# Accurate Complementary WIP System for Foot Placement in VR

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**Abstract**

The virtual reality (VR) systems of today are gaining in popularity and promise a new way of approaching immersive experiences. Nowadays, one of the biggest problem areas within VR is the concept of virtual traveling. For instance, users are often faced with the predicament of disproportional workspaces. The dimensional mismatch of the real and virtual space heightens the risk of bumping into furniture or walls. Aside from breaking the perception of presence in the VEs, it makes the user susceptible to accidents. Developing static means of travel in VR is a legitimate goal for these reasons. Walk In Place (WIP) is a promising technique, that is safe and does not restrict the user's ability to move his body and limbs. WIP can also offer a natural way of traveling in the VR. However, the concept of general WIP system shows many significant problems. These are often related to reduced fidelity compared to Real Walking technique. To investigate the notion of naturalness in WIP systems, we decided to design an experiment that gives us a closer look at the potential of the WIP compared to Real Walking. The experiment measures users in two condition: a controlled (Real Walking) condition versus an experimental (WIP) condition. During the experiment, the accuracy of the user's steps is measured on various step lengths with following distances $(0.250m, 0.275m, 0.300m, 0, 325m, 0, 350m)$. We hypothesize that the WIP performances deviates less at longer step distances compared to Real Walking. Results indicate that this is not the case. However, the standard deviations of the Real Walking performances decrease as step lengths increases. Our WIP system also avoids motion sickness, and results indicate that it can provide accuracies of close to that of Real Walking, at some distances. Our approach is not flawless, as

it stands the standard deviations for WIP performances are shown to be higher than for Real Walking, but the results are otherwise encouraging.

# Contents

# Introduction

The concept of putting on a headset and being transported into a virtual environment is by no means new, but it has come a long way from just being a concept. Virtual reality (VR) has been present in pop-culture as early as 80'ties and although many of these ideas were conceptualized in the 80'ties the fact remains that computer technologies were not a major aspect of daily life back then, nonetheless, the term 'Virtual Reality' acquired cultural currency during this period (Chan, 2014). The term was first coined by Jaron Lanier, who later expressed his concerns as he felt the term had acquired an overly optimistic tone (Chan, 2014). Back then many foresaw that virtual reality would eventually help computer users abandon their keyboard, mouse and computer display successful more intuitive and immersive interfaces (Robert J. Stone, 2012). Since then many endeavours had been undertaken to realize the technology, but like tidal waves, those dreams were eventually swept away by time and laid to rest. With companies and enthusiasts now wagering to make VR popular again based on renewed interest, it seems we may finally see a time, where VR will rise to its own fame.

With the surge in popularity over the years, and the VR being domesticated into more homes, new challenges arise. One of the more interesting questions that is being asked is how we can create virtual travel techniques that are comfortable and safe, without disrupting presence. Present techniques provides solutions with various trade-offs e.g. treadmills can provide omni direction tracking while ignoring the physical constraints of the room in which the experience is taking place. However, these solutions are often bulky and limit the types of movements the user can perform. Other techniques such as Walk-In-Place (WIP) seems to provide a good trade-off in this regard, but also offers less insurance that the user will bump into walls or furniture. WIP also lacks naturalness as the user's movements does not truly resemble walking. Many existing solutions also induce motion sickness stemming from their simplified models of walking. This project will seeks to solve some of these issues with WIP while providing a foundation and/or ideas for developers.

## Initial Problem Statement

We formulate the following initial problem statement, based on interesting direction in virtual travel techniques in VR:

*How can we create a WIP system that allows control of step length in VE?*

# Analysis

Development of travelling techniques and user-interfaces in VR is a challenging task. Movement algorithms, motion tracking systems and user performance ideally should not limit the possibilities given by the Virtual Environments (VE).

This challenges researchers to search and experiment with various solutions for locomotion in VR.

In the analysis chapter, we will start off with brief overview of virtual reality and taxonomy of virtual travel techniques. Afterwards we will research the perception of presence, perception of walking and body ownership in order to support the feeling of naturalness in a travelling technique. To follow natural movement while performing a walking technique in VR we elaborate on the biomechanics of walking and its implementation in WIP systems followed by a break down of a general WIP system including examples. Finally we will close the chapter by looking at UIs and their application in the VR to provide an helpful form of displaying information to the user.

## Virtual Reality

In this chapter, we seek to explain the success and failures of VR and what means different Relevant Social Groups (RSGs) attribute to the technology. Some effort will also go into explaining technical limitations of VR and how they have been solved as well as outline continued efforts to improve the immersive experience.

### Definition of VR

Virtual reality (VR) is an ambiguous term touching on a broad spectrum of media technologies. It can be defined in terms of four types of components: *"effectors (input and output devices), a reality simulator (the computer and synthesis hardware), an application (i.e., software), and geometry (information within the application that describes physical attributes of objects)"* (Pimentel, 1993). Typically VR systems can be categorized as either: fully-immersive, semi-immersive or non-immersive (Costello, 1997). The keyword here is 'immersion' which is oftentimes used erroneously to describe the sense of presence (Roy S. Kalawsky, n.d.). To avoid confusion, we ought to think of presence as a cognitive or perceptual parameter. As such immersion is mainly concerned with the physical extent of the sensory information presented to the user through the peripheral display (Roy S. Kalawsky, n.d.). A CAVE-like system that relies on a 360° display is then a fully-immersive display. Head Mounted Displays (HMD) – although they do not physically envelope the user – are usually characterized as fully-immersive since many are capable of simulating the whole viewing angle of the visual system.

According to (Slater, 2009b) we can extend the definition of immersion in a more conceptually useful way e.g. immersive systems can be classified by the sensorimotor contingencies (SCs) that they support (Slater, 2009b). SCs refers to the notion of the actions that we know we can carry out to perceive. An example could be shifting our perspective by changing our gaze. Furthermore, according to (Slater, 2009b):

*"The SCs supported by a system define a set of valid actions that are meaningful regarding perception within the virtual environment depicted"*

This means that for a system with head tracking enabled bending down to see underneath something should illicit a change of virtual perspective similar to real life. As such a given immersive virtual reality system comprises a set of so-called 'valid sensorimotor actions' depending on its tracking modalities. What they have in common is that they all result in changes to the images (in all sensory modalities) so that perception is transformed in a meaningful way. (Slater, 2009b) also define set of valid effectual actions. These actions are the ones the user can take resulting in changes in perception or the environment itself. The synergy of sets above is known as the set of 'valid actions'.

### Successes and Failures in VR

Products such as Sony's HMZ series, Carl Zeiss Cinemizer, Sensics zSight, Silicon Micro Display ST1080 (James Templeman, Robert Page, & Patricia Denbrook, 2015) has all offered personal 3D viewing experiences to consumers in the past, nontheless, consumer VR did not become popular until recently. Much of this can be attributed to Oculus's successful crowdfunding campaign. On top of that the Oculus Rift headset was cheaper than competitors. However, mounting evidence shows that a successful funding campaign, publicity and affordable prices cannot solely explain this success (Kay M. Stanney, Kelly S. Hale, & Michael Zyda, 2015).

The success of VR can be said to be a matter of timing; mainly because powerful and relatively cheap CPUs and GPUs that are needed to render stereoscopic images are now broadly available. The same can be said about display technologies, that have become much cheaper over the years. Technical issues also persisted in older VR devices such as motion-to-photon, low field of view (FOV) among other things.

It goes to prove that there are still issues to overcome to ensure VR's continued success. In (Kay M. Stanney et al., 2015) they outline important areas that need improvement; the following is an excerpt of the points that are deemed relevant to our research:

- Improvements in locomotion devices beyond treadmills and exercise machines
- Address fit issues associated with body-based linkage tracking devices; workspace limitations associated with ground-based linkage tracking devices; accuracy, range, latency, and interference issues associated with magnetic trackers; and sensor size and cost associated with inertial trackers

## Virtual Travel Techniques

As the field of *Immersive Virtual Reality* (IVR) is expanding the conflicting disproportion between virtual and the real operating area (workspace) is becoming a crucial problem in the pursuit of improving immersive experience within VR. Developers are trying to come up with hardware solutions that would allow users to explore the space of VR without restrictions of the real world. That is why one of the major focuses within IVR development today is design of an intuitive, flexible and affordable movement control mechanism that allows users to travel within VR. Despite many techniques and devices have been/are being introduced they often come with expenses of limited functionality, price, obstruct hardware or unadaptable operation of the device for the user. Following sub-chapters will reveal basic taxonomy in the field of IVR travel techniques and describe some of the recent examples.

### Taxonomy of Virtual Travel Techniques

Various virtual travel techniques were developed in order to serve immersive experience in different scenarios specifically suited for the case. The taxonomy for virtual travel techniques (Nilsson, 2015) is inspired by existing categorization (Slater & Usoh, 1993), (Suma, Bruder, Steinicke, Krum, & Bolas, 2012), (J. Wendt, (2010)) and divides the techniques into three groups: user mobility, virtual movement source, and metaphor plausibility.

**Metaphor plausibility:** Virtual travel techniques are divided into two groups: mundane (virtual movement is based on a metaphor adopted from real-world movement, e.g., vehicle simulators where user physical movement is translated through number of controllers into the VR movement) and magical (virtual movement is based on metaphor that is not restricted by real-world conditions; e.g., teleports, super jumps).

**Virtual movement source:** Virtual travel techniques differ in sources of the movement force. Body-centric movement source (the forces are taken directly from the real body movement; e.g., walking, swimming etc.) or vehicular (the forces are produced by devices/interfaces that the user is interacting with in real life; e.g., joystick, steering wheel, simulator builds).

**User mobility:** The last category distinguishes between techniques where the user is mobile (user has to move in real world space in order to move in VR space) and stationary (the user may remain in one place within real space controlling movement in VR space).

Today's travel techniques find their place within the 8 subgroups (figure 1) created by the categories above. Even though each subgroup delivers a mean of travelling within VR, their relevance is limited by the scenario they are used for (Nilsson, 2015). It should be noted that the subgroups may be combined in order to deliver optimal experience depending on the case (e.g., WIP combined with teleports or super jumps to cover huge distances). However, in most cases there will be that natural aspect of ourselves(naturalness) that makes us want to wander around on foot perceiving and observing environments using our natural biomechanical movement, paying no attention to the mechanical execution of the movement. Since this project is strictly focused on WIP means of travel other techniques will not be elaborated any further.

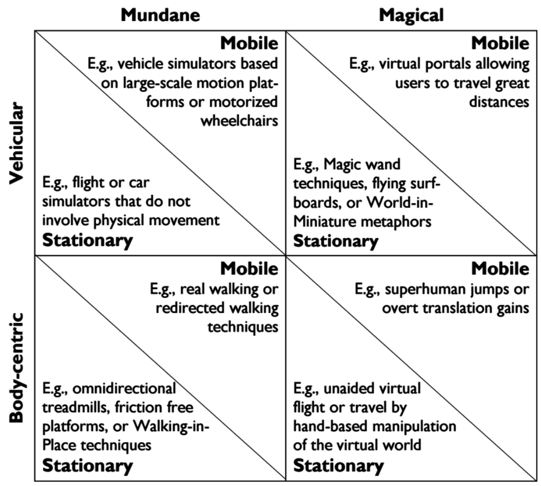


Figure 1: Taxonomy of virtual travel techniques. The vertical axis subdivides the techniques based on the virtual movement source. The horizontal subdivides the techniques based on the metaphor plausibility. The division of each cell represents the degree of user movement relative to the physical environment. (Nilsson, 2015)

### Walk in Place

Walk-In-Place (WIP) belongs to the category of low-cost means of VR travel techniques because of very wide range of sufficient hardware needed for the construction. The implementation of WIP technique provides much more versatility to the controls of the character than other travel techniques. WIP is body-centric-stationary mean of travel in virtual space thanks to its design that allows users to control the entire range of motions within VR by only their own bodies (body-centric) and it does not require the user to walk around in real space (stationary). Depending on further design and implementation the final form of the WIP-technique-controls can contain elements of either mundane or magical metaphor plausibility (degree of realistic behaviour) or even both.

It is argued WIP offers promising solution compared to other travel techniques owing to the fact that WIP requires user's full body movement to interact with the VR world and it comes with no cost of real-world space. That means effective interface, direct engagement and immersive experience for the user as well as accurate user data input crucial for the development.

## Perception of Presence in VEs

The feeling of presence grounds us in reality, it is the grand illusion of the subjective experience, as such it also a curious topic. What is this feeling exactly? For one thing, it is a culmination of our exteroceptive senses; traditionally we think of these senses as vision, audition, gustation, olfaction and somatosensation. However, there are many other senses such as equilibrioception, thermoception, proprioception, and nociception. According to Slater (2009), an ideal immersive virtual reality system (IVR) is comprised of a set of displays, primarily visual, auditory, haptic and a tracking system. This implies that an IVR system does not necessarily need to engage all senses to give a sense of presence. Obviously, the type of system needed depends on the task, e.g. if the virtual experience happens in a perfume shop a device that synthesises scents would be beneficial. Another thing to consider, that has less to do with our senses, is whether the virtual world meets our expectations. Take for example a lit candle sitting on a table. It might be tempting for to blow on the flame. Under normal circumstances, the flame would be extinguished or the sudden gust of wind would cause the flame to flicker. In virtual reality rules are imposed by the developers; as such the representation of reality can lack in certain aspects e.g. blowing the candle may yield no effect. Evidently, sensory and logical incongruities have the capacity to lift the curtain of the immersive experience. To provide a believable experience one must engage both the exteroceptive senses and rational mind.

**Perception in VEs**

VR exploits our natural human skills and sensory characteristics and by doing so our relationship with the technology will inevitably become more intimate. To avoid breaking the illusion of presence in the virtual environment (VE), the technology, therefore, makes use of tricks such as optics, electronic displays, and sensors – the analogy would be that of a magician using mirrors to fool his audience. But the magician's tricks pale in comparison VRs ability to engage all senses. These senses may include vision, touch, smell, vestibular, sound and so forth. Hardware and software must work in tandem to achieve this level of engagement. (James Templeman et al., 2015). Perhaps one of the more interesting challenges in this regard is our own body perception and the roles it plays in deceiving the mind. Within many VEs our *avatar*, usually serves as the vantage point from which we interact with the environment. From the user's perspective, the degree of realism of the VE is determined by "*[...] how realistically he senses the environment and controls his avatar to act in the environment and how realistically the VE responds to his actions*". (James Templeman et al., 2015) It is for that reason vital for these experiences that we employ naturalistic gestures for controlling virtual motions. Failing to do so we risk that users dissociate and reject the VE.

According to Seth, Suzuki and Critchley (Seth, Suzuki, & Critchley, 2012), one possible explanation is a neurocognitive mechanism underlying conscious presence. The proposed model associates presence with "*successful suppression by top-down predictions of informative interoceptive signals evoked by autonomic control signals and, indirectly, by visceral responses to afferent sensory signals*". In short predictive coding describes top-down/feed-forward prediction signals (based on *in prior* knowledge i.e. expectations and experience) and bottom-up/feed-backward prediction error signals (pattern-detection driven). Successful perception, cognition, and action allude to the suppression of the latter. This overturns the classical notion of perception which is almost exclusively based on bottom-up processes. (Seth et al., 2012)

The preceding claims also add leverage to previous work. In a study by Verschure, Voegtlin and Douglas (Verschure, Voegtlin, & Douglas, 2003) it is proposed that a good match between expected and actual sensorimotor signals are associated with the sense of presence in VE. Presently, solutions that deal with *motor substitution* has yet to find a good tradeoff between DoFs of motion and sensory (proprioceptive) expectations of users. (James Templeman et al., 2015). This especially holds true for VR control schemes such as walk-in-place (WIP) or similar methods, because it is in their nature to limit the user's movements to certain predefined walking gestures. Not only does it give rise to a low correspondence between real and virtual limbs, but with the added complexity of traversable 3-dimensional terrain, a mismatch of the physical and virtual environment is almost certain to break presence. (James Templeman et al., 2015) Conducting research into adequate control schemes in VR is important to tackle issues of walking in VR and virtual locomotion. Many VR experiences still rely on unpolished control schemes or try to avoid the issues entirely i.e. by using teleportation to avoid virtual walking.

### Place Illusion

The term 'place illusion' (PI) refers to the feeling of being there (Slater, 2009b). It describes the phenomena that can be perceived during the immersive virtual reality experience when the user responds to a virtual environment as if he would be located there even though it is just a rendered image delivered by VR system (Sanchez-Vives & Slater, 2005). This illusion mainly depends on the hardware capacity of the VR systems. In order to produce the realistic visual and audio experience, the system must be able to replicate the visual and audio experience that is felt during the Real-Life events. The range of conditions determining the quality of PI includes the graphic frame rate ( the time needed to execute each frame of the environment), field of view (the amount of visible environment that can be observed per frame), latency of tracing system (time needed to update the position and of head mounted display and tracked body parts if any), the quality of generated image and rendering (brightness, colour, spatial execution, contrast resolutions, how realistic the graphics are in the perspective of special placement, distances, occlusions etc.) audio should correspond to the locations of the audio source and more (Slater, 2009b). Mel Slater in his article noted that due to the qualia (individual instances) of the experience of this illusion there are not direct methods to measure it, during or after the experiment (Slater, 2009b). However ever self-reported data can be collected (questionnaires, interviews can be conducted) to evaluate the sense of PI during the virtual experience.

### Plausibility Illusion

While PI is all about how one perceives the virtual environment the plausibility illusion (PSI) concerns what is perceived. PSI term describes the illusion that actions that are happening within the virtual environment are perceived as if they were real ("what is apparently happening is really happening" (Slater, 2009b)), even it is known that these actions are only a digital simulation produced by the VR system. To accomplish such illusion natural or specifically to program designed principles or nature must be followed through the whole virtual experience. Given the example, if the virtual object is pushed it should move depending on forces that were applied during the collision. Furthermore, while moving around the object the continuous rendering of the object must be flawless with the effect of changing lighting direction, distance, shadows, etc. (Slater, 2009b). Plausibility illusion is vastly important when it comes to communication between digital character and VR user. The expectation of eye contacts, reactions and responses must be dynamic and non-repetitive (Xueni Pan, 2007). It must be noted that environment and character do not have to be realistic to produce plausibility illusion, but they must follow the laws of nature and be dynamic (Slater et al., 2006). The PSI can be tested using various sensory systems (heart rate sensor, galvanic skin response sensor for intense situations). As well it can be observed in user's behaviour and interaction/communication with the digital environment. Furthermore, self-reported test (interviews and questionnaires) would help to ensure the validity of the collected data.

Place and plausibility illusions contribute towards the naturalness and realistic experience of the virtual environment. If any or both of the illusions are broken the user might lose the immersion factor of the digital environment. Moreover, it could create distractions for the user or even misinterpretations of the environment itself.

## Body Ownership

The mechanism that makes us feel an ownership of our body is still perplexing a lot of psychologists and scientists who study presence and perception in VEs. A wide range of studies has therefore been conducted concerning how our mind recognizes the difference between real and virtual body parts in VEs (Ehrsson, 2012). One reason for pursuing an answer to how the feeling of embodiment emerges is that body ownership has the ability to enhance the user's engagement and presence in VR.

### Rubber Hand Illusion

One of the classical examples of body ownership is the so-called rubber hand illusion (Botvinick & Cohen, 1998). This illusion has been illustrated in experiments conducted in both real and virtual environments (Ehrsson, 2012), (Slater, Spanlang, Sanchez-Vives, & Blanke, 2010). The subject is sat in a chair and asked to observe a prosthetic hand whilst his hand is resting behind a screen in close proximity but hidden from view. The experimenter then applies stimulation i.e. using a brush to stroke both the real and fake hand mirroring his actions on both sides. To the subject, this creates the illusion that the fake hand belongs to him under certain conditions. For example, it is known that rubber hand illusion can only be achieved if multiple perceptive cues are involved. (Botvinick & Cohen, 1998) explain it as three-way interaction among vision, touch, and proprioception.

Futhermore, (Lloyd, 2007) discovered an nonlinear decrease in body ownership illusion during the rubber hand experiment. During an experiment, users felt strong embodiment for distances less than 27,5 cm from the limb. Once the distance was increased the strength of illusion decreased rapidly.

### Ventriloquism Effect

The phenomenon of rubber hand illusion has been observed in similar experiments, one of which is ventriloquism effect (Woods & Recanzone, 2004). When the user's brain receives multiple cues that indicate the connection between the prosthesis and his own body, it takes over the physiological limb connection. This illusion is as well dependent on the distance between the prosthesis that acts as a body part and the actual body part.

### Inducing Illusiory Ownership of a Virtual Body

In the article "Inducing illusory ownership of a virtual body" (Slater, 2009a) researchers observed hand ownership illusion without introducing any tactile stimulation. In this experiment users were introduced with a digital hand in VE. In the first condition the hand opening and closing motion was synchronised with the users motion while second condition displayed independent motion of a digital hand. Test results showed that people exposed to synchronised digital hand felt the illusionary ownership after approximately 5 minutes of interaction. However, people exposed to asynchronous digital limb failed to experience the illusion.(Slater, 2009a)

## Gait-Understanding of Real Walking

When simulating walking in virtual spaces it is important to study and analyse the real motion of walking and properly design the walk cycle or gait cycle based on the collected data. Understanding of real walking cycle is, therefore, vital for developing a natural walking animation in the VR.

### Walking Gait Cycle

Walking is a process in which our body act as a vehicle for movements in space aided by our legs. Throughout our lifetime our brain learns how to move around and keep our balance. It is, without a doubt, a very complex mechanism that requires a lot of sensory information and processing of said information. Even so, we do not usually need to concentrate a lot to perform the task, according to literature this is because part of walking is cognitive and the other is automated by neural circuitry e.g. central pattern generators in the spinal cord and the supraspinal structures (Iosa, Gizzi, Tamburella, & Dominici, 2015). According to (Nilsson, 2015): *"We are generally able to describe the act of walking in terms of repeated gait cycles—the period from initial contact of one foot until the same foot makes contact again"* (see figure 2 and 3).

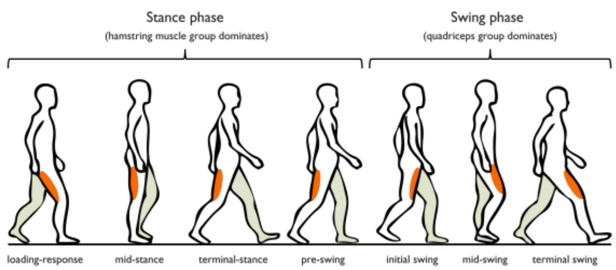


Figure 2: "*Illustration of the two general phases of the gait cycle. The dominant muscle groups are highlighted with orange.*" (Nilsson, 2015)

The gait cycle is divided into two main parts the stance, which takes up around 60% of the cycle, and the swing, covering approximately the last 40% that starts with (see figures 4 and 5). The double support happens twice within the cycle, during the initiation and termination of the state, taking up to 20% of the total Gait cycle progression. It must be mentioned that double support, as well as stance or swing phase's lengths, may vary depending on the speed (Nilsson, 2015).

An important measure in the gait cycle of walking is step frequency. Step frequency is directly related to the gait phases' times. As step frequency increases, the stance phase's gait-cycle percent-time decreases (Figure 5).

Real walking speed is estimated under following formula where step frequency (f) and step length (l) produce walking speed (|v|):

$$|v| = f \times l \tag{1}$$

Literature on topic of biomechanics of walking indicates that stepping frequency and step length are positively correlated (Pheasant, 1981). Moreover the literature proves that the subject's height is correlated the same way to the step length. Dean proposed the following relationship between walking speed $|n|$, step frequency $f$, and subject height $h$ (Dean, 1965):

$$|v| = \left(\frac{f}{0.157} \times \frac{h}{1.72}\right)^2 \tag{2}$$

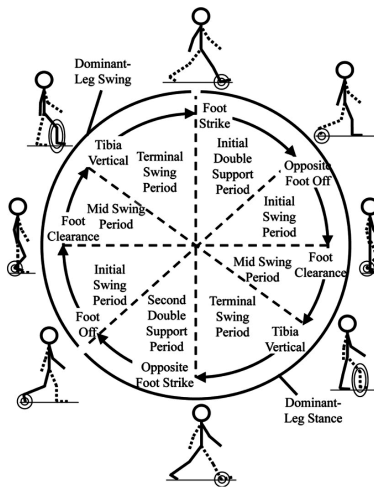


Figure 3: "*The gait cycle defined for rhythmic Real Walking. Gait-cycle periods are shown within the inner cycle. The dominant leg's stance and swing phases are shown in the outer arcs. Gait cycle events are named on the inner cycles perimeter*"(J. D. Wendt et al., 2010)

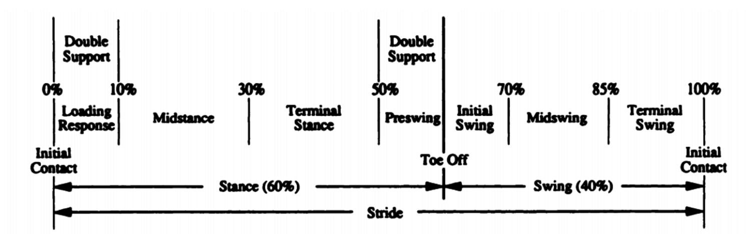


Figure 4: *"Schematic representation of the walking gait cycle. The stance phase is separated into four components (loading response, mid-stance, terminal stance and pre-swing ), and swing phase into three components (initial, middle and terminal swing). The position in the cycle where each phase begins is recorded as a percentage.Initial contact and toe-off are instantaneous events."* (Bharti & Gupta, 2012)

## Gait-Understanding-Driven Walking-In-Place (GUD WIP)

Now that the gait cycle of real walking was settled it is essential to understand the differences between real world gait cycles and gait cycles in WIP. This

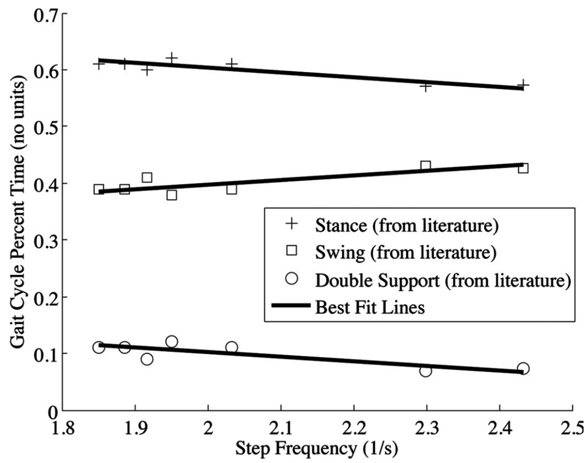


Figure 5: "Step frequency vs. gait-component gait-cycle percent time. Stance, swing a double-support percent-times vary linearly with step frequency"(J. D. Wendt et al., 2010).

chapter will describe and illustrate the differences and provide reasoning behind the design.

### WIP Gait Cycle

WIP gait cycle (Figure 6) is generally simpler since the real walking cycle contains unnecessary swing periods that are technically difficult to be distinguished between. Therefore the three swing phases are merged into two swing phases: Initial and Terminal. Events that use to differ the three swing phases in real walking gait cycle are redundant after this adjustment. The only event between final two swing phases in WIP gait cycle is maximum leg height. (J. D. Wendt et al., 2010)

WIP gait cycle can be represented by a state machine (Figure 7). Self-loops are omitted to simplify the figure.

"*The state-transition diagram indicates a direct way to measure steady-state step frequency: After the user completes three successive gait states, the time required to complete those three states is a full step's time. This frequency estimate persists during the following gait state. When any state finishes, the estimate is updated to include only the three most-recently-completed states.*" (J. D. Wendt et al., 2010)

The estimated frequency combined with the user's height yields intended speed just like it was in case of the speed formula for real walking.

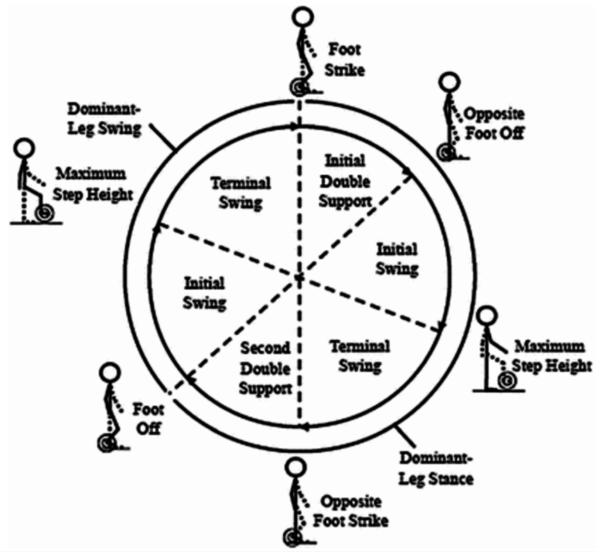


Figure 6: The gait cycle for rhythmic in-place stepping (J. D. Wendt et al., 2010)

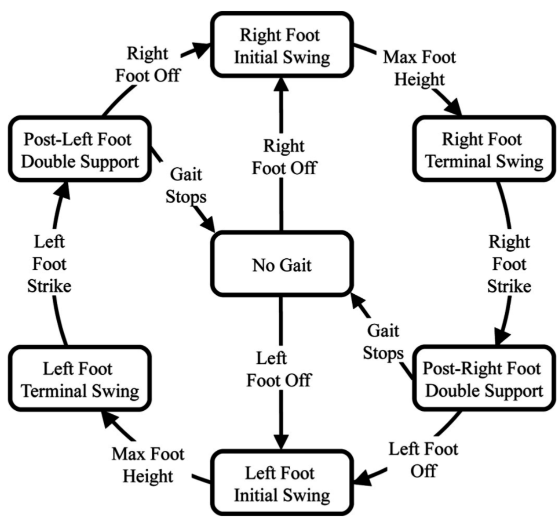


Figure 7: GUD WIP state machine. The current state is maintained until a state-exit criterion ( shown on transitions) is fulfilled. (J. D. Wendt et al., 2010)

## UI Elements as Visual Indicators

Immersion is playing key role on the way of improving user's experience in VR. The field of studies on immersion is valuable source for game development industry. Immersion factor in games closely resembles Klevjer's definition of realistic agency (Klevjer, 2006):

"*Realistic agency is achieved when you do not have to play the game by following a set of instructions and when the behaviors of characters, objects and processes in the game can be ascribed to their own properties and capabilities rather than to rules that are external to them.*"

Immersion in games is achieved by various criterias being met. One of the main criterias for the immersive experience in games is building proper user interface (UI).

**Taxonomy of UI Elements**

UI elements can be divided into four groups depending on correlation of two factors: If the element is rendered in the 3D space and if the element exist in the fictional world of the character. Basic terminology used for this area can be found in the work from Fagerholt and Lorentzon (Fagerholt & Lorentzon, 2009) see figure 8.

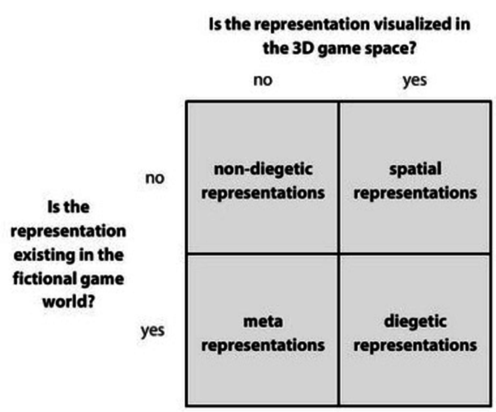


Figure 8: Terminology from "Beyond the HUD - User Interface for Increased Player Immersion in FPS Games" (Fagerholt & Lorentzon, 2009)

For the sake of improving the experience in the VR, UI elements that are rendered in the 3D space could be used to deliver new experiences to the user and could be subject to experiments in the effort of improving user's experience in WIP.

### Visual Indicators

Different UI elements/representations serve as hints in artificial environments in order to guide the user. It is a common tool to help navigate and help to progress through different scenarios. Various diegetic or spatial UI elements can be used as an extension of human senses in combination with the use of visual computing to deliver new or improved experiences and abilities to the user (e.g., spatial representation of aim or trajectory that helps predict impacts and improves accuracy). Such tool could have very practical use in finding an alternative way of visually representing users' step/foot placement in the artificial environments in process of WIP.

### Visual Indicators in WIP Systems

When talking games, depending on the pace and genre of the game one can conclude validity of a certain information being displayed in different forms UI elements for a user. As an example, a user playing FPS (first person shooter) game, with fast-paced content and goal of killing enemies, is probably not interested in UI element indicating character's current movement speed relative to the environment. Therefore, an indicator of speed, in this case, would be unpractical and useless for the game purpose. However, considering a different example, such as a simulator or of any kind could be, it is obvious that the validity of realism element is in the place. In this case UI elements indicating a state or raw output based on physical values that accompany the events the user is experiencing is vital for the game validity relative to its genre. A solution for such scenario could be implementing UI elements indicating translation of the information into the understandable form of the user (e.g., coloring line representing a range of colors mapped to a range of speed indicating speed value and warning).

## Walking-in-Place Systems

Today's WIP techniques share the general order of key mechanics to be implemented. The process of making a virtual walking from WIP can, therefore, be described in three steps: (1) Proxy step detection, (2) Speed estimation, and (3) Steering (Whitton & Razzaque, 2008).

### Proxy Step Detection

The detection of the actual steps can be done in many different ways. They differ in the type of sensors used and body parts the sensors are attached to. However, no matter the hardware we can distinguish two step proxy detection approaches. Systems that detect discrete gait events (e.g., foot-ground contact) and systems that monitor continuous movement (e.g., foot position, velocity) (Medina, 2008). Even though projects of both methodologies are sharing the same theoretical base ground - gait cycle events of WIP, previously described in

GUD Locomotion chapter, their implementation of this theory is very different mostly because of their hardware's capabilities.

Most famous discrete gait events WIP techniques are implementing devices such as treadmills (S. Bouguila, 2013) and other often custom-made platforms (F. E. C. M. H. B. Bouguila L., 2005) that are used to track the foot-surface contact or simulate various terrain attributes. However, these techniques are robust, time-consuming to build and not very user-friendly when it comes to maintaining. The discrete gait systems have one major problem when it comes to IVR experiences. The problem is that the systems are struggling to recognize the start and end of the steps which is then observed by the user as moderate delays when starting/stopping to walk in VR (Feasel, Whitton, & Wendt, 2008). In the end, the nature of discrete-gait-events systems is to react to an event – contact and deriving the events in between using only predictions and scaling. This makes the discrete gait systems very tricky to develop and calibrate.

There are also other ways that do not involve such robust implementations and promise similar functionality with the use of minimal amount of hardware. Systems using continuous movement tracking naturally seems to generate a more valid representation of the data that are so crucial for the accurate WIP-to-IVR movement translation (e.g., LLCM-WIP) (Feasel et al., 2008). Tracking different leg parts in real time is allowing developers to create systems evaluating user actions with a better understanding of user's intentions based on the data generated by the movement.

For this project, it seems reasonable to go with the continuous movement tracking system design. The reasons revolve around affordability, accessibility, data-validity, relevance to the date and simplicity of the implementation.

### Speed Estimation

This topic is still considered to be evolving and there is no 'the best' solution to be found. Speed estimation of WIP is directly connected to perceived experience in IVR. There exist various algorithms implemented in the WIP projects. The LLCM-WIP (Low-latency Continuous-motion) system is using magnetic tracking of vertical heel velocity to determine speed (Feasel et al., 2008). The GUD-WIP (Gait-understanding-driven) system is calculating speed based on the optical capture of vertical heel velocity (J. D. Wendt et al., 2010). The SAS-WIP (Speed-amplitude-supported) system uses a similar approach by measuring step amplitude with optical capture to calculate speed (Bruno, Pereira, & Jorge, 2013). The SF-WIP (sensory-fusion) system is using magnetic together with acceleration sensors and Kinect to calculate the speed (Kim, Gracanin, & Quek, 2012) (Langbehn, 2015). One more system known as LAS-WIP (Leaning-amplified-speed) is similar to previous methods but implements leaning as a factor for amplifying the speed (Langbehn, 2015)).

An example of the basic speed estimation implemented in a GUD WIP system (J. D. Wendt et al., 2010) is using the formula suggested by Dean (Dean, 1965) that we previously mentioned in the chapter on the biomechanics of walking:

$$|v| = \left(\frac{f}{0.157} \times \frac{h}{1.72}\right)^2 \tag{3}$$

### Naturalness in WIP

Naturalness is the key to delivering immersive experience in VR. The naturalness of the perceived motion in VR translated from WIP motion is one of the issues we want to address. According to (Nilsson, Serafin, & Nordahl, 2016):

"*The question of how to facilitate natural actions may be subdivided into at least two different, albeit interconnected, challenges; namely, the challenge of finding the gestural input which is perceived as the most natural by the user, and the challenge of how to provide the user with the most natural method for steering.*"

This project is mainly related to the first challenge of gestural input perception also limited to the forward-only movement (no backward or lateral movement). From some of the past experiments on this topic, we can see that among top natural gestures tapping gesture competes with traditional WIP gesture (Medina, 2008). Subjects performing tapping gesture were also observed to drift less than other gestures in the experiment. Other study proved that arm swinging gesture is also a big competitor with the traditional gesture when talking naturalness and even proven to be preferred match for real walking in terms of physical strain (Nilsson, Serafin, & Nordahl, 2015). The fact that arm swinging gesture prevents users from using hands to interact with the environment while performing WIP puts the tapping gesture ahead of other gestures in terms of preferability as a result from these two experiments.

Another key aspect of the naturalness of WIP as the mean of travel in IVR is self-perception during WIP locomotion. This aspect covers "sensation of virtual body-ownership may be crucial to compelling IVR experiences" (Slater, 2009b). The problem of visuomotor asynchrony may occur in process of maintaining such illusion and endanger its validity (Kokkinara & Slater, 2014).

## Final Problem Statement

We initially defined our problem statement as follow:

*How can we create a WIP system that allows control of step length in VE?*

After investigating this problem area we were able to converge to a final problem statement that encapsulates aspects that we feel are worthy of more attention. Specifically, as the research have shown us, most WIP systems are focused on continous walking and the naturalness of these systems. However, they falter when it comes to being accurate e.g. our analysis showed that start and stop delays are persistant issues with these types of systems. Our focus will be on non-continous walking or stepping in place with intuitive and accurate controls as well as the implementation of a graphical user interface. We believe such a system would work complimentary to existing WIP techniques, thereby providing higher step accuracy where needed in application (e.g. games) that involve difficult terrain. Our final problem statement thus becomes:

*How can we design a WIP system that allows for accurate and intuitive foot placements using visual cues?*

# Methods

## Measuring Presence

When testing the naturalness of a virtual environment (VE) it is necessary to account for the feeling of presence. The most common way of testing presence comes as an evaluation of the results from the user feedback or sensory data before, during or/and after the VE (Witmer & Singer, 1998). The examination can be attained using various data collection techniques. The data can be self-reported, where users describe their awareness of presence or physiological, gathered during the experiment using miscellaneous sensory systems (Seth et al., 2012). Serf-reported data can be gathered during the test using think aloud protocol . The veracity of such data is unstable since it can be affected by multiple factors during the experiment. For example, test participant might try to pander to a test conductors or be dishonest while reporting their state (Sanchez-Vives & Slater, 2005). As well, some of the test participants might be distracted by the talking which can contribute towards the decline of presence experience itself. Subjective measures of self-repots can be also produced using questionnaires before or/and after the experiment (Witmer & Singer, 1998). However, direct questions concerning the feeling of presence might introduce bias, by inducing or reducing experienced presence especially prior knowledge of the purpose of the experiment is revealed (Sanchez-Vives & Slater, 2005). As a substitute, behavioral observations can be conducted, observe the correlation between the user's performance in the real life and VE (Sanchez-Vives & Slater, 2005).

Researchers Anil K. Seth, Keisuke Suzuki and Hugo D. Critchley in their paper "An interoceptive predictive coding model of conscious presence" list several physiological presence measurement methods (Seth et al., 2012). One of the examples would be measuring the heart rate during stressful situations in VR. However, this approach requires intense or noticeable stimuli and might not be applicable for stress-free VE. In addition, the electro-dermal activity can be measured using galvanic skin responses (Boucsein, 2012). Furthermore, the technology of electroencephalography can be used to evaluate changes in cognitive brain activity. (*Handbook of Virtual Environments: Design, Implementation, and Applications, Second Edition (Human Factors and Ergonomics)*, 2014) Presence also could be valued by the user's ability to perform cognitive memory and performance tasks, that are highly depended on a VE (Bernardet et al., 2011), but these measures might coincide with behavior rather than the perceptive experience of presence in VR (Seth et al., 2012).

Since none of the aforementioned evaluation technique guarantees the reliability of the gathered results it is advisable to use a combination of several methods. This would allow to observe and recognize possible bias. Also, it might contribute towards the quality of the results (Seth et al., 2012).

## Measuring Precision

To measure the precision of the steps in the VR we would focus on experimental approach with the support of a post-experiment questionnaire. The experiment design would revolve around two tested conditions: Real walking (Control condition) and Walking in place (Experimental condition).

### Experiment

The precision of stepping within each of these conditions would be based on the accuracy of stepping on the targets (lines) generated in front of the user in the VR environment. The accuracy of a step would be represented by distance value of the step position from the current target. Errors in this experimental part of the test could be caused by abrupt distances from the targets caused by either technical failure of the system or design, motoric failure of the participant or failure of a participant's comprehension during instruction phase of the experiment before each of the tested conditions. Further statistical operations applied to the gathered data across the samples would then reveal potential in the precision of steps of the Walking-in-place technique relative to the Real walking in VR.

### Questionnaire

The experimental research would be then supported by a post-experiment questionnaire that would among other aspects target the feeling of control and precision of steps in each of the conditions of the experiment. The questions targeting control and precision of the steps would share quantitative format (scale) with the rest of the questionnaire. Data gathered from these answers could support or question the experimental data gathered from the testing.

# Design

In this chapter we will go through the design decisions that we have made during the project. By the end of this chapter it should be clear which factors influenced the design decisions and the principles behind the implementation of the final prototype. In order to attempt to answer the final problem statement it was decided to make an experiment comparing our WIP step mechanic to real walking in VR where the accuracy of steps would play the key role in determining the success of the WIP mechanic.

## Design Requirements

Based on the analysis of topics related to our initial problem statement a list of design requirements was constructed (see table 1). The design requirements were used as the basis for our implementation by acting as guidelines throughout the conceptual stage of the project. Futhermore, we have chosen to priotize items from the list reflecting what we consider valuable propositions.

## Concept

Two main step mechanics were developed and brought to the experiment where one used a WIP mechanism as input, and another one using Real Walking as the input. They also differ in visual feedback. WIP technique has a UI step length indication elements that change color depending on a stepping phase while the Real Walking technique displays indicators that continuously represent the user's foot location on the ground plane.

### Stepping Mechanisms

The WIP system is divided into different phases (a) calibration (b) standby (c) aiming (d) trigger (e) execution

- (a) The user stands with straight legs and his feet together as the system calibrates height based on HMD position and the position of the left and right tracker placed on the legs.
- (b) The user is standing with both feet on the ground. The system knows this because it determines that the delta height of legs is close to zero. Furthermore, it determines that the angle of the legs is below a threshold (15 degrees).
- (c) Aiming happens when the user lifts his leg above a threshold (20 degrees). Factoring in the threshold in (b) we get a deadzone from (15-20 degrees). When aiming the UI indicator appears on the ground in front of the lift leg. The user sees a blue circle indicating the previous position of the foot and a white circle indicating the new position. The user can continue to aim as long as his movements are slow.
- (d) The trigger is given to the system by the user when he has found the location that he is satisfied with. To give the trigger, the user makes a fast motion with the leg returning to a neutral standing pose.
- (e) The location of the user is mapped such that the downward motion of the leg results in forwarding motion interpolating between the prior location and the target defined by the pointer.

Table 1: Design requirements based on the analysis.

| Section | rqmt. # | Criteria | Importance | Explanation |
|---|---|---|---|---|
| Design Principles | | | | |
| 'Virtual Reality' | DR1 | Prefer body-mounted tracking devices over stationary devices (i.e. treadmills and exercise machines) | HIGH | Stationary devices are bulky and take up space. On the other hand, body-mounted tracking devices are cost effective, convenient, offers good proprioceptive feedback and has the ability to elicit a strong sense of presence. |
| | DR2 | Addresses workspace limitations associated with ground-based linkage tracking devices | HIGH | When wearing ground-based linkage tracking devices the workspace often resembles that of the natural motions of the limbs the controllers are attached to. |
| | DR3 | Keep the cost to a minimum | MEDIUM | The hardware used should be efficient, attacking actual problems and should be affordable to the user. |
| | DR4 | Addresses fit issues associated with body-mounted linkage tracking devices | LOW | Aligining sensors of body-mounted linkage tracking devices with the user's limbs is cumbersome. |
| 'Perception' | DR5 | Employ naturalistic gestures for controlling virtual motions | HIGH | Gestures should be as natural as possible to maintain the perception of presence in the VE. |
| | DR6 | Ensure a good match between expected and actual sensorimotor signals to avoid breaking presence | HIGH | Ensure high correspondence between sensorimotor signals and how the system responds to the user. |
| | DR7 | Ensure high correspondence between real and virtual limbs | MEDIUM | User controls need to feel natural and realistic. |
| 'Measuring presence' | DR8 | Combination of several observation techniques (Test design) | LOW | To be able to measure presence different observation techniques need to be implemented into the testing procedure |
| Technical requirements | | | | |
| 'Virtual travel techniques' | DR9 | WIP traveling technique in VR | HIGH | WIP techniques address issues with workspace limitations of body-mounted devices. |
| 'GUD Locomotion' | DR10 | GUD Locomotion | LOW | Gait cycles introduce events that are vital for the realistic behaviour of virtual limbs in WIP |
| 'Walk in Place' | DR11 | Continuous movement tracking | LOW | A continous movement tracking system ensures high data validity for virtual walking. |
| | DR12 | Avoid starting/Stopping delays | HIGH | Delivering realistic and fast feedback to the user. |
| 'Animation' | DR13 | High frame rate | HIGH | Realistic motion requires smooth and natural visual feedback. |
| | DR14 | Realistic movement | HIGH | Realistic motion requires smooth and natural visual feedback |
| 'UI elements as visual indicators' | DR15 | Spatial elements | HIGH | User needs UI assistance with performing tasks when expected visual feedback is not present. |

### Platform

At the time of making the project HTC Vive platform was popular VR device and it was accessible to the common user. Moreover, VR laboratory equipped with the HTC Vive-platform was accessible throughout the whole development. These two factors played a major role in choosing the target platform. Steam powered HTC Vive support allowed the connection of the HTC Vive to the VR environment engine.

### Setup

HTC VIVE system :

- Lighthouse A
- Lighthouse B
- Left Controller
- Right Controller
- Head mounted display (HMD)
- Stationary computer (figure 9)

```
------------------
System Information
------------------
      Time of this report: 5/8/2017, 15:46:58
             Machine name: ME-LAB-SMALL-2
               Machine Id: {B8ED0483-3DA0-43A2-A8E4-91DAD5CCF22A}
         Operating System: Windows 10 Enterprise 64-bit (10.0, Build 14393)
(14393.rs1_release_sec.170327-1835)
                 Language: Danish (Regional Setting: Danish)
      System Manufacturer: Gigabyte Technology Co., Ltd.
             System Model: To be filled by O.E.M.
                     BIOS: BIOS Date: 10/26/15 19:28:05 Ver: 05.0000B
                Processor: Intel(R) Core(TM) i7-6700K CPU @ 4.00GHz (8 CPUs), ~4.0GHz
                   Memory: 16384MB RAM
      Available OS Memory: 16336MB RAM
                Page File: 8630MB used, 10137MB available
              Windows Dir: C:\WINDOWS
          DirectX Version: DirectX 12
      DX Setup Parameters: Not found
         User DPI Setting: Using System DPI
       System DPI Setting: 96 DPI (100 percent)
          DWM DPI Scaling: Disabled
                 Miracast: Available, with HDCP
Microsoft Graphics Hybrid: Not Supported
           DxDiag Version: 10.00.14393.0000 64bit Unicode
```

Figure 9: System information of the personal computer used for the testing.

### HTC Vive Setup

The HTC Vive platform was set up in one of the laboratories where the development computer was located (Figure 10). Restricted space of the room required manual mapping of the area of movement.

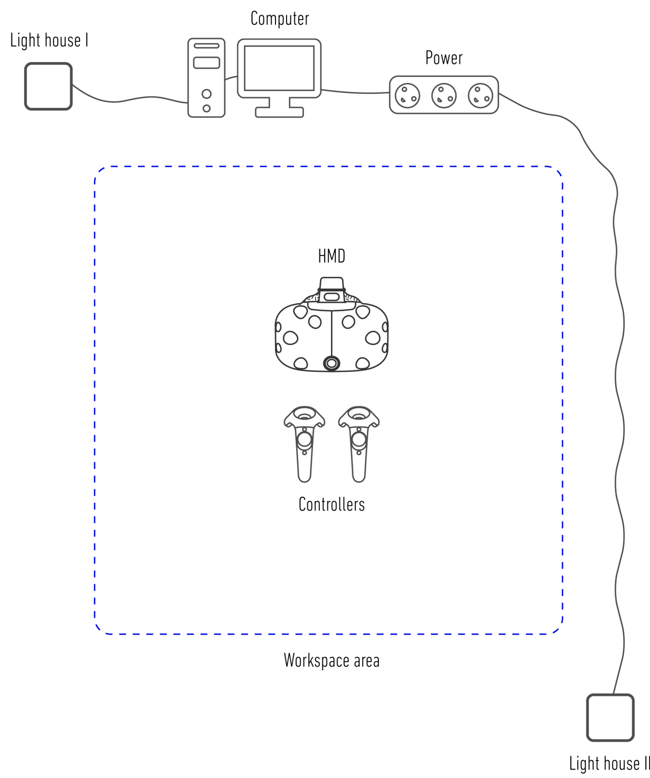


Figure 10: Room Setup

### Controllers

A combination of a Vive head-mounted display with both hand-held controllers and external headset was implemented in the final prototype (Figure 11). Two controllers in combination with the head-mounted display are forming a sufficient source of data necessary for both WIP and Real Walking motion.

For the purpose of tracking legs' movement while performing WIP and real walking motion both hand-held controllers were attached each to one leg right above the knee for WIP movement and right below the knee for real walking motion (Figure 12). The indicators are shown to the user also seen in figure 12.

### Virtual Environment

The perspective view of the scene composition can be seen in figure 13. In the figure, $P$ represents the user's avatar performing a step mechanic with an effort to place the foot as accurately as possible on the targets. The final score is averaged of accuracy across all turns grouped by step length for the one step

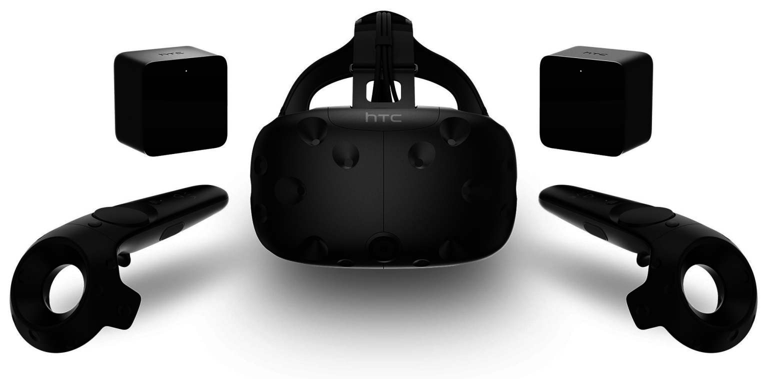

Figure 11: HTC Vive controller, head mounted display and lighthouses used for the experiment **(Passary, 2016)**

mechanic. The final scene composition visuals are visible in figures 15 - 19.

### Questionnaire

After both test conditions were completed, each test participant had to fill in a questionnaire. The questionnaires consisted of three parts. General questions inquiring about:

- Gender
- Experience with VR devices
- Experience with WIP system
- Motion sickness

This was followed by questions reflecting on the 'Real Walking' experience. We were interested in the participant's feedback regarding:

- Understanding of the procedure
- Controls
- Sense of accuracy
- Naturalness
- Presence
- Distractions

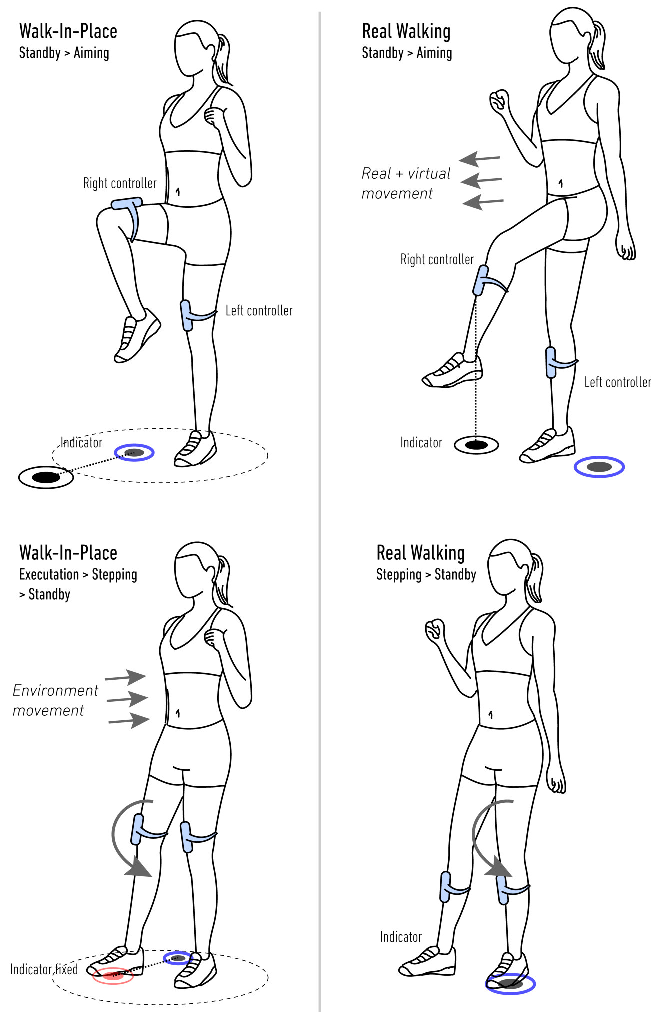


Figure 12: HTC Vive controller placements on the user's legs for WIP (left) and RW (right) conditions.

Finally a set of similarly phrased questions that reflected reflecting on the 'Walk In Place' experience:

- Understanding of the procedure
- Controls
- Sense of accuracy
- Naturalness

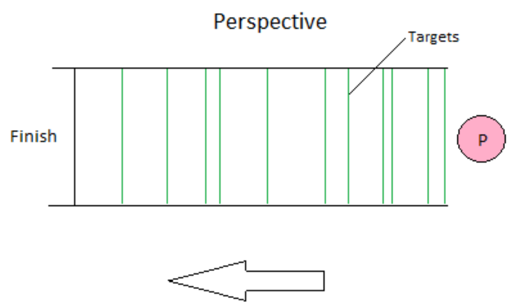


Figure 13: Perspective view on the scene composition where P is the user's position

- Presence
- Distractions

# Implementation

This chapter provides a technical overview of the code implementation for our 'Walk In Place' and 'Real Walking' systems used of the experiment. Throughout the chapter examples are provided that best illustrate our approach.

The implementation is a WIP system that allows the user to walk without moving physically. The system offers a graphical interface for the user to evaluate the step length before triggering a step. The UI consists of a step indicator (a white dot) to show the step target as well as indicators that show the current location of the feet (blue circles). As the user performs a step, the step indicator will initially appear inside the blue circles. As the user lifts his legs the indicator moves outside the circle indicating the step location. When a desired target location has been acquired the user moves his legs back down; the indicator turns red and the player will start moving to the targeted position as his foot returns back to a the standby pose. The diagram (see figure 14) shows the general principle of the implementation, but a more detailed explanation of the system will be presented further on in the chapter.

## Prerequisites

For the implementation we decided to use Unity specifically version 5.5.2f1 as it is stable and provides great compatibility for the HTC Vive and Steam VR. The implementation is fully written in C#, on a side note, we did use a few

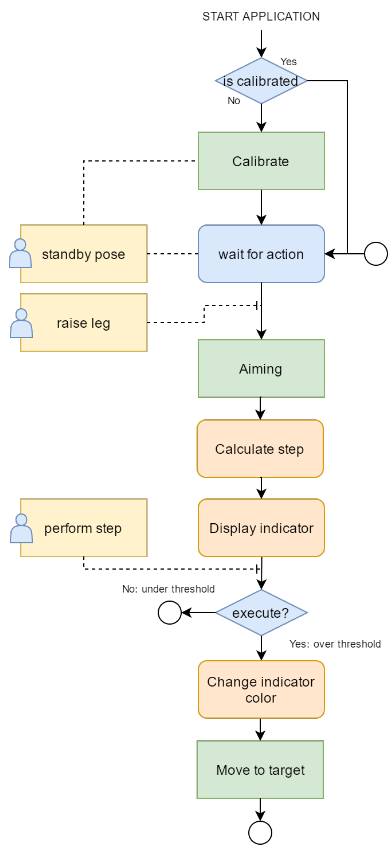


Figure 14: Diagram of implementation

shaders that are written in the Cg programming language, which is a high-level shading language developed by Nvidia. The shaders for the GUI and the virtual environment were all standard Unity shaders, using the deferred lighting rendering path. The Unity engine offers many additional features that makes it useful, like the component based programming architecture and hierarchical organization of game objects in the scene making transforming children a breeze.

## Recording Walking Sequences

Before implementing the WIP method we wanted to record data from the HTC Vive that could be played back on demand. This was done as a measure to accelerate the development as it would allow us to work without the constant need for a HTC Vive setup. We therefore implemented a tool specifically for this purpose which is capable of collecting data (location and rotation in world space) from the HMD and the two controllers strapped to both legs. To ensure that the data is played back at the correct speed (since frame rates tend to fluctuate) after collecting it, we ensured that the data was being collected at a fixed frame rate using the FixedUpdate()-method. A custom SaveLoadManager-class was then responsible for serializing data and saving it in a specified path. Since Unity does not flag both the Vector3 and Quaternion types that we need as serializable, we needed to create our own structs that convert them into serializable formats. The code below shows how this is accomplished for Quaternions, but the exact same approach is used to convert Vector3:

```
[Serializable]
public struct SerializableQuaternionArray
{
    public float[] x;
    public float[] y;
    public float[] z;
    public float[] w;

    public SerializableQuaternionArray (float[] rX, float[] rY,
    float[] rZ, float[] rW)
    {
        x = rX;
        y = rY;
        z = rZ;
        w = rW;
    }

    // Returns a string representation of the object
    public override string ToString ()
    {
        return String.Format ("[{0}, {1}, {2}, {3}]", x, y, z, w);
    }

    // Automatic conversion from SerializableVector3 to Quaternion
    public static implicit operator Quaternion[] (
    SerializableQuaternionArray rValue)
    {

        Quaternion[] output = new Quaternion[rValue.x.Length];

        float[] tempX = new float[rValue.x.Length];
        float[] tempY = new float[rValue.x.Length];
        float[] tempZ = new float[rValue.x.Length];
        float[] tempW = new float[rValue.x.Length];

        for (int i = 0; i &lt; rValue.x.Length - 1; i++) {
            output [i] = new Quaternion (rValue.x [i], rValue.y [i
    ], rValue.z [i], rValue.w [i]);
        }

        return output;
    }

    public static implicit operator SerializableQuaternionArray (
    Quaternion[] rValue)
    {
```

```
        float[] tempX = new float[rValue.Length];
        float[] tempY = new float[rValue.Length];
        float[] tempZ = new float[rValue.Length];
        float[] tempW = new float[rValue.Length];

        for (int i = 0; i &lt; rValue.Length - 1; i++) {
            tempX [i] = rValue [i].x;
            tempY [i] = rValue [i].y;
            tempZ [i] = rValue [i].z;
            tempW [i] = rValue [i].w;
        }

        return new SerializableQuaternionArray (tempX, tempY, tempZ
    , tempW);
    }
}
```

Methods for saving and loading are implemented in the same class. We serialize the whole inner class called SaveManager as an object. Through object serialization we takes an object's state, and convert it to a stream of data, that we can later de-serialize. After loading the data it is assigned to the MotionAnimator-class that stores and replays the data stored in arrays at a fixed frame rate. Below is an excerpt of the MotionAnimator-class responsible for playback. To animate we simply increment the index $i$ of the arrays and assign the values to the position and rotation of the game object that matches the device type (HMD, left controller, right controller) that we define with an enumerator inside the DeviceManager-class.

```
void FixedUpdate ()
    {
        if (SaveLoadManager.loaded) {
            if (playback &amp;&amp; simulated &amp;&amp; i &lt;
    pos_left_controller.Length) {

                switch (gameObject.GetComponent<devicemanager> ().
    deviceType) {
                case StringID.Left_Controller:
                    transform.localPosition = pos_left_controller [
    i];
                    transform.localRotation = rot_left_controller [
    i] * Quaternion.Euler (new Vector3 (90, 0, 0));
                    break;
                case StringID.Right_Controller:
                    transform.localPosition = pos_right_controller
    [i];
                    transform.localRotation = rot_right_controller
    [i] * Quaternion.Euler (new Vector3 (90, 0, 0));
                    break;
                case StringID.HMD:
                    transform.localPosition = pos_hmd [i];
                    transform.localRotation = rot_hmd [i];
                    break;
                default:
                    print ("Index out of bounds");
                    break;
```

```
            }
            i++;
        } else if (i &gt;= pos_left_controller.Length) {
            i = 0;
        }
    }
}
```

Note that if we wish to use the Vive Controllers instead of playing back recorded movements we can do so simply by switching the boolean called 'simulated' to false. Doing so will assign the movements of the motion controllers inside the Update()-method meaning that the delta time between frames will not be fixed. This is to ensure that game objects update at the highest rate possible so the tracking is as close to 1:1 as possible. An excerpt of the code is shown below.

```
    if (!simulated) {
        if (TrackerTransforms.trackingIsValid ()) {
            switch (gameObject.GetComponent<devicemanager> ().
deviceType) {
            case StringID.Left_Controller:
                transform.position = tracker.GetTransform ("
left_Controller").position;
                transform.rotation = tracker.GetTransform ("
left_Controller").rotation;
                break;
            case StringID.Right_Controller:
                transform.position = tracker.GetTransform ("
right_Controller").position;
                transform.rotation = tracker.GetTransform ("
right_Controller").rotation;
                break;
            case StringID.HMD:
                transform.position = tracker.GetTransform ("hmd
").position;
                transform.rotation = tracker.GetTransform ("hmd
").rotation;
                break;
            default:
                print ("Index out of bounds");
                break;
            }
        }
    }
```

## Simulated Walking

### Calibration Phase

The calibration step is necessary before we can calculate step length and perform WIP since we need the y-coordinate of the controllers when the user is standing as reference points. Calibration is simple; the user stands in a neutral pose with his legs together. When triggered the position of the controllers are saved as references or 'control anchors' inside the UserProfile-class. We can then reference these values later on.

### Standby Phase

A step can be performed by the user under certain conditions. First and foremost the system checks whether or not the user's legs are grounded by comparing the y-coordinates of the controllers to that of the control anchors. If the y-position of the controller is below the control anchors y-position plus a threshold value (set to 0.01) or if the angle between the down direction and the controller is below 15 degrees then the foot is grounded. The code below demonstrates this.

```
        // Check if grounded for each leg.
        if (CheckGroundedHeight(0.01f) || CheckGroundedRotation(15)
    ) {
            if (!isStepping) {
                if ((int)GetComponent<devicemanager> ().deviceType
    == 0) {
                    leftLegIsGrounded = true;
                } else {
                    rightLegIsGrounded = true;
                }
            } else {
                if ((int)GetComponent<devicemanager> ().deviceType
    == 0) {
                    leftLegIsGrounded = true;
                    prevStepLeg = false;
                } else {
                    rightLegIsGrounded = true;
                    prevStepLeg = true;
                }
            }
        } else {
            if ((int)GetComponent<devicemanager> ().deviceType ==
    0) {
                leftLegIsGrounded = false;
            } else {
                rightLegIsGrounded = false;
            }
        }
```

### Aiming Phase

When the user lifts his leg and the ground conditions return false the systems initiate an aiming phase. The leg that is aiming is set as the active leg by switching the static boolean activeLeg (refer to the code example below). This means only one leg can be active at a time, we use this constraint since one can only step with one leg at a time; the system should reflect this. We also need to ensure that the other leg cannot become active before the user either cancels or triggers a step, as this would be an error, the system takes care of this by using static variables to determine when the user is stepping. Note that when the aiming phase is initiated for the active leg the indicator (a white dot) representing the location of the step will become visible, this is simply a matter of checking when the boolean isAiming is true and turning on the renderer for the billboard with the step indicator texture.

```
    // Change to aiming phase when above a threshold.
    if (!CheckGroundedHeight(0.01f) &amp;&amp; !
CheckGroundedRotation (15) &amp;&amp; !isStepping) {
        rayColorIfGrounded = Color.red;
        activeLeg = Convert.ToBoolean ((int)GetComponent<
devicemanager> ().deviceType);
        isAiming = true;
    }
```

The step length is determined by taking the difference between the controllers strapped to the legs and the control anchors (3-dimensional fixed vectors from the calibration step). We ensure that the float is always positive using a max function to remove values below zero (see code below). The step length is applied to the step indicators position to give the user feedback about how long the step is.

```
    // Calculate the stride length
    stepLength = Mathf.Max (0, transform.position.y -
Administrator.admin.userProfile.controlAnchor [(int)
GetComponent<devicemanager> ().deviceType].y);
```

### Trigger Phase

A 'dead zone' is defined to allowing to avoid false positive, the user will have to exit the dead zone to trigger a step - in other words, within the dead zone the system cannot change state. The dead zone is an area of 10 cm extending above the control anchor plus its threshold value. To trigger a step the user has to move his leg back down to a standing pose, when system measures that the local angular velocity and local angular acceleration are both negative around the x-axis it triggers a step. In the real walking implementation this part of the code is removed entirely as steps are performed by moving around physically. When the step is triggered the SetMovementDistance()-method sets the distance of the movement and the currentPosition is set to the last known position of the parent transform before the root position is changed. We use the root transform to transform all its children including the player, the reason we do not only use the HMD to estimate the player's position in world coordinates is that it is non-static and therefore not reliable. We use an empty game object as a static reference point for the player position for this reason; we then use the HMD to calibrate the user's position inside the local space of the parent game object only when he is standing with both legs on the ground, when he enters the aiming phase the position is frozen until the step is either triggered or cancelled. When the user triggers a step indicator changes colour to red and locks to its position at the time of the trigger.

```
    // Step trigger should be here
```

```
        if (!isStepping &amp;&amp; !CheckGroundedHeight (0.2f) &amp
;&amp; !CheckGroundedRotation (15) &amp;&amp; canStep) {
            if (angularVelocity.x &lt; 0 &amp;&amp;
angularAcceleration.x &lt; 0) {
                isStepping = true;
                canStep = false;
                SetMovementDistance ();

                // Update the current position for later use
                currentPosition = transform.root.position;
            }
        }
```

### Execution

When the player moves a vector is applied to the root position, we decided to interpolate to the targeted step location by mapping the stepLength from the interval defined as $[0, movementDistance]$ inversely to the interval of targetPosition $[0, Vector3.Magnitude(targetPosition)]$. As such, when the user moves his leg down to a standing pose, he will gradually move towards the targeted step position resulting in a 1:1 correspondence between the user's gesture and the resulting motion. The cde below illustrates this. When the stepInterpolation value is greater than or equal to the magnitude of the targetPosition vector the step has been successfully executed and the state of the system is reset to its initial state.

```
        // Decide what happens if isStepping is true/false
        if ((int)GetComponent<devicemanager> ().deviceType ==
Convert.ToInt32 (activeLeg)) {
            if (isStepping) {
                isAiming = false;
                stepInterpolation = MathExtension.map (stepLength,
movementDistance, 0, 0, Vector3.Magnitude (targetPosition));

                if (stepInterpolation &gt;= oldStepInterpolation) {
                    transform.root.position = currentPosition + new
 Vector3 (stepInterpolation, 0, 0);
                    oldStepInterpolation = stepInterpolation;
                }

                if (stepInterpolation &gt;= Vector3.Magnitude (
targetPosition)) {
                    stepInterpolation = Vector3.Magnitude (
targetPosition);
                    isStepping = false;
                }

            } else if (isStepping == false) {
                targetPosition = new Vector3 (strideLength, 0, 0);
                stepInterpolation = 0;
                oldStepInterpolation = 0;
                movementDistance = 0;
            }
        }
```

## GUI for WIP

The UI that we implemented for WIP aims to give users high precision and is takes inspiration from UIs used for many pointing devices such as mouse or laser pointers.

For the prototype we restricted the movement to a single axis, as such the pointer currently only moves on th axis. The system was implemented this way to simplify the experiment. Below we illustrate the current state of our interface:

### Standby Phase

In the standby phase the user is standing with both legs on the ground. In figure 15 the blue circles illustrate the position of the feet, the boxes represent the position of the controllers and the gray dotted circle indicate the spot the user needs to walk in during WIP.

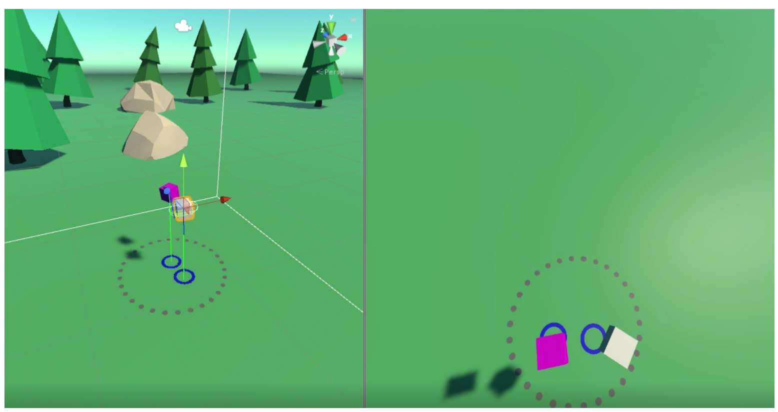

Figure 15: Standby phase: The user is not moving. Blue circles indicate the position of the user's feet, the. The gray circle shows the user if they move around physically.

### Aiming Phase

In the aiming phase the user is lifting one leg above the ground. When the WIP system detects this it displays a white indicator (see figure 16) that shows where the resulting location will be after stepping. During the experiment, when the participant lifts his leg a black line appears that he will have to step on.

The white indicator is mapped to the height of the user's leg, see figure 17. This is if the user lifts his leg the indicator moves forward. Currently, it is only possible for the indicator to move forward, as the step trigger is when the user moves the leg back, however, it is possible to cancel the step early on before exiting the deadzone.

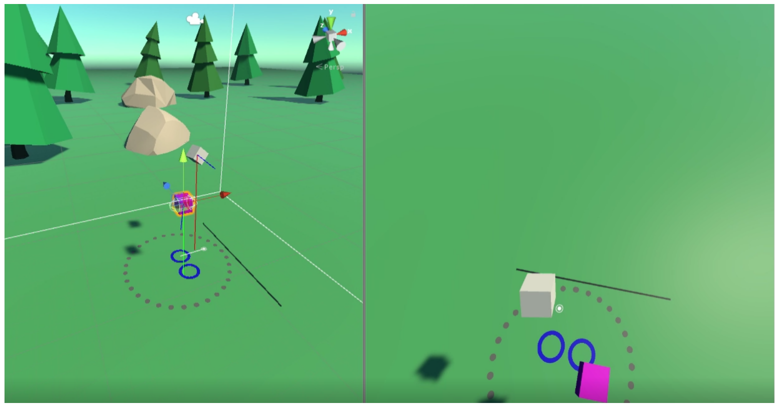

Figure 16: The white indicator appears when the user lifts his leg, and indicates the new position after performing the step.

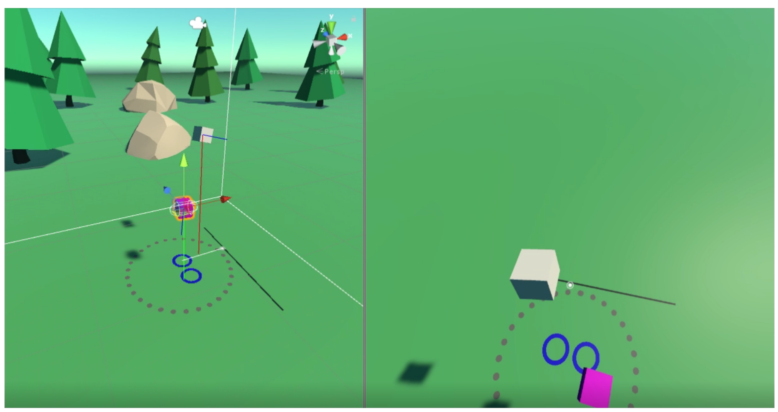

Figure 17: As the user raise his leg the white step indicator moves forward.

#### Trigger

The user can trigger a step at any time except when inside the deadzonen. The step is triggered by moving the leg back down. The step indicator will turn red to indicate that its position has been locked to the targeted location (see figure 18).

#### Execution

After triggering, the user is able to move forward by lowering the leg back down. Doing so will move his digital body towards the red step indicator in VE until the target has been reached (see figure 19).

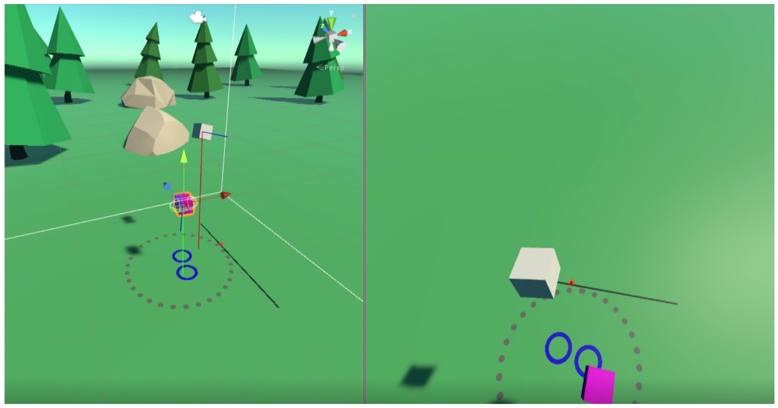

Figure 18: After triggering the step, the indicator turns red telling the user that the system recognized the intend to step.

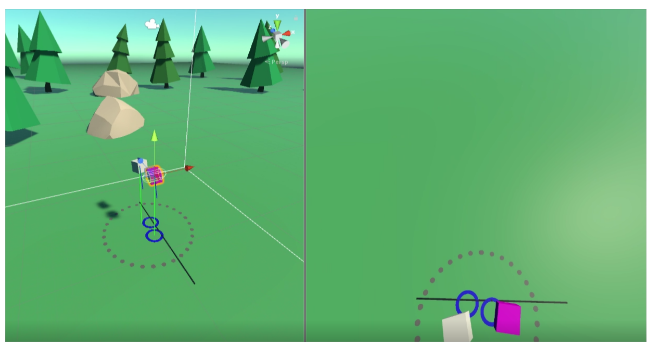

Figure 19: Lowering the leg down after triggering results in a forward movement. When the leg is grounded the target position (red indicator) has been reached.

## Experimental Procedure

There are numerous ways one can design the experiment procedure to obtain reliable and valid results. In this section, we recapitulate the test conditions, procedures, target group and test environment. The goal is to provide a clear overview of our approach to evaluate our WIP solution.

### Summary of the Experiment

The experiment compared the accuracy of stepping in the VR environment using two systems: WIP with UI indicators and Real Walking with UI indicators. Both systems use identical setups as described further in this chapter. For our experiment we used the repeated measure test design in which test participants had to take a part in both control and experimental test conditions. The participants will be presented with step targets that they will have to step on with these specific distances $[0.250m, 0.275m, 0.300m, 0.325m, 0.350m]$ each will appear exactly 5 times for a total of 25 step targets in each condition.

#### Samples

To ensure that the sampling distribution can be normal according to the central limit theorem, we have to collect enough samples. We estimated that a minimum of 20 was sufficient if the effect size was high enough. We ended up testing on 25 participants that were exposed to the experimental and control conditions in a randomized order that was generated.

#### Target group

We decided to have a broad target group consiting of individuals with no conditions that affect heir walking. To find people for the test we started off creating a Facebook post informing about our project and asking for volunteers, without revealing exact details about our objectives. In addition, we personally approached people in and around the university campus soliciting them to join our experiment. Participants were invited to partake in the experiment one at the time.

#### Room Size Limitation

While designing our experiment we faced the issue that the virtual workspace did not conform to the real one in size (the room in which we setup the HTC Vive), this was only a problem in the Real Walking condition, as participants risked bumping into walls. Since the work space area were not big enough to execute 25 step in RW experiment both conditions were divided into 3 walk-segments and segments in-between where the participant would have to re-locate (in the control condition only) or rest (in the experimental condition only). This way we ensure that any influence of the delay in one experiment would be present in the second one. The sequence for the real walking (control condition) was as follows:

- Start,
- Step 10 times,
- Move back to start,
- Step 10 times,
- Move back to start,
- Step 5 times,
- Finish

For the WIP (experimental condition) the sequence looked like this:

- Start,

- Step 10 times,
- break,
- Step 10 times,
- break,
- Step 5 times,
- Finish

**Randomization**

The test conditions were assigned from the generated list mentioned in the samples section. Each test participant follow the same test procedure for each testing condition (see figure **??**).

## Procedure

(1) The participant is brought into the room and the experimenter instructs him/her about what is going to happen. The experimenter makes sure that the information given to the participants is exactly the same.

(2) The experimenter helps the participant attach the controllers and checks to see if they are secured and whether they are pointing in the right direction.

WIP: The controllers are attached above the knees.
RW: The controllers are attached below the knees.

(3) Instructions are given on how to perform a step that the system can recognize before the HMD is given.

WIP: Steps are demonstrated by the experimenter lifting one knee above the waist, then the opposite knee (repeated a few times). The participant is asked to do the same.
RW: Steps are demonstrated by the experimenter lifting one knee above the waist, then stepping forward. After placing the foot down, the experimenter moves his whole body to the same position and repeated with the other leg. The participant is asked to do the same.

(4) The participant is given the HMD and asked to look around. After a while he/she is asked to inspect his/her legs.

(5) The participant is given a trial run of the experiment. They are first asked to look at the tree to the side and walk, when they have grown accustomed to the system they are asked to look down and use the indicators to walk to targets on the ground (indicated by lines). Participants are informed that the target only appears when they initiate walking by lifting one knee.

WIP: Participants lift one leg, and the step indicator (white dot) appears showing where the step will take them. The participant is informed that steps are performed by lifting (aiming) the leg followed by lowering the leg (execution). They are also told that when the indicator turns red, the system recognizes the

step.
RW: Participants are told to lift one leg and move physically when the indicator appears. Since real walking should be familiar the only important thing here is teaching them how to initiate the step, as the system need to know when they start stepping.

(6) When participants are familiar with the walk mechanism and the indicators the actual experiment starts. The experiment proceeds until 25 step objectives have been accomplished.

(7) We thank for the participation and ask the participant to fill out a questionnaire.

### Hypothesis

Since our experiment compares accuracy of steps in two conditions (Walk in Place and Real Walking) we want to see whether the population means are equal or differ. We expect that the population means will be equal for one or more step distance parameters, especially at smaller step lengths as smaller steps should be easiest to perform. As the step length increases we can reasonably assume that errors (differences between step target location and the actual step location) will also increase as the task becomes more strainous, especially in Real Walking where the participants physically move. We hypothesize that our WIP solution does not suffer from the problem to the same extent since it is less strainous to lift the knees than actual walking. This should be visible by looking at how the standard deviation change over step length. Our hypothesis becomes:

$H_1$: Walk In Place performances deviates less at longer step distances compared to Real Walking.

$H_0$: Walk In Place performances does not deviate less at longer distances compared to Real Walking.

## Evaluation

### Results from the Experiment

In this chapter we present the results of experiments performed to evaluate the precision of stepping using our 'Walk In Place' system and a 'Real Walking' counterpart. The data gathered from participants in both conditions, is grouped by the step distance parameter $d = [0.250m, 0.275m, 0.300m, 0.325m, 0.350m]$. Furthermore, as the experimental used repeated measures, participants with random assignment we compare Walk-In-Place (WIP) and Real Walking (RW) in with the respective distance parameters. Next we perform the Anderson-Darling goodness-of-fit test ($a = .05$, $a_{critical} = .7262$) to check for the normality condition, if the data is found to be normally distributed we check for equal variances between samples. If all conditions are met we perform a parametric test. In case the normality condition is violated the parametric test is performed anyways alongside a non-parametric Wilcoxon Signed-Ranks test to corroborate. We tested 25 participants in total, but one was deemed an outlier and was promptly removed. The amount of samples is therefore $N = 24$.

figures/1/1-eps-converted-to.pdf

Figure 20: Box plot of stepping errors during WIP (left) and RW (right) experiment conditions (d = 0.250m)

The results for each of the normality test on stepping errors for step distances $d = 0.250m$ is indicative of a normal distribution for WIP ($p$ = .1504, $A^2$ = .5417) and for RW ($p$ = .1861 , $A^2$ = .5058). A paired-samples two-tailed t-test showed no significant difference in the precision of steps between WIP ($M$ = 0.0020, $SD$ = 0.0425) and real walking ($M$ = 0.0061, $SD$ = 0.0214) conditions, $t(23) = -.3673$, $p = .7167$.

The results for each of the normality test on stepping errors for step distances $d = 0.275m$ is not indicative of a normal distribution for WIP ($p = .0005, A^2 =$ 1.9002) and for RW ($p$ = 0.0026., $A^2$ = 1.2308). A paired-samples two-tailed t-test showed a significant difference in the precision of steps between WIP ($M = -0.0179$, $SD$ = 0.0371) and real walking ($M$ = 0.0055, $SD$ = 0.0194) conditions; $t(23) = -2.7996$, $p = .0102$, $r = 0.46$. A Wilcoxon Signed-ranks test indicated that there is a significant difference between WIP ($Mdn = -0.0171$) and RW ($Mdn = 0.0078$), $Z = -2.6571$, $p < .0079$, $r = -0.38$.

The results for each of the normality test on stepping errors for step distances

figures/ASE250/ASE250-eps-converted-to.pdf

Figure 21: Histogram of average stepping error in meters of participants (d = 0.250) in WIP (red) and RW (blue) conditions.

$d = 0.300m$ is not indicative of a normal distribution for WIP ($p = .0046, A^2 = 1.1307$) and for RW ($p = .0236, A^2 = .8527$). A paired-samples two-tailed t-test showed a significant difference in the precision of steps between WIP ($M = -0.0217$, $SD = 0.0317$) and real walking ($M = 0.0052$, $SD = 0.0246$) conditions; $t(23) = -2.7996$, $p = .0102$, $r = 0.50$. A Wilcoxon Signed-ranks test indicated that there is a significant difference between WIP ($Mdn = -0.0160$) and RW ($Mdn = 0.0029$), $Z = -2.9143$, $p < .0036$, $r = -0.42$.

The results for each of the normality test on stepping errors for step distances $d = 0.325m$ is not indicative of a normal distribution for WIP ($p = .0018, A^2 = 1.2935$) and for RW ($p = .0005, A^2 = 1.7179$). A paired-samples two-tailed t-test showed a significant difference in the precision of steps between WIP ($M = -0.0240$, $SD = 0.0372$) and real walking ($M = 0.0043$, $SD = 0.0336$) conditions; $t(23) = -2.9116$, $p = 0.0079$, $r = 0.52$. A Wilcoxon Signed-ranks test indicated that there is a significant difference between WIP ($Mdn = -0.0213$) and RW ($Mdn = 0.0101$), $Z = -2.6000$, $p < .0093$, $r = -0.038$.

The results for each of the normality test on stepping errors for step distances $d = 0.350m$ is not indicative of a normal distribution for WIP ($p = .0005, A^2 = 1.8855$) and for RW ($p = .0011, A^2 = 1.3714$). A paired-samples two-tailed t-test showed a significant difference in the precision of steps between WIP ($M = -0.0270$, $SD = 0.0395$) and real walking ($M = 0.0132$,

figures/2/2-eps-converted-to.pdf

Figure 22: Box plot of stepping errors during WIP (left) and RW (right) experiment conditions (d = 0.275m)

$SD = 0.0307$) conditions; $t(23) = -3.6796$, $p = 0.0012$, $r = 0.61$. A Wilcoxon Signed-ranks test indicated that there is a significant difference between WIP ($Mdn = -0.0327$) and RW ($Mdn = 0.0046$), $Z = -3.4000$, $p < .007$, $r = -0.49$.

## Results from the Questionaires

In this chapter, we will present the data gathered from the questionnaires. We will look into each question that was asked in all three categories: general questions, 'Real Walking' experiment and the 'Walk In Place' experiment.

### General Questions

While looking at the data collected in the first part of the questionnaire, we learn the general information about test participants that completed our test procedure. From the figure 30 it is clear that majority of test participants were males, 75% of 24 participants. Question 2 (see figure 31) let us identify the scope of previous experience with VR systems among all test participants. We can tell that only 4.1% of the test participants had no experience using VR systems before the experiment. Moreover, 16.7% have been working within the field of VR themselves. Furthermore, question 3 (see figure 32) shows that about half

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Figure 23: Histogram of average stepping error in meters of participants (d = 0.275) in WIP (red) and RW (blue) conditions.

of the participants (45.8%) have tried Walk In Place traveling technique for traveling in VR. We must note that none of the testers reported feeling motion sickness during the experiment.

**Real Walking Experiment**

While evaluating data from Questionnaires in regards to the Real Walking (RW) Experiment and the control of the step length (see figure 33) we can see that 7 participants out of 24 felt completely in control of their step length. In addition to that ten testers felt almost in control. None of the users expressed the feeling of not being in control at all; however, four participants reported feeling a lack of control regarding step length during the RW.

To the question of how accurate the step lengths were during the RW condition (see figure 34) four participants reported step lengths being very accurate and fifteen participants reported it to be positively accurate. None of the participants described step length as being not accurate, and only 3 of them expressed a sense of negative accuracy.

While asked about the difficulties of hitting the targets (see figure 35), nine participants answered that it was not difficult. Eleven of them leaned towards it not being difficult and only one person found it slightly difficult. None of the

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Figure 24: Box plot of stepping errors during WIP (left) and RW (right) experiment conditions (d = 0.300m)

testers found it very difficult to hit the target.

The histogram for question seven (see figure 36) illustrates the naturalness of the walking during the RW experiment. The majority of test subjects (nine in total) were not sure if stepping was natural or if it was not. Two of the testers found it very natural while another two found stepping unnatural.

Question 8 (see figure 37) shows if users were aware of the VE during the RW experiment. The majority of test subjects (twelve in total) leaned towards not being aware of the digital environment. Three participants were not aware at all, and only two participants were slightly aware of the VE. None of the participants were very aware of the virtual environment during the RW condition.

Figure 38 represents the feeling of distraction created by the VR equipment. Thirteen test participants reported to be toward the side of not being distracted. Four test subjects report to be not distracted at all and only one participant felt a bit distracted.

### Walk in Place Experiment

While evaluating data from questionnaires in relation to the WIP (see figure 39) we can see that 5 participants out of 24 felt completely in control of their step length in addition to that seven testers felt almost in control. None of the

figures/ASE300/ASE300-eps-converted-to.pdf

Figure 25: Histogram of average stepping error in meters of participants (d = 0.300) in WIP (red) and RW (blue) conditions.

users expressed the feeling of being not in control. However, four participants reported a lack of control regarding step length during the WIP.

To the question of how accurate the step lengths of participants were during the WIP experiment (see figure 40) two participants reported that step lengths were very accurate and thirteen participants reported it to be positively accurate. None of the participants described step length as being inaccurate, and only two of them expressed a sense of bad accuracy. The remaining seven testers were not sure about it.

While asked about the difficulties of hitting the targets (see figure 41), six participants answered that it was not difficult, fourteen of them leaned towards it not being difficult and only two participants found it slightly difficult. None of the testers found it very difficult to hit the target.

The histogram for question 13 (see figure 42) illustrates the naturalness of the walking during the WIP experiment. Most people (seven in total) were not sure if stepping was natural or if it was not. Three of the testers found it very natural while another three found stepping to be unnatural.

Question 14 (see figure 43) shows if users were aware of the VE during the WIP experiment. The majority of test subjects (a total of ten) reported towards the side of not being aware of the digital environment. Four participants were not aware, and another four participants were slightly aware of the VE. None

figures/4/4-eps-converted-to.pdf

Figure 26: Box plot of stepping errors during WIP (left) and RW (right) experiment conditions (d = 0.325m)

of the participants were very aware of the virtual environment during the WIP condition.

Figure 44 represents the feeling of distraction created by the VR equipment. Eleven test participants reported being toward the side of not being distracted. Five test subjects report to be not distracted at all and only one participant felt a bit distracted.

# Discussion

In this chapter, we will discuss the results gained from our experiments on participants in both the Walk-In-Place and Real Walking conditions. We will start by reviewing the results and hypothesis; we will then discuss what factors may have affected our measurements.

Our data seem to suggest that WIP is more prone to deviation from zero in the negative domain. There could be several explanations for this. Comparing the results for the two-tailed t-test for $d = 0.250m$ gives us a p-value well above the 5% significance level, which would indicate that at the lowest step distance, population means are at least similar. However, this was not the case for distances above $0.250m$. Interestingly and not surprisingly so, we see that the

figures/ASE325/ASE325-eps-converted-to.pdf

Figure 27: Histogram of average stepping error in meters of participants (d = 0.325 m) in WIP (red) and RW (blue) conditions.

standard deviation of step errors for real walking is smaller than that of the WIP for all step distances. We did, however, expect this to change at higher distances; this is not the case. This may indicate that getting used to the WIP mechanism is more difficult (refer to questionnaire, question 4 (figure 33) and 10 (figure 39)) which makes sense since WIP in practice is not as natural as Real Walking (refer to a questionnaire data, questions 7 (figure 36) and 13 (figure 42)). Another thing to note is that the results for tests with step lengths above $0.250m$ yielded non-normal distributions. Those above was true for both Walk-In-Place and Real Walking. We performed non-parametric tests on this data, that seemed to corroborate the results of the t-tests, however, since we did encounter problems in the experiments (that will discuss later) we remain wary as to the reliability of the data. Finally, looking at how standard deviations change over the course of the experiment – though we hypothesize a lower standard deviation for WIP performances at longer distances, we do not observe this – we can see that the standard deviations for the WIP are more stable, while for Real Walking they increase with the step length. Aforementioned supports the alternative hypothesis, but more data is needed to be sure. For now the results of the experiment favor the null hypothesis which states that WIP performances do not deviate less at longer distances compared to Real Walking.

figures/5/5-eps-converted-to.pdf

Figure 28: Box plot of stepping errors during WIP (left) and RW (right) experiment conditions (d = 0.350m)

### Accuracy of steps

In the questionnaire, participants had mixed responses to whether they felt in control of step lengths during WIP (refer to the questionnaire, question 4 (figure 33), while most were positive, other people found WIP to be less than ideal. We do also see more positive than negative responses when we ask about how accurate the participants thought their steps were (see figure 40, 41). Looking at Real Walking the responses are even more positive (see figure 33, 34, 35), indicating that the WIP system is a bit more difficult and possibly that more time is needed to become familiar with the system. It is worth noting that biases exist in the WIP system, due to the method used to detect steps. We have tried to accommodate for such biases having an almost identical step detection algorithm in both conditions. However, one thing we did not account for is that although many users correctly hit the target during WIP, their virtual body position would not move to the exact location of the step indicator. The culprit is a method in the program that decides when the user's legs are grounded, that unexpectedly overwrites the interpolation of the step a few centimeters before reaching the target location. Most of the time this does not seem to be an issue, but it should be addressed in a future iteration of the program.

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Figure 29: Histogram of average stepping error in meters of participants (d = 0.350) in WIP (red) and RW (blue) conditions.

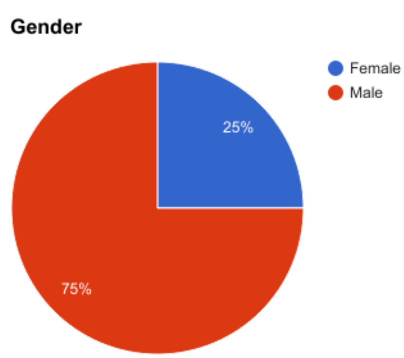


Figure 30: Question 1

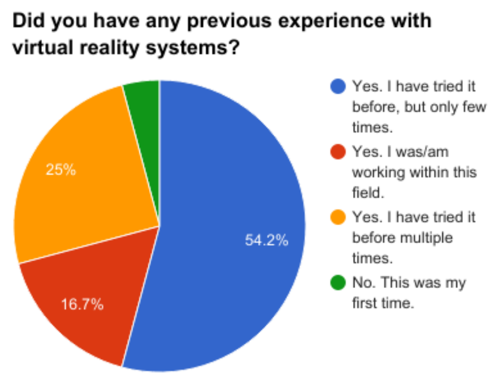


Figure 31: Question 2


Figure 32: Question 3

## Sensor issues and fitting

During both experiments we experienced issues with tracking e.g. sometimes, the HMD would stop tracking because participants had a habit of holding onto the HMD thereby obscuring the sensors. We should ensure that the HMD is secured properly for each participant, as first-time users seem to have trouble tightening the straps properly. During the experiment, we should also make sure that the controllers on the legs do not move too much, as the WIP system

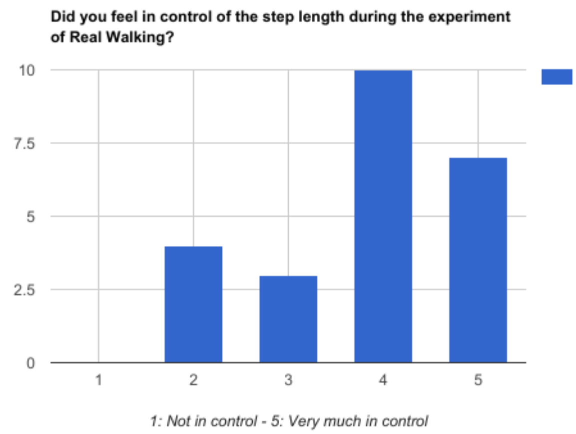


Figure 33: Question 4

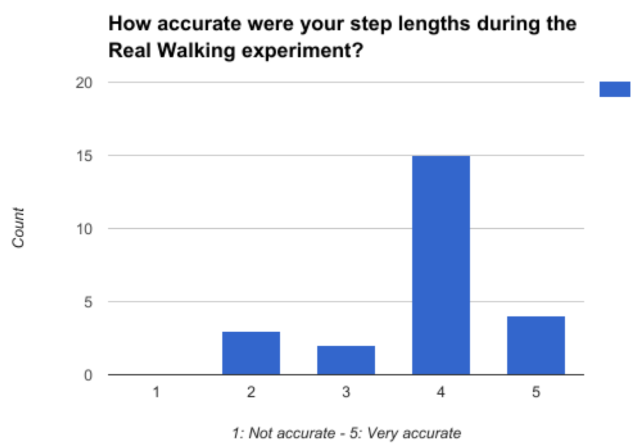


Figure 34: Question 5

assumes that they are always pointing down and that their height only changes during stepping. In a few instances, we had to re-adjust and re-calibrate the controllers, better straps or lighter trackers could potentially solve the problem.

## Workspace limitations

Many participants also reported that they did not feel safe while moving around in the Real Walking experiment, the problem was that the cage (or 3D grid)

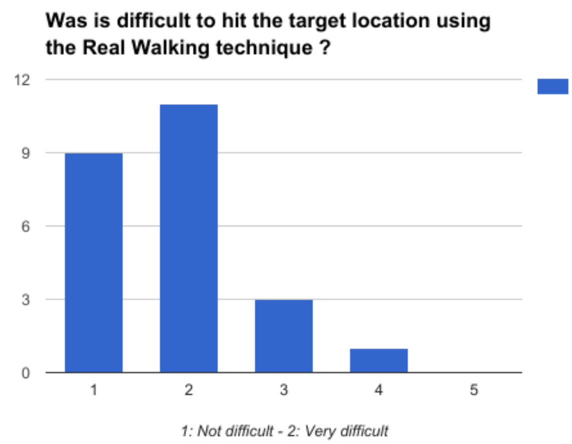


Figure 35: Question 6

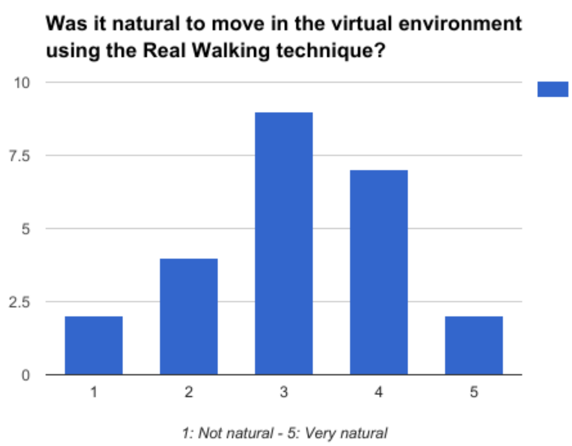


Figure 36: Question 7

that normally shows up near walls did not work properly during the experiment. We had one of us had to tell the participant when they were close to walls and obstacles, but the cage would have provided better insurance.

## Different walking styles

One thing we noticed during the experiments is that although the same information was given to participants, they interpreted it differently. Furthermore,

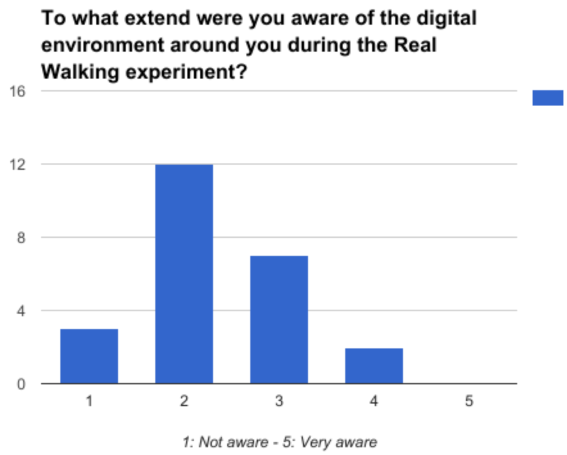


Figure 37: Question 8

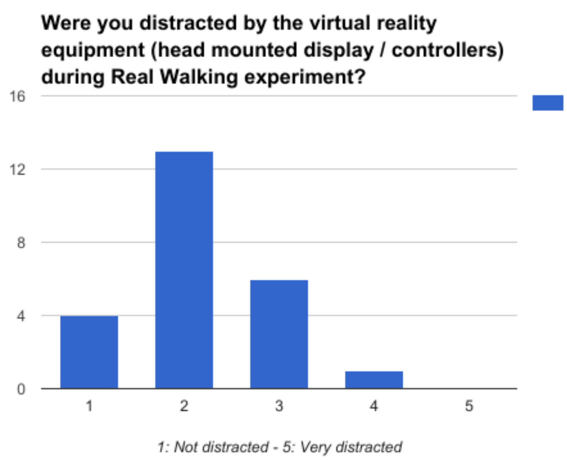


Figure 38: Question 9

some participants seemed not too focused on accuracy. One participant who was deemed an outlier did not follow repeated instructions, and just plainly ignored the stepping objectives.

## Motion sickness

Through our questionnaire, we learned that none of our participants experienced any motion sickness during the experiment. This evidence shows that

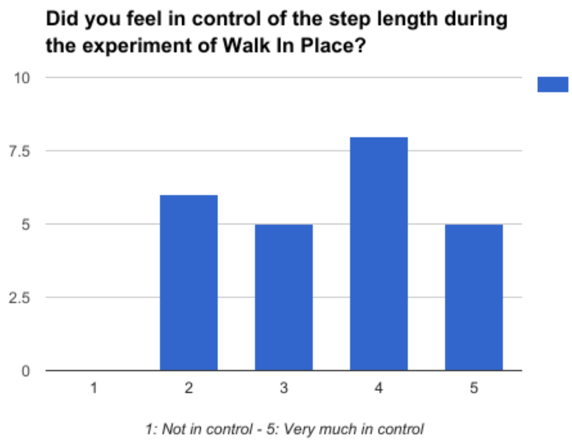


Figure 39: Question 10

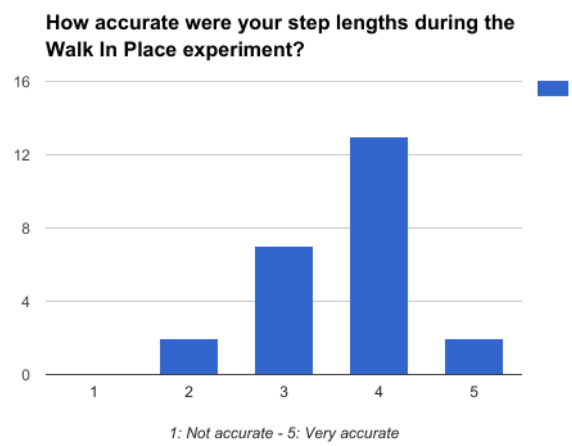


Figure 40: Question 11

although our WIP solution was not as natural for moving around in the virtual environment compared Real Walking, using interpolation of movements mapped to the user's legs in WIP has advantages when it comes to reducing incongruent of sensory inputs associated with motion sickness. In a broader perspective, this is interesting finding since many WIP approaches suffer from this problem. We do however acknowledge the fact that our system differs from other WIP systems as it does not implicate continuous movement. Due to these findings,

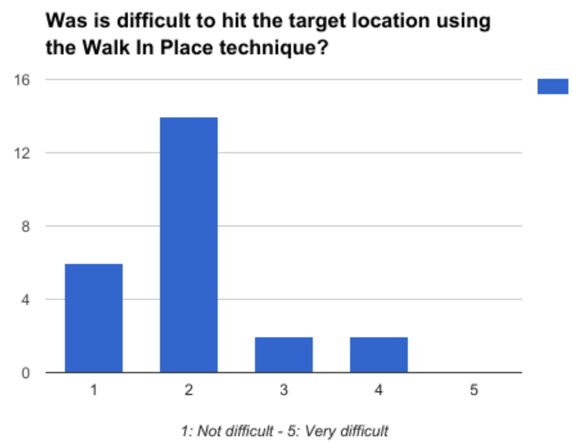


Figure 41: Question 12

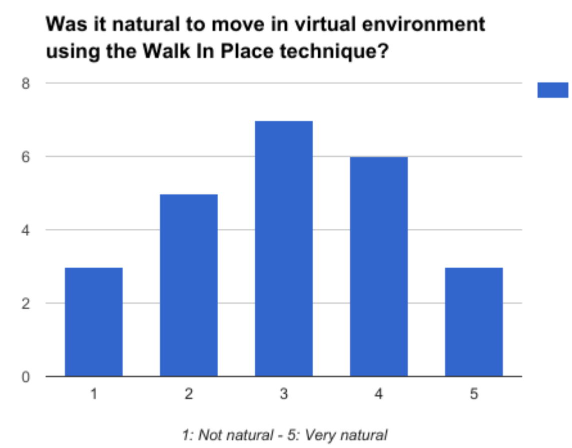


Figure 42: Question 13

we can say our system is good for stepping, but not so much for walking over long distances.

# Conclusion

We have tested the accuracy of Walk-In-Place performances against Real Walking performances and hypothesized that performances using our WIP system

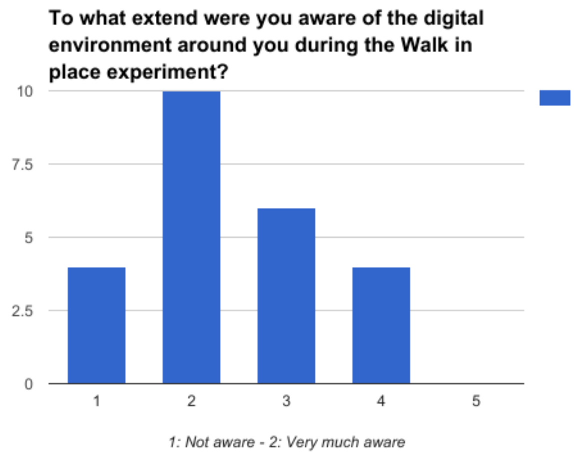


Figure 43: Question 14

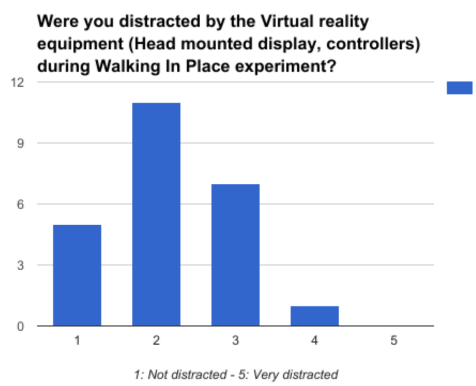


Figure 44: Question 15

would see less deviation at longer step lengths. Our results indicate that WIP does not show less deviation at longer step lengths between $0.250m$ and $0.350m$. However, whether this is the same outside this range is not known at this point. To answer our final problem statement; our WIP system allows for foot placements that according to participants felt both intuitive and precise. Compared to Real Walking our WIP system performance still lacked behind a little which is expected. The positive responses from the questionnaire were encouraging, and show that users can benefit from WIP and visual foot indicators.

# Future Works

## Changes to the WIP mechanism

The approach that we use for WIP would benefit from a few adjustments to make it more flexible when it comes to different styles of walking. We would also like to eliminate some of the biases the system creates e.g. the offset of the distribution of WIP performances into the negative domain (below zero) can be somewhat attributed to this.

## Longer time for practicing

Since WIP is less natural than Real Walking, it is also not as intuitive and getting used to the system takes time. We could solve this problem by having a trial level before each condition that checks whether the participants have learned how to use the system. Only when they finish the trial level can they proceed to the actual test. Proper conditions have to be considered to ensure that one condition does not benefit more from this.

## Constructing a predictive model

To evaluate the system a predictive model which can be obtained using regression, would be desirable. Making a regression model based on the data entails that we make a few changes to the experiment, namely, it requires us to gather more data where the length parameter is continuous instead of discrete values. Doing so allows us to make a scatter plot of both WIP and Real Walking and get a more detailed view of performances over length. It would be interesting to see what type of regression would fit the WIP model and if it is the same as Real Walking.

## Consider using textured surfaces

Some participants did not initially feel like they were moving since the ground plane was flat without any visual cues to indicate movement. We could improve upon this simply by adding textures to the ground plane or small details such as rocks, grass and so forth. One would still have to keep in mind that the environment should not distract from the task.

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