VR locomotion: walking > walking in place > arm swinging

Conference Paper · December 2016

DOI: 10.1145/3013971.3014010

Betsy Williams
Rhodes College

VR Locomotion: Walking>Walking in Place>Arm Swinging

Preston Tunnell Wilson, Rhodes College
William Kalescky, Rhodes College
Ansel MacLaughlin, Rhodes College
Betsy Williams*, Rhodes College

Abstract

There are many methods of exploring an HMD-based virtual environment such as using a game controller, physically walking, walking in place, teleporting, flying, leaning, etc. The purpose of this work is to introduce a simple method of implementing "walking in place" using a simple inexpensive accelerometer sensor. We then evaluate this method of walking in place by comparing it to normal walking and another previously published inexpensive method of exploration, arm swinging. In an experiment that compares the spatial awareness, we show that walking in place is not as good as walking on foot, but it is is better than arm swinging. Subjects also complete blind locomotion distance estimation trials in each of the locomotion conditions.

Keywords: locomotion, walking in place, virtual reality, perception

Concepts: •**Computing methodologies** → **Perception; Virtual reality;**

Figure 1: *This picture shows a user using the Myo armbands while wearing an Oculus DK2 HMD.*

1 Introduction

Inexpensive haptic devices like standard game controllers and joysticks have been shown to cause disorientation in immersive virtual environments (IVEs) [Chance et al. 1998; Ruddle and Lessels 2006; Lathrop and Kaiser 2002]. It is not clear how to effectively and inexpensively explore an IVE. Finding ways to spatially navigate in IVEs that perform comparably to the way we navigate in the real world is a challenging and important problem. In the real world, humans naturally spatially update their location with respect to objects in their environment. A significant body of work has shown that exploring a IVE by physically walking results in the most realistic experience [Ruddle and Lessels 2006; Waller and Hodgson 2013]. That is, a user's spatial orientation in a IVE is best when the proprioceptive cues of walking match the visual input. Physically walking in an IVE requires that the physical location of the user be obtained from some sort of tracking device. However, large tracking systems are expensive, limit exploration to the size of the tracking system, and the physical space requirements suggest that it will never be a commodity level product.

We turn our attention to alternatives which avoid these constraints of tracking systems. Two inexpensive methods of exploring a virtual environment are arm swinging [McCullough et al. 2015] and "walking in place" (WIP) [Williams et al. 2011; Williams et al. 2013; Wilson et al. 2014]. These techniques are compelling because they seem to provide more proprioceptive cues than traditional inexpensive virtual navigation techniques like a joystick. More specifically, WIP and arm swinging seem to result in better spatial awareness of the environment.

We think that the "walking in place" research to date is promising. However, as outlined in Section 2, problems exist with the current inexpensive methods of walking in place. Thus, we devise a new algorithm called Accelerometer walking in place (A-WIP). The basic idea of A-WIP is that an accelerometer is mounted just above each of the ankles of participants. These accelerometers are then used to detect "walk in place" steps and thus translate the user forward in the IVE in the direction that they are looking. In our particular implementation we use the accelerator sensors that are a part of the Thalamic Labs Myo™armband (199 USD). We used this wearable armband because we found it comfortable, easy to put on, and stayed in position with different clothing. A picture of this can be seen in Figure 1. Although, this A-WIP method employs using the Myo armband, our WIP could be used with other devices that have accelerometers.

In this work we compare our A-WIP algorithm to the arm–swinging algorithm presented by McCullough et al. [McCullough et al. 2015] In this work, a Myo™armband was worn on one arm and the users were able to freely explore a virtual environment by swinging their arms. They found that their arm swinging method outperforms a simple joystick and that spatial orientation is comparable to physically walking on foot.

Both walking in place and arm swinging locomotion methods do not suffer from the same space constraint as tracking systems do. They have also both been shown to outperform the joystick and show spatial updating similar to physically walking. The purpose of this paper is to compare the arm swinging algorithm presented by McCullough et al. [McCullough et al. 2015] to our walking

*e-mail:sandersb@rhodes.edu

VRCAI '16,, December 03-04, 2016, Zhuhai, China
ISBN: 978-1-4503-4692-4/16/12…$15.00
DOI: http://dx.doi.org/10.1145/3013971.3014010

in place algorithm. We add a third condition, physically walking, because the literature suggests that this is the best way to explore a virtual environment and maintain spatial awareness[Ruddle and Lessels 2006; Waller and Hodgson 2013]. Thus, the within-subject experiment presented in this work compares subjects' spatial orientation and distance perception under three different locomotion conditions: Myo walking in place, Myo arm swinging, and physically walking. In all three methods, subjects rotate physically. In both the Myo arm swinging and the Myo walking in place conditions, subjects translate in the yaw direction that they are looking. Spatial orientation is used to evaluate navigation because learning the layout and the information in the environment is often the goal of a virtual experience. For example, a person walking home from work must identify his or her location and direction within the surrounding environment before determining in which direction to proceed. This sense of spatial orientation relies heavily on visual information and whole-body information while moving in an environment [Wartenberg et al. 1998]. In other words, both environmental cues and path integration (the process of integrating self-motion cues over time) inform spatial orientation. Thus, spatial orientation is generally tested by performing experiments that require participants to combine the use of environmental cues and path integration. A popular way to assess a user's spatial orientation in an IVE is to measure turning errors and latencies in tasks where subjects are asked to turn to face previously learned target objects [May 1996]. To measure spatial orientation, we recorded the turning errors and latencies associated with subjects turning to face a remembered object from different positions in the IVE. Turning error is defined as the difference between the subjects' actual facing direction and direction needed to face the target correctly.

This work also aims at understanding how well people can adapt to these locomotion techniques by having them perform a series of blind locomotion distance estimation trials in each condition [Creem-Regehr et al. 2015]. That is, observers viewed a target in a large open field and indicated the perceived distance of the target which ranged from 1.25m to 6.25m by navigating without vision to these targets.

2 Background

Previous research has explored various techniques of navigating a IVE. Haptic devices, such as a joystick or keyboard, allow users to virtually explore large environments [Ruddle et al. 1999; Bowman et al. 1999; Waller et al. 1998; Darken and Sibert 1996; Pausch et al. 1995]. However, studies have shown that using physical bipedal locomotion rather than haptic devices produces significantly better spatial orientation [Chance et al. 1998; Ruddle and Lessels 2006; Lathrop and Kaiser 2002]. Suma et al. [2007] show that using position and orientation tracking with an HMD is significantly better than using a system that combines the orientation tracking and a haptic device for translations. However, Riecke et al. [2010] found that joystick translations and physical rotations led to better performance than joystick navigation, and yielded almost comparable performance to actual walking in terms of search efficiency and time.

Other methods of exploring large IVEs have been proposed. In our prior work, Williams et al. [2006; 2008] show that the translational gain of walking can be scaled (where one step forward carries one several steps forward in virtual space). Interrante et al. [2007] proposed a method called "seven league boots" in which they scale gain based on wand control. Another method of navigating a large IVE is manipulating rotation such that the locomotion of the subject fits within the limits of the tracking system [Razzaque et al. 2001; Engel et al. 2008; Nitzsche et al. 2004; Steinicke et al. 2010]. These methods require a large tracking area for the rotational manipulation to be imperceivable and could be physically dangerous because users could easily trip and fall. All of the above methods of manipulating locomotion require the use of a relatively expensive tracking system to capture the physical position of the user. Virtual flying [Usoh et al. 1999] and teleporting are other ways of exploring large IVEs, yet they lack locomotive feedback.

One way to permit free exploration of a human–scaled IVE and provide some of the inertial cues of walking is to have the users "walk in place" (WIP). WIP can be implemented inexpensively (with Microsoft Kinects, [Williams et al. 2013; Wilson et al. 2014]; with Wii Balance Boards, [Williams et al. 2011]; with Smartphones, [Tregillus and Folmer 2016; Brajdic and Harle 2013]). When WIP with the Wii Balance Boards, Williams et al. [Williams et al. 2011] showed participants' spatial orientation was the same as normal walking and superior to joystick navigation. They also implemented an alternative WIP algorithm later with Microsoft Kinect sensors [Williams et al. 2013; Wilson et al. 2014]. However, they found some problems using the Kinect as the basis of a virtual environment system. The most immediate trouble was occlusion of body parts: when the user was facing certain orientations, the Kinect would not be able to correctly determine the user's skeletal data. They tried to remedy this by adding an additional Kinect to their system, but this did not completely solve the problem. To prevent the faulty Kinect data from causing users to shift forward unintentionally, they increased the angle of the inner knee necessary to record a step. This forced the users to practically march rather than walk in place. Users found this to be uncomfortable. Finally, users could only move forward in full step increments, thus did not have precise control over their movement. More recently, WIP has been implemented using a smartphone. [Tregillus and Folmer 2016] A strong advantage of this system is that the smartphone is also used as the virtual display thus elinating the need for extra sensors. Due to the limitations of the smartphone, their algorithm suffers from high stopping latency and no control over speed. Different techniques of WIP to explore an IVE have been proposed [Slater et al. 1995; Templeman et al. 1999; Feasel et al. 2008; Wendt et al. 2010]. These works have mainly focused on step detection algorithms and use relatively expensive tracking systems to track the position of the knees, shins, feet, or head. Additionally, Whitton et al. [2005] compared walking, WIP, and joystick locomotion and found that physically walking to explore an IVE was better than both WIP and joystick locomotion. Harris et al. [2014] propose an inexpensive method of leaning to explore an IVE and find it to be comparable to WIP.

Other systems to explore a large IVE involve large screen caves with a locomotion input such as a bicycle or treadmill [Plumert et al. 2004]. Cave–based systems are expensive, and most only contain three virtual walls. Treadmill systems are difficult and expensive to construct with enough degrees of freedom to allow for free exploration. Other expensive hardware solutions to explore a large IVE include the Cyber Sphere [Fernandes et al. 2003] and the Cyber Walk [Schwaiger et al. 2007].

We directly compare participants' spatial orientation in a virtual environment when the environment is explored by WIP, physically walking and using our Myo arm swinging method. One limitation of our work is that we did not do a real world baseline comparison. We know that many studies, [Bowman et al. 1999; Waller et al. 1998; Williams et al. 2007], have found a difference in virtual exploration versus real world exploration. In this work, we were interested in seeing how well our WIP method compares to Myo arm swinging method. However, we would like to follow up on this idea in future work.

3 Myo Locomotion Methods

The Myo Armband is a wearable band that can be seen in Figure 1. The armband fits arm sizes that vary between 7.5in and 13in in circumference by adding or removing the expanders that come with the product. The Myo arm band has two types of sensors, a medical grade stainless EMG sensors and a 9 axis inertial measurement unit (IMU). The IMU contains a three-axis gyroscope, three-axis accelerometer, and three-axis magnetometer. Thus, the Myo SDK provides several kinds of spatial data: orientation in terms of pitch, yaw and roll, acceleration vector data which represents the acceleration of the armband, and angular velocity data provided by the gyroscope. It is important to note that the IMU in the Myo armband is nice for measuring the orientation of the arm (roll, pitch, yaw) but position data has a significant amount of error. The Myo armband is better suited to getting the relative orientations of the arms rather than the absolute position and can achieve a sampling rate of 50 Hz. All data from the Myo is communicated via Bluetooth to a computer. The graphics were rendered using the Unity 3–D game engine.

3.1 Myo Arm Swinging

To use the arm swinging system presented by McCullough et al. [McCullough et al. 2015], subjects wear a Myo armband on the thickest part of their forearm, just below their elbow. The basic idea of the algorithm is that users swing their arms to move in the direction that they are looking. We note that this method only uses one armband in this locomotion method. This approximation works well because when one arm is swinging, the other arm usually swings too. To infer steps from arm movement with this algorithm, we calculated the velocity in the y-direction. We note that when one swings their arms, the movement is mostly in the z and y positions. We chose to measure the y-velocity because it was consistent regardless which way the user was facing. Additionally, this helps prevent accidental movement due to gesticulation. If the user moved their arms too much in the x or z direction, we counted it as gesticulation and would not move the user forward. Later, we discuss possible alternatives to this algorithm. To stop moving, participants stopped moving their arms. With this arm swinging algorithm, if subjects swing their arms faster, they propel themselves forward faster due to the increased velocity.

3.2 Accelerometer Walking in Place

With this algorithm, we used two accelerators that were mounted We used two armbands to implement this walking in place algorithm that connect via Bluetooth. With our walking in place algorithm, users place a Myo armband around each of their ankles. We obtained the data from both armbands on one computer, and Unity supported using two.

Our walking in place algorithm relied on the accelerometer data. We simply measured the change in velocity from the Myo armband. This enabled users to walk in a way that is most comfortable to them rather than pick up their feet awkwardly. Like the arm swing method, we measure change in the y-position. However, since the knee has fewer degrees of movement, we do not need to account for gesticulation. We also made the assumption that one leg is stationary while another is moving. This is not accurate for actual walking, but works well enough for walking in place. Thus, we simply summed the change in differences for each leg. Later, we discuss improvements and alternatives to this algorithm.

Using accelerometers avoids the problem of occlusion faced by the Kinect. No optical data is needed as data is read directly from the user. There is much less noise. Additionally, as we used the data

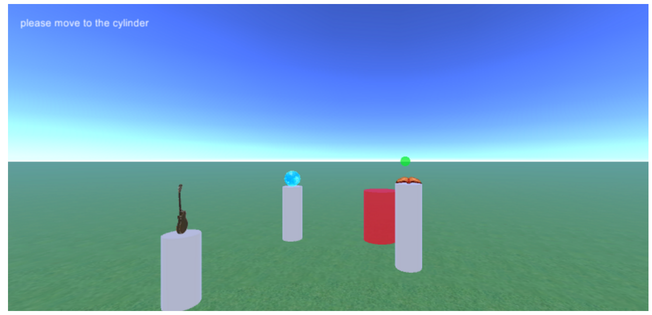

Figure 2: *A view of the virtual environment.*

from the accelerometer, users had more precise control over their movement. The faster they walked in place, the faster they moved in the VE. They could quickly stop and move slightly and comfortably. It is important to note that we were able to solve a limitation of walking in place in that users can only explore the virtual environment in whole step increments.

4 Experimental Evaluation

We compare arm swinging, walking in place, and physical walking in an experiment. We tested 18 subjects on their spatial orientation and perception of distances in the environment using a within-subjects design. After a user finished all three navigation methods, we asked them a series of questions.

4.1 Materials

The experiment was conducted in a 9m by 12m room. The IVE was viewed through an Oculus Rift Development Kit 2 (DK2) head-mounted display (HMD) which had a resolution of 960x1080 per eye, a field-of-view of 100° diagonally, a weight of 0.32 kg and an optical frame rate of 75Hz. Orientation was updated using the orientation from the sensor found on the Oculus Rift DK2. Graphics were rendered using the Unity. In the walking condition, position was interpolated by the WorldVIz PPT software using 8 optical cameras that track 2 LED lights mounted on the HMD.

The IVE used in the experiment was a circular shaped grassy plane (50m diameter) with a generic dome backdrop depicting the sky as seen in Figure 2. For each condition, the user would memorize the positions of 6 objects placed around the environment on columns (Figure 2). The heights of the cylinders varied so that the top of the objects were always at the same level. After the user had memorized the locations of the objects, the tests would begin. These six target objects were arranged in a particular configuration, such that the configuration in all three conditions varied only by a rotation about the center axis. In this manner, the angles of correct yaw-angle responses were preserved across all conditions. The random order of trials and the different objects concealed the fact that the arrangement was the same throughout the experiment. Objects were similar in size and height. We used a cylinder and an arrow to indicate the position and orientation, respectively, of the testing location for a particular trial.

In all three conditions, the target objects and testing locations where located with a radius of 8m from the center of the plane. Subjects were instructed to remain relatively close to to the center and the experimenter told the participants to move more towards the center of the environment if they were venturing too far from the space. In this manner, the explored space across all three conditions was roughly the same.

4.2 Procedure

Each of the 18 participants explored each of the environments under the three different translational locomotion conditions, A-WIP, normal walking, and Myo arm swinging. In all three conditions, rotation in the virtual environment matched rotation in the physical environment. In the Myo arm swinging condition and A-WIP conditions, participants also moved in the direction of gaze. In the walking condition, each physical step directly corresponded to one step in virtual space.

Since there were six orders of the three locomotion conditions, three subjects were tested in each order in a counter-balanced fashion. The experimental procedure was fully explained to the subjects prior to seeing the virtual environments. Before the subject saw the target objects in each condition, the participant was shown two objects on pillars that did not appear in our test set. Participants performed several practice trials in this environment so that they were familiar with the setup and the experimental design. After the subject understood the task and the condition, the practice target objects disappeared. The participant then practiced the locomotion condition by moving to various targets in the environment for 2 minutes. Once the participants were comfortable with this, they were asked to memorize the set of target objects. During the learning phase, subjects were asked to learn the positions of the six target objects while freely moving around the virtual environment according to the condition that they were in. After about five minutes of study, the experimenter tested the subject by having them close their eyes, and point to randomly selected targets. This testing and learning procedure was repeated until the subject felt confident that the configuration had been learned and the experimenter agreed.

Participants' spatial knowledge was tested from six different locations. A given testing position and orientation was indicated to the subject by the appearance of a red cylinder and a red arrow in the environment. Participants were instructed to locomote to the cylinder until it turned green and then turn to face the arrow until it turned green. When both the cylinder and arrow were green, the participants were in an appropriate position. When the subject reached this position, the objects were hidden so that the participant only saw the cylinder and the arrow on a black background. After the participant was told which object to turn to face, the cylinder and arrow disappeared and the participant briefly saw the name of the target object. Specifically the subjects were told "turn to face the <target name>". Once the participant indicated that they had turned to face the object, the angle turned, the angle of correct response and the latency associated with turning to face the object were recorded. The cylinder and arrow reappeared and the participant then turned back to face the arrow until it turned green again. Then, the subject was instructed to face another target object. At each location, the subject completed three trials by turning to face three different target objects in the environment, making 18 trials per condition. After completing three trials at a particular testing location, the participant was asked to face the arrow until it turned green before the environment and objects were displayed again so that the participant would not receive any feedback. After the environment and objects were shown again, the cylinder and arrow were moved to the next target location. Subjects were encouraged to re–orient themselves after completing a testing location.

To compare the angles of correct responses across conditions, the same trials were used for each condition. The testing location and target locations were analogous in all three conditions, and targets varied randomly across the environments. The trials were designed so that the disparity was evenly distributed in the range of 20–180°. Also the testing locations were positioned in such a way that they would never turn to face a target object closer than 0.8m.

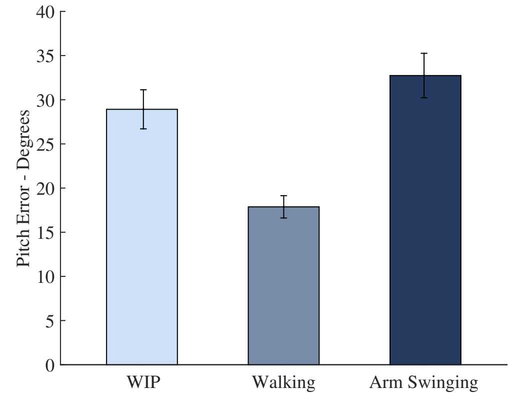

Figure 3: *Mean turning error for the walking in place (WIP), walking, and arm swinging conditions. Error bars indicate the standard error of the mean.*

To assess the degree of difficulty of updating orientation relative to objects in the virtual environment, latencies and errors were recorded. Latencies were measured from the time when the target was identified until subjects said they had completed their turning movement and were facing the target. Unsigned errors were measured as the absolute value of the difference in initial facing direction (toward the arrow) minus the correct facing direction. The subjects indicated to the experimenter that they were facing the target by verbal instruction, and the experimenter recorded their time and orientation. The time was recorded by computer, and the rotational position was recorded using the orientation sensor on the Oculus DK2 HMD. Subjects were encouraged to respond as rapidly as possible, while maintaining accuracy.

After each spatial orientation test for a given condition, subjects would perform a distance estimation task in that condition. Thus, after the user was finished with the spatial orientation task for a condition, the objects in the environment were removed and subjects were placed in the middle of the room if they were in the tracking condition. An avatar would appear either 1.25m, 2.5m, 3.75m, or 5m away from the user. After the user saw where the avatar was, the display would go black, and the user navigate to where they thought the avatar was. We tested each distance twice. The order of the distances was randomized between navigation methods and between subjects. We recorded the correct distance, how far the user was from the avatar when they said they were at the avatar, and how long it took the user to move to that position.

4.3 Results

Figures 3 and 4 show the subjects' mean turning errors and latencies by locomotion condition in the virtual environment. All subjects completed each of the 3 conditions in one of six orders. We compared mean turning error on the three conditions using a repeated measures ANOVA with order between subjects. The analysis revealed a significant effect of condition, $F(2,16) = 6.4, p < .01$; t-tests further revealed a significant difference between all three conditions. People made fewer errors if they explored the virtual environment physically on foot and made the most errors in the arm swinging condition. They also made fewer errors in the WIP condition as compared to the arm swinging condition. There were no effects of order or the interactions of condition and order on participants' errors. We compared the latency in a similar repeated measures ANOVA with order between subjects. There was no ef-

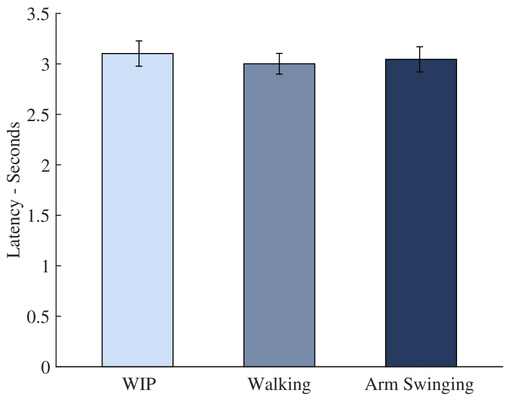

Figure 4: *Mean latency for the walking in place (WIP), walking, and arm swinging conditions. Error bars indicate the standard error of the mean.*

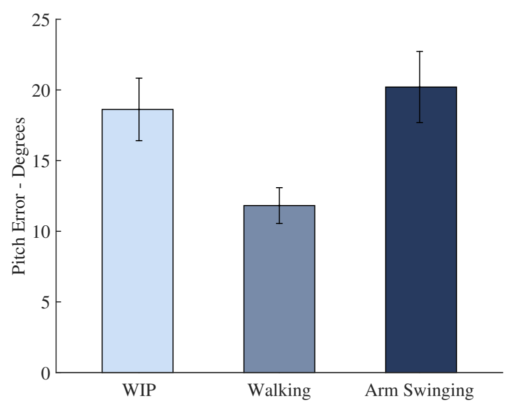

Figure 5: *Median turning error for the walking in place (WIP), walking, and arm swinging conditions. Error bars indicate the standard error of the mean.*

fect of condition, order, or the interaction of condition and order. Thus, the response time for each participants was approximately the same across the conditions.

Figure 5 shows the subjects' median turning errors by locomotion condition. The related median latency figure was omitted because it is similar to Figure 4. Although the trends are similar to Figure 3, the turning errors are lower. The reason for the difference between the median and mean data was mainly due to the existence of large outliers. We did run a similar statistical analysis on the median data. That is, we compared median turning error on the three conditions using a repeated measures ANOVA with order between subjects. The analysis revealed a significant effect of condition, $F(2, 16) = 5.3, p < .01$; t-tests further revealed a significant difference between the walking condition and the two other conditions. However, we do not find a statistical difference between WIP and arm swinging.

Figures 6 and 7 show the results of the blind distance estimation portion of our experiment. Figure 6 shows the mean error plotted as a function of distance for each of the three conditions. Similarly, Figure 7 shows the latency plotted as a function of distance for each of the three conditions. The mean error was calculated as the judged

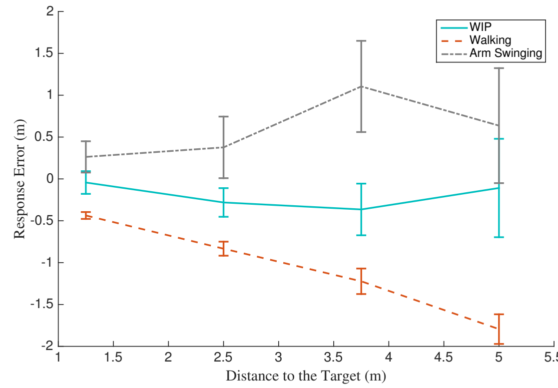

Figure 6: *Blind locomotion distance judgement error for the walking in place (WIP), walking, and arm swinging conditions by distance. Error bars indicate the standard error of the mean. Negative values indicate distance underestimations.*

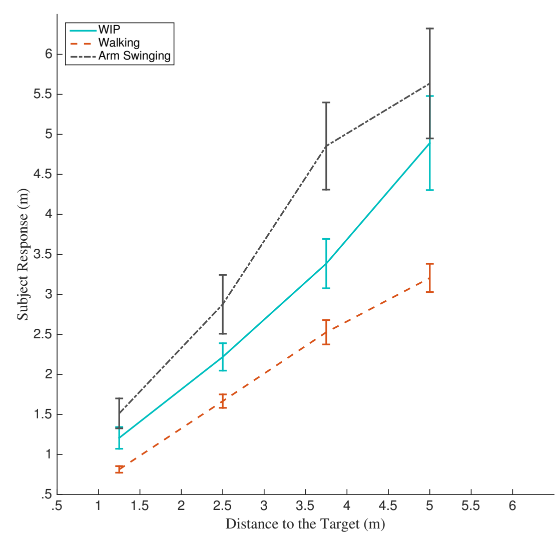

Figure 7: *Blind locomotion response time for the walking in place (WIP), walking, and arm swinging conditions by distance. Error bars indicate the standard error of the mean.*

distance subtracted from the actual distance. Thus, positive errors represent foreshortening (or distance underestimation) and negative errors represent anti-foreshorenting (or distance over estimation). The ideal or accurate responses would be plotted as a straight line at 0m error across the different tested distances. We did repeated-measures ANOVA on participants' errors, with experimental condition (WIP, walking and arm swinging) and distance (1.25m, 2.5m, 3.75m, and 5m) as repeated factors. There was a highly significant main effect of condition ($F(3, 51) = 278.2, p < .01$), and the interaction of condition and distance($F(3, 51) = 537.1, p < .01$). The blind locomotion response was significantly different across the conditions. Thus, the distance perception as indicated by locomoting with eyes closed under different locomotion methods was different across the conditions. Moreover, subjects response was systematic across the distances for each condition. Similarly, we did repeated-measures ANOVA on participants? latency. There was a highly significant main effect of condition ($F(3, 51) = 54.9, p < .01$), distance ($F(3, 51) = 181.4, p < .01$), and the interaction of condition and distance ($F(3, 51) = 78.1, p < .01$).

5 Discussion and Conclusion

This paper presents an inexpensive method of walking in place (WIP) using an accelerometer. In an experimental evaluation, we compare WIP to another inexpensive method of exploration arm swinging [McCullough et al. 2015] and physically walking. We found that physical locomotion out performed both WIP and arm swinging in terms of turning error. We also found that WIP was better than arm swinging in terms of turning error, and users were strangely accurate at walking to the correct distance in the walking in place condition. Our results are a little different than prior work that shows that arm swinging is the same as walking in terms of spatial awareness [McCullough et al. 2015] and WIP is the same as walking in terms of spatial awareness [Williams et al. 2011], although our tasks are very similar. In the present study we have 18 participants, and the previous studies involved 12 subjects per experiment. Also, the studies ran by McCullough et al. [McCullough et al. 2015] and Williams et al. [Williams et al. 2011] also included a joystick condition.

Interestingly, we found a statistical difference between all three conditions when we analyzed the mean turning errors of the participants. We did not find a statistical difference between WIP and arm swinging when we analyzed the results using the median data. The reason for the difference in the median data to the mean data was due to outliers in our data. We hypothesize that subjects might need more training with the arm swinging condition and were more likely to make produce outliers in the arm swinging condition. However, we still feel that the low errors present in our results with respect to both methods suggest that they are still viable alternatives to physically walking. We did not add the joystick or game controller as a condition to this experiment because we felt that these methods are clearly inferior as shown by the prior work. We think that this work suggests that WIP might be better than arm swinging as a means to exploring a large virtual environment.

The blind locomotion results are interesting. There was consistent significant overestimation of distances after the IVE was explored using arm–swinging, and consistent significant distance underestimation after the IVE was explored using normal walking. The distance underestimation that we found when users physically walk to respond is consistent with the literature that shows that people consistently underestimate distances in virtual environments [Creem-Regehr et al. 2015]. However, we did not find underestimation with arm swinging or WIP. Interestingly, participants were the most accurate with WIP. To understand this result, we asked participants to describe the strategies that they used to figure out how to respond accurately in the arm swinging and WIP conditions. Some subjects reported that they simply guessed the number of steps and then completed that many arm swings or WIP steps to get to the target. Others simply said that they just imagined that they were in the locomotion mode and responded appropriately. We hypothesize that subjects may not simply be comfortable walking and wearing the HMD itself while walking might make people subconsciously walk less because they do not feel confident.

One of the huge benefits of this newly created WIP algorithm is that it allows users to move in smaller increments. To take smaller "steps" the user would simply move their legs slightly. This is a new concept to the WIP literature

Both arm swinging and WIP are simple, robust algorithms. Moreover, these methods of navigation based on the Myo armband do not suffer from either space limitations or occlusion. We used the Myo armband because it is simple to put on and use. However, these algorithms can be implemented using stand alone sensors that could be mounted to clothing.

Acknowledgements

This material is based upon work supported by the National Science Foundation under grant 1351212. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsors. We thank the Rhodes College Fellowship program for also supporting this research.

References

BOWMAN, D. A., DAVIS, E. T., HODGES, L. F., AND BADRE, A. N. 1999. Maintaining spatial orientation during travel in an ive. *Presence 8*, 6, 618–631.

BRAJDIC, A., AND HARLE, R. 2013. Walk detection and step counting on unconstrained smartphones. In *Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, ACM, New York, NY, USA, UbiComp '13, 225–234.

CHANCE, S. S., GAUNET, F., BEALL, A. C., AND LOOMIS, J. M. 1998. Locomotion mode affects updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration. *Presence 7*, 2, 168–178.

CREEM-REGEHR, S. H., STEFANUCCI, J. K., THOMPSON, W. B., NASH, N., AND MCCARDELL, M. 2015. Egocentric distance perception in the oculus rift (dk2). In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception*, ACM, New York, NY, USA, SAP '15, 47–50.

DARKEN, R., AND SIBERT, J. 1996. Navigating in large virtual worlds. *The Int. J. of Human-Computer Interaction 8*, 1, 49–72.

ENGEL, D., CURIO, C., TCHEANG, L., MOHLER, B., AND BÜLTHOFF, H. H. 2008. A psychophysically calibrated controller for navigating through large environments in a limited free-walking space. In *2008 Symp .on VR software and technology*, ACM, New York, NY, USA, 157–164.

FEASEL, J., WHITTON, M. C., AND WENDT, J. D. 2008. Llcm-wip: Low-latency, continuous-motion walking-in-place. In *Sym. on 3D User Interfaces*, IEEE, Washington, DC, 97–104.

FERNANDES, K. J., RAJA, V., AND EYRE, J. 2003. Cybersphere: the fully immersive spherical projection system. *Commun. ACM 46*, 9, 141–146.

HARRIS, A., NGUYEN, K., WILSON, P. T., JACKOSKI, M., AND WILLIAMS, B. 2014. Human joystick: Wii-leaning to translate in large virtual environments. In *Proceedings of the 13th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and Its Applications in Industry*, ACM, New York, NY, USA, VRCAI '14, 231–234.

INTERRANTE, V., RIES, B., AND ANDERSON, L. 2007. Seven league boots: A new metaphor for augmented locomotion through moderately large scale ives. In *IEEE Symp. on 3D UIs*, 167–170.

LATHROP, W. B., AND KAISER, M. K. 2002. Perceived orientation in physical and ves: Changes in perceived orientation as a function of idiothetic information available. *Presence 11*, 1, 19–32.

MAY, M. 1996. Thinking outside the body: An advantage for spatial updating during imagined versus physical self-rotation. *Psychologische Beitrge 38*, 418–434.

MCCULLOUGH, M., XU, H., MICHELSON, J., JACKOSKI, M., PEASE, W., COBB, W., KALESCKY, W., LADD, J., AND WILLIAMS, B. 2015. Myo arm: Swinging to explore a ve. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception*, ACM, New York, NY, USA, SAP '15, 107–113.

NITZSCHE, N., HANEBECK, U., AND SCHMIDT, G. 2004. Motion compression for telepresent walking in large target environments. *Presence 13*, 1, 44–60.

PAUSCH, R., PROFFITT, D., AND WILLIAMS, B. 1995. Quantifying immersion in virtual reality. In *SIGGRAPH 95*, 399–400.

PLUMERT, J. M., KEARNEY, J. K., AND CREMER, J. F. 2004. Child's perception of gap affordances: Bicycling across traffic-filled intersections in an immersive ve. *Behavior Reseach Methods, Instruments, and Computers 75*, 1243–1253.

RAZZAQUE, S., KOHN, Z., AND WHITTON, M. C. 2001. Redirected walking. *Eurographics Short Presentation*.

RIECKE, B. E., BODENHEIMER, B., MCNAMARA, T. P., WILLIAMS, B., PENG, P., AND FEUEREISSEN, D. 2010. Do we need to walk for effective vr navigation? physical rotations alone may suffice. In *7th Inter. Conf. on Spat. Cogn.*, 234–247.

RUDDLE, R. A., AND LESSELS, S. 2006. For efficient navigational search, humans require full physical movement, but not a rich visual scene. *Psychological Science 17*, 6 (June), 460–465.

RUDDLE, R. A., PAYNE, S. J., AND JONES, D. M. 1999. Navigating large-scale ves: What differences occur between helmet-mounted and desk-top displays? *Presence 8*, 2, 157–168.

SCHWAIGER, M., THUMMEL, T., AND ULBRICH, H. 2007. Cyberwalk: An advanced prototype of a belt array platform. *Haptic, Audio and Visual Environments and Games. HAVE 2007. IEEE International Workshop, 12-14 Oct.*, 50–55.

SLATER, M., USOH, M., AND STEED, A. 1995. Taking steps: The influence of a walking technique on presence in virtual reality. *ACM Trans. on Human Interaction 2*, 3, 201–219.

STEINICKE, F., BRUDER, G., JERALD, J., FRENZ, H., AND LAPPE, M. 2010. Estimation of detection thresholds for redirected walking techniques. *IEEE Transactions on Visualization and Computer Graphics 16*, 17–27.

SUMA, E., BABU, S., AND HODGES, L. 2007. Comparison of travel techniques in complex, mulit-level 3d environment. In *IEEE Symposium on 3D User Interfaces*, 149–155.

TEMPLEMAN, J. N., DENBROOK, P. S., AND SIBERT, L. E. 1999. Virtual locomotion: Walking in place through ves. *Presence 8*, 6, 598–617.

TREGILLUS, S., AND FOLMER, E. 2016. Vr-step: Walking-in-place using inertial sensing for hands free navigation in mobile vr environments. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, ACM, New York, NY, USA, CHI '16, 1250–1255.

USOH, M., ARTHUR, K., WHITTON, M. C., BASTOS, R., STEED, A., SLATER, M., AND BROOKS, F. P. 1999. Walking > walking-in-place > flying, in ves. In *SIGGRAPH 99*, 359–364.

WALLER, D., AND HODGSON, E. 2013. Sensory contributions to spatial knowledge of real and virtual environments. In *Human Walking in Virtual Environments*. Springer, 3–26.

WALLER, D., HUNT, E., AND KNAPP, D. 1998. The transfer of spatial knowledge in ve training. *Presence 7*, 2, 129–143.

WARTENBERG, F., MAY, M., AND PÉRUCH, P. 1998. Spatial orientation in ves: Background considerations and experiments. In *Spatial Cognition, An Interdisc. Appr. to Rep. and Proc. Spat. Knowledge*, Springer, London, 469–489.

WENDT, J. D., WHITTON, M. C., AND JR., F. P. B. 2010. Gud wip: Gait-understanding-driven walking-in-place. In *VR*, 51–58.

WHITTON, M. C., COHN, J. V., FEASEL, J., ZIMMONS, P., RAZZAQUE, S., POULTON, S. J., MCLEOD, B., AND BROOKS JR, F. P. 2005. Comparing ve locomotion interfaces. In *Virtual Reality, 2005. Proceedings. VR 2005. IEEE*, IEEE, 123–130.

WILLIAMS, B., NARASIMHAM, G., MCNAMARA, T. P., CARR, T. H., RIESER, J. J., AND BODENHEIMER, B. 2006. Updating orientation in large ves using scaled translational gain. In *3rd Symp. on Appl. Percept. in Graph. and Vis.*, ACM, 21–28.

WILLIAMS, B., NARASIMHAM, G., WESTERMAN, C., RIESER, J. J., AND BODENHEIMER, B. 2007. Functional similarities in spatial representations between real and ves. *TAP 4*, 2.

WILLIAMS, B., BAILEY, S., NARASIMHAM, G., LI, M., AND BODENHEIMER, B. 2011. Evaluation of walking in place on a wii balance board to explore a ve. *ACM Trans. Appl. Percept. 8*, 3 (Aug.), 19:1–19:14.

WILLIAMS, B., MCCALEB, M., STRACHAN, C., AND ZHENG, Y. 2013. Torso versus gaze direction to navigate a ve by walking in place. In *SAP '13: Proceedings of the symposium on Applied perception*, to appear.

WILLIAMS, B. 2008. *Design and Evaluation of Methods for Motor Exploration in Large Virtual Environments with Head-Mounted Display Technology*. PhD thesis, Vanderbilt University, Nashville, Tennessee, USA.

WILSON, P. T., NGUYEN, K., HARRIS, A., AND WILLIAMS, B. 2014. Walking in place using the microsoft kinect to explore a large ve. In *Proceedings of the 13th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and Its Applications in Industry*, ACM, New York, NY, USA, VRCAI '14, 27–33.