reality technology (five minutes), then you will be asked to wear the VR equipment and complete the objectives indicated while navigating through a virtual environment. After completing the objectives, you will have a two to five minute break while you are prepared to use a different virtual reality walking user interface. During the experiment, you will have the opportunity of using different locomotion techniques. Including the breaks, this portion of the experiment will take 30 to 45 minutes.

Once the task is completed for each walking interaction, you will complete a questionnaire regarding your opinion of the usability of the locomotion technique. This questionnaire will take five minutes to complete.

Potential Benefits:
The participants will benefit from the chance to use exciting new technology that is not commonly accessible. The community will benefit from this study by furthering our

understanding of locomotion techniques for VR, and which techniques perform better than others.

Potential Risk or Discomforts:
You may experience motion sickness caused by latency and tracking issues induced by the hardware.

If you feel any signs of motion sickness, please inform the researchers immediately and indicate if you would like to withdraw from the experiment.

Confidentiality:
All data will be collected anonymously, and therefore no collected data can be used to identify you. The questionnaire will not ask for any information that holds the expectation of privacy. Data collected and consent forms will be kept confidential by Alvaro Joffre Uribe Quevedo on an encrypted hard drive and will not be available to persons outside of the research team. The questionnaire data will be retained indefinitely.

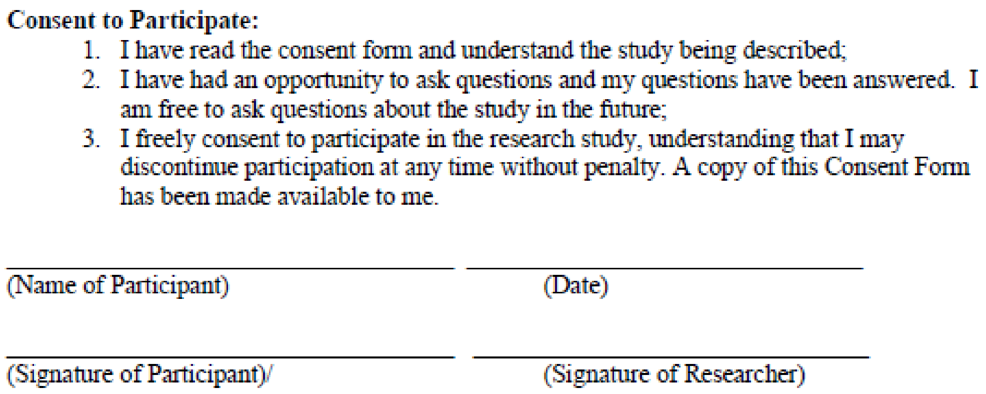
Right to Withdraw:
Your participation is voluntary, and you can answer only those questions that you are comfortable with answering. The information that is collected will be held in strict confidence and discussed only with the research team. You have the option to withdraw from the study and have your data destroyed immediately after completing the study at the latest. After you leave the experiment it will be impossible to link the data back to you for removal as it is recorded anonymously. You are not required to give a reason for withdrawing from the study, and there will not be any consequences if you withdraw.

Conflict of Interest:
If you are a current student of any of the researchers, your grades will not be affected by your participation in or withdrawal from this study.

Debriefing and Dissemination of Results:
You can email the Principal Investigator, Dr. Uribe Quevedo, if you are interested in the results from the experiment. Results will be available two weeks after the experiment was taken.

Participant Concerns and Reporting:
If you have any questions concerning the research study or experience any discomfort related to the study, please contact the researcher Alvaro Joffre Uribe Quevedo at 905-721-8668 x2615 or alvaro.quevedo@uoit.ca.
Any questions regarding your rights as a participant, complaints or adverse events may be addressed to Research Ethics Board through the Research Ethics Coordinator – researchethics@uoit.ca or 905.721.8668 x. 3693.

By consenting, you do not waive any rights to legal recourse in the event of research-related harm.



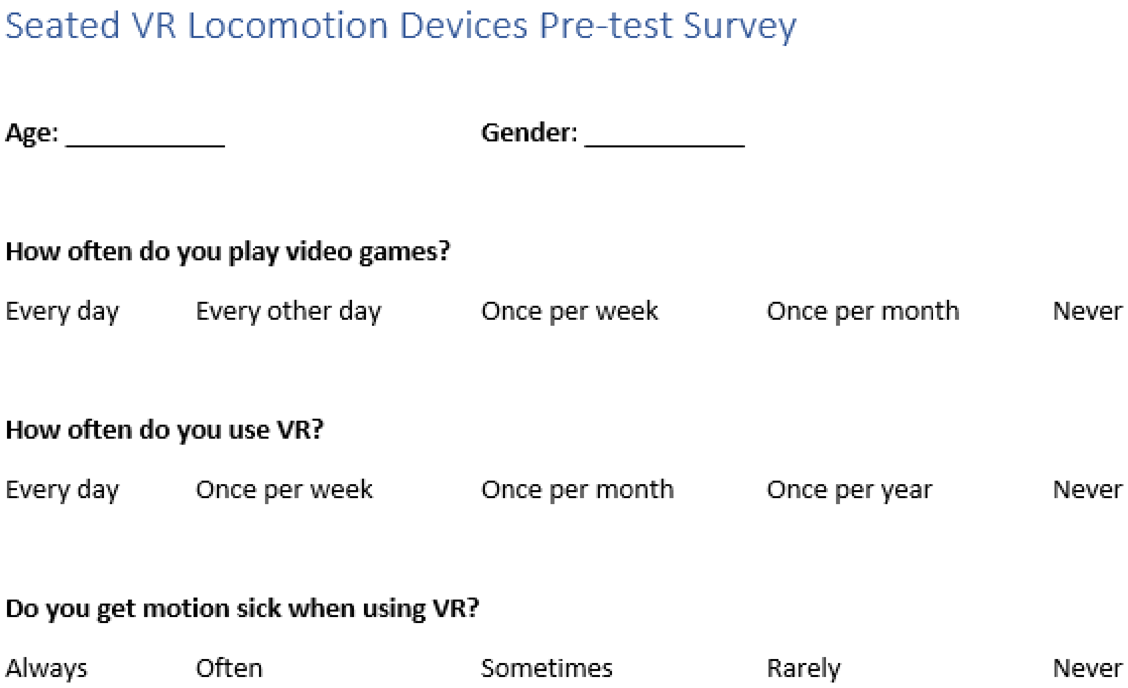
Consent to Participate:

1. I have read the consent form and understand the study being described;
2. I have had an opportunity to ask questions and my questions have been answered. I am free to ask questions about the study in the future;
3. I freely consent to participate in the research study, understanding that I may discontinue participation at any time without penalty. A copy of this Consent Form has been made available to me.

____________________________________ ________________________________
(Name of Participant) (Date)

____________________________________ ________________________________
(Signature of Participant)/ (Signature of Researcher)

D.3 Pre-Test Demographic Survey



Seated VR Locomotion Devices Pre-test Survey

Age: ____________ **Gender:** ____________

How often do you play video games?

Every day Every other day Once per week Once per month Never

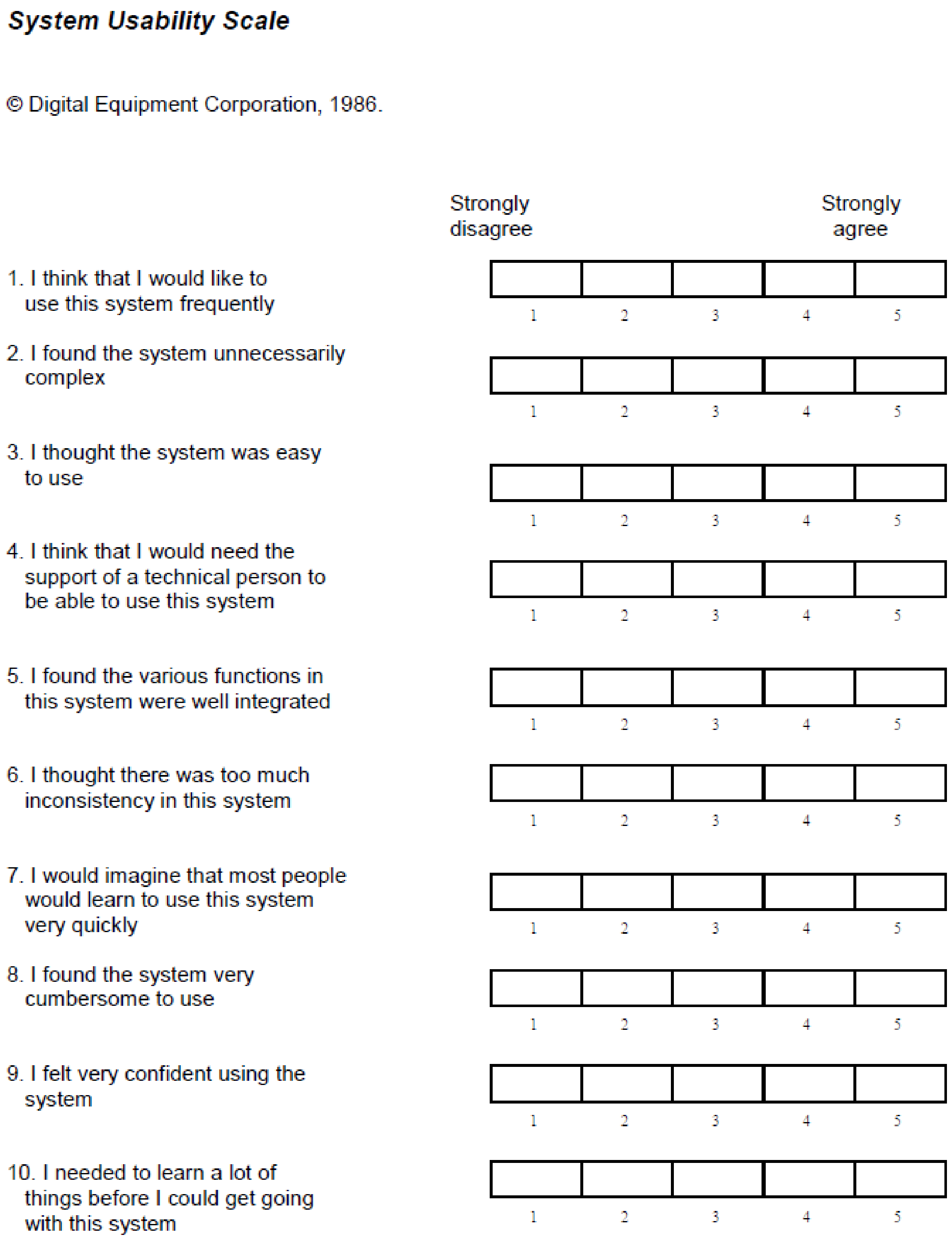
How often do you use VR?

Every day Once per week Once per month Once per year Never

Do you get motion sick when using VR?

Always Often Sometimes Rarely Never

D.4 System Usability Scale

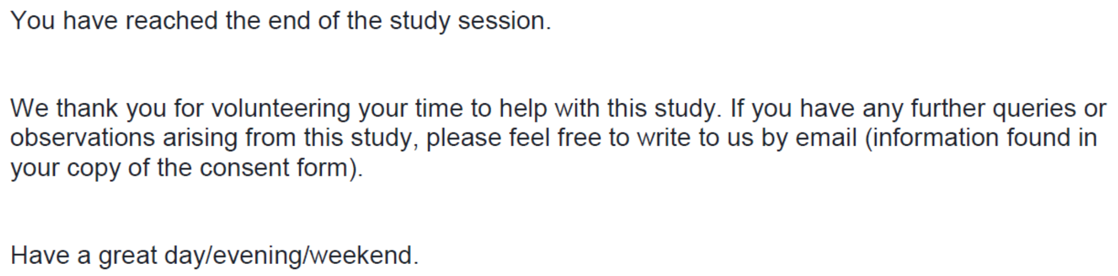


System Usability Scale

© Digital Equipment Corporation, 1986.

	Strongly disagree 1	2	3	4	Strongly agree 5
1. I think that I would like to use this system frequently	☐	☐	☐	☐	☐
2. I found the system unnecessarily complex	☐	☐	☐	☐	☐
3. I thought the system was easy to use	☐	☐	☐	☐	☐
4. I think that I would need the support of a technical person to be able to use this system	☐	☐	☐	☐	☐
5. I found the various functions in this system were well integrated	☐	☐	☐	☐	☐
6. I thought there was too much inconsistency in this system	☐	☐	☐	☐	☐
7. I would imagine that most people would learn to use this system very quickly	☐	☐	☐	☐	☐
8. I found the system very cumbersome to use	☐	☐	☐	☐	☐
9. I felt very confident using the system	☐	☐	☐	☐	☐
10. I needed to learn a lot of things before I could get going with this system	☐	☐	☐	☐	☐

D.5 Verbal Thank-You Script



You have reached the end of the study session.

We thank you for volunteering your time to help with this study. If you have any further queries or observations arising from this study, please feel free to write to us by email (information found in your copy of the consent form).

Have a great day/evening/weekend.