# Omnidirectional VR Treadmills Walking Techniques: Comparing Walking-in-Place and Sliding vs Natural Walking

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Figure 1: The three different VR walking techniques compared in the study. (A) Walk-in-Place using the Kat VR mini, (B) Sliding using the Cyberith Virtualizer ELITE 2, and (C) Natural Walking.

## ABSTRACT

In Virtual Reality (VR), exploring a large virtual environment is still an open research area, as software-based solutions can be challenging to use or contribute to motion sickness. Past work has used omnidirectional treadmills to emulate natural walking in a small space. Yet, the impact on user performance and experience of the different walking techniques these omnidirectional treadmills utilize is still unclear. This study assessed the effects of WALK-IN-PLACE, used with devices like KAT VR mini, and SLIDING, as used by devices like Cyberith Virtualizer ELITE 2, and compared them to NATURAL WALKING. Using a within-study design methodology, eighteen participants navigated a VR maze. We found that participants completed tasks fastest with NATURAL WALKING while SLIDING provided a balanced compromise between immersion and moderate physical effort, and WALK-IN-PLACE required the highest exertion with lower usability. These findings provide practical insights into performance and user-experience differences among the three VR walking techniques, informing VR-ODT selection for applications such as rehabilitation and training.

**Index Terms:** Virtual Reality, Navigation, Walking, Treadmills

## 1 INTRODUCTION

Modern Virtual Reality (VR) head-mounted displays (HMDs) offer a highly realistic and seamless viewing experience, featuring precise interactions with virtual objects and high-resolution graphics with low latency in rendering and tracking [33]. These technological advances have made VR applications increasingly popular across various fields, including education, rehabilitation, and training [67]. For example, table tennis players use VR to practice shots and serves [30], radiology students use VR to learn procedures [82], and stroke survivors use VR to improve limb function [12]. One of the challenges of using VR HMDs is navigating inside large virtual environments (VE) [41], as moving large distances that exceed the dimensions of a physical room requires controlled-based navigation techniques. Yet, being able to emulate natural walking is important for rehabilitation and training applications where realistic biomechanical movements are required [28, 59, 45].

Another way to explore large VE is by using specialized hardware, e.g., VR omnidirectional treadmills (VR-ODTs). VR-ODTs mimic natural walking within VR in reduced spaces by enabling stationary navigation that emulates the sensation of walking [7]. They are also a safe way to explore large VE without the fear of crashing into walls or colliding with other physical objects [17, 7]. These two characteristics make VR-ODTs frequently used for rehabilitation [42, 72] and training [14] VR applications where realistic environments are essential. However, using VR-ODT results in unnatural walking with movement patterns that can diminish the sense of immersion and increase discomfort [47, 2]. This difference between VR-ODT walking and natural walking has consequences when using VR-ODT for rehabilitation and training, where the goal is to transfer the skills learned to real life. Yet, the question remains as to which VR-ODT walking technique compares better to natural walking, as past work has focused on evaluating specific VR-ODT devices and not walking techniques [77, 1].

This paper compares the two most common VR walking tech-

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niques used in VR-ODT with each other: WALK-IN-PLACE, where the user lifts their legs to take a step but stays in the same place [54] and SLIDING, where the person takes a step forward, and the incline of the treadmill causes the foot to slide towards the center [17, 25]. We also compare them against NATURAL WALKING, where the user can physically translate in space and does not need special devices to emulate movement. Our goal is to understand the differences between the VR walking techniques used in VR-ODTs regarding user performance, user experience, spatial navigation, and motion sickness to identify their effect on locomotion, e.g., the physical act of movement and wayfinding, e.g., the cognitive aspect that determines the route [69]. By comparing the effectiveness of these VR walking techniques to give users the ability to navigate comfortably and efficiently within a large VE, we aim to inform future VR rehabilitation and training applications where users must correctly emulate natural walking [28, 59, 45].

In a within-participants users study, eighteen participants navigated a VR maze in three different conditions (WALK-IN-PLACE, SLIDING, and NATURAL WALKING); while doing this, they had to find four spheres and the exit. See 1 for the different walking techniques evaluated. We evaluated the participants' performance in terms of time and ability to remember the maze. We also collected data regarding the devices' usability, the participant experience, and motion sickness. The results revealed significant differences in physical exertion and movement efficiency among the different walking techniques. In contrast, the measures of navigation behaviour and exploration patterns showed no significant differences, indicating that the walking technique did not affect how participants interacted with the virtual environment. These results extend previous work [1, 77] that evaluates specific VR-ODTs by comparing the two different walking techniques used with VR-ODTs, e.g., WALK-IN-PLACE and SLIDING. We also extend that work by conducting a comprehensive analysis of user interaction focusing on the locomotion and wayfinding of VR walking techniques.

## 2 RELATED WORK

Navigation is one of the three basic interaction techniques in VR [37], with earlier work focusing on controlled-based navigation methods [5]. Since then, multiple VR navigation techniques where users press buttons or move the joystick to navigate have been proposed [3, 40, 48]. Yet, navigating large virtual spaces remains a significant challenge when users are confined to small physical spaces [70, 73]. This paper focuses on VR walking techniques that try to emulate natural walking. In the rest of this section, we discuss the challenges of emulating walking in VR and the different VR walking techniques.

### 2.1 Simulating Walking in VR

Walking to navigate in VR involves 1:1 mapping of the user's steps to the position and orientation of the camera movement. This way of VR navigation, called natural walking, is intuitive and immersive [77], as it aligns with the user's expectations of walking [46]. By stimulating vestibular and proprioceptive feedback, natural walking significantly improves navigation and spatial awareness compared to walking-in-place or joystick-based methods [60]. Yet, unrestricted natural walking in VR requires a large physical area, which is often impractical in typical VR setups [55].

Multiple past works have tried to emulate walking using various methods; see next section. Yet, there are numerous challenges to implementing VR walking techniques due to the technological limitations of VR HMDs and human factors. One primary challenge is accurately replicating the complex multisensory feedback associated with real-world locomotion. Walking involves coordinated inputs from visual, vestibular, and proprioceptive systems [38], and discrepancies between these sensory inputs can lead to sensory conflicts, resulting in discomfort or motion sickness [58]. To address these challenges, researchers have explored solutions involving multisensory feedback. For example, Turchet et al. [79] investigated the integration of haptic feedback in walking simulations and found that plantar vibrotactile feedback significantly enhanced the realism of virtual locomotion experiences, thereby improving user immersion in multimodal environments. Other work also demonstrated that interactive auditory feedback, such as footstep sounds, can significantly influence walking speed and gait patterns in VR environments [80].

These studies highlight the importance of designing VR-ODTs incorporating multisensory feedback to bridge the gap between physical and virtual experiences. Considering these findings, our study evaluates how two different VR walking techniques used in VR-ODTs (WALK-IN-PLACE and SLIDING) emulate walking and compares their ability to replicate it.

### 2.2 VR Walking Techniques

The main goal of a VR walking technique is to utilize the user's gait, e.g., the movement of the feet and legs, to control the camera position, which emulates the sensation of walking without requiring the user to move the same distance as with natural walking [34]. VR walking techniques are divided into three groups:

- *Full gait techniques* involve the full gait cycle. Examples include redirect [62, 76] and scaled [24] walking that subtly manipulate the virtual environment to keep users within a confined space [63, 74]. However, these methods can introduce noticeable distortions if overused, potentially breaking immersion [75]. Additionally, variations in the boundary shapes and sizes of virtual and real spaces can further restrict the effectiveness of real walking techniques [46, 56].

- *Partial gait techniques* mimic some of the biomechanics by involving aspects of the gait cycle. The most popular technique is walk-in-place (WIP) [81], which allows users to perform stepping-like motions on the spot, serving as a proxy for actual steps, enabling users to walk through infinitely large VEs without needing to move physically. Past work [81, 83] has evaluated WIP against natural walking and found that natural walking outperforms WIP, where WIP requires more exertion than natural walking and uses unnatural movements. Yet, Langbehn et al. [36] designed a novel WIP system that uses the torso leaning angle to control speed and found that it improved user experience and performance over traditional WIP. Nilsson et al.'s [53] also evaluated different ways to do the WIP technique and found that alternatively lifting each heel of the ground while keeping the toes in contact with the ground, reduces user fatigue and improves the perceived naturalness of locomotion, particularly for longer VR interactions.

- *Gait negation techniques* are designed to keep the user walking within a defined space by negating forward motion. The most common gait negation technique is sliding, which requires VR-ODTs to negate movement. VR-ODTs use different technologies, for example, active methods like a belt-based [25] or roller-based treadmill [64]. Other VR-ODTs use passive methods like hamster balls [49] and low friction surfaces [7]. These VR-ODTs vary in complexity, with some providing both rotational and translational body-based cues [25, 7, 51, 9], while others offer only translational movement [65, 66]. Finally, past work found that VR-ODTs enhance immersion without requiring large physical spaces [42]. However, device design significantly affects user preference, with bowl-shaped models often favored for their comfort and ease of use [2, 20].

Past work has studied how VR walking techniques compare to natural walking. Here, we focus on the work that evaluated VR-ODTs [1, 77, 8, 45]. For example, Chakraborty et al. [8] compared the Cyberith Virtualizer ELITE 2 [7] with natural walking and found that participants significantly overwalked distances and path integration performance was degraded when using the Cyberith Virtualizer ELITE 2. Lewis et al. [45] compared natural walking with VR-ODT walking and turning using an Infinadeck [23] and found that VR-ODT walking resulted in significantly slower gait speeds, shorter step lengths, and increased variability in step length compared to natural walking. Our work extends these studies by comparing two distinct VR walking techniques employed by VR-ODTs (WALK-IN-PLACE and SLIDING).

## 3 MOTIVATION

The ability to navigate within large VE by walking is essential for applications in areas such as training and rehabilitation [26], as it will allow for a more realistic environment [77] and a greater sense of presence [71]. Moreover, walking is also a low motion-sickness navigation method [9, 8, 45] that can help more people enjoy VR games and other applications. Past work has proposed using VR-ODTs [11] to enable users to navigate large virtual spaces while remaining physically stationary [11]. These devices use different navigation techniques to control the walking. For example, the Cyberith Virtualizer [7] employs SLIDING, and the KAT VR [31] uses NATURAL WALKING. Past work has compared different VR-ODT against walking [45, 8] or redirect walking [77] and identified an effect on the user. However, the effectiveness of the different VR walking techniques supported by the different VR-ODTs regarding locomotion and wayfinding is not fully understood. How they compare to walking regarding user performance is also poorly understood. Thus, understanding how different VR-ODTs use different VR walking techniques is important for future VR applications, especially as past work has found that different locomotion techniques affect the users' abilities to navigate and orient themselves in virtual spaces [13, 18, 8].

In our research, we focus on two different VR walking techniques supported by VR-ODTs, WALK-IN-PLACE and SLIDING, and compare them to NATURAL WALKING. We aim to understand how these different VR walking techniques affect users' locomotion, user experience, physical exertion and movement efficiency in a non-deterministic environment. This focus is critical, as effective spatial navigation is vital to creating immersive and intuitive VR experiences, especially in training and rehabilitation applications that require users to explore large, complex virtual spaces [26]. Our research questions are the following:

- **RQ1:** What are the differences in user performance of different VR walking techniques?
- **RQ2:** What are the differences in user experience of different VR walking techniques?
- **RQ3:** What is the difference in physical exertion and movement efficiency of utilizing different VR walking techniques?

By answering these questions, our aim is to understand the tradeoffs involved in choosing between different VR-ODTs based on the VR walking method they use (NATURAL WALKING or SLIDING). Our goal is to understand participants' performance across these navigation techniques to provide insights into VR-ODTs' relative benefits and drawbacks versus natural walking. These insights are essential for developers and designers seeking to optimize VR systems for specific use cases, ensuring that the chosen navigation method aligns with the intended spatial navigation experience.

## 4 USER STUDY

We conducted a within-subject user study to investigate two different VR walking techniques that VR-ODTs use: SLIDING (Figure 4) and WALK-IN-PLACE (Figure 3). We compared them with each other and against NATURAL WALKING see Figure 2. This study was approved by Dalhousie University Research Ethics Board.

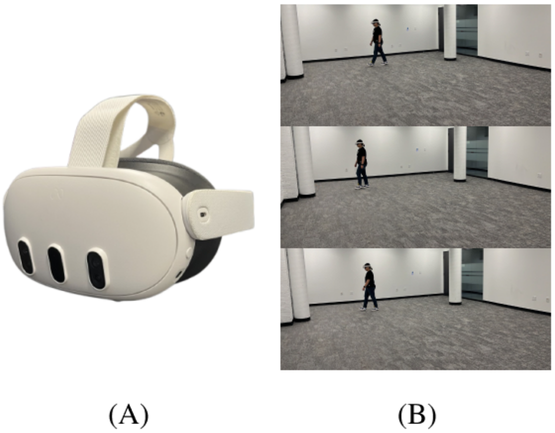

Figure 2: (A) Meta Quest 3 VR Headset (B) Natural walking in a physical space

### 4.1 Participants

We recruited 18 participants from Dalhousie University through email advertising and poster distribution. We used Schoenfeld's statistical methodology to determine the required sample size for this study. We considered continuous scales, a within-subject design, an 85% power test, and a 0.5 effect size for the calculations. The estimated sample size required for our study was 12 participants. However, we recruited 18 participants due to the possibility of losing participants, as longitudinal studies where participants need to attend multiple sessions over different days are known to lose participants [39].

Participants' ages were between 20 and 38 (mean = 25.2, SD = 5.12), and we had a balanced gender ratio, with nine men and nine women. All our participants were physically capable of stepping onto the treadmill, maintaining balance on one leg, and did not have any health issues that would prevent safe treadmill use. In terms of eye dominance, 4 participants were left-eye dominant, and the remaining 14 participants were right-eye dominant. Prior VR experience was limited for most participants, with 12 participants having 0-2 sessions and 6 participants having 2-8 sessions of VR usage. Participants rated their physical fitness levels between 5 and 10 (M = 7.44, SD = 1.51). Using the metabolic equivalent (MET) scores [61], eleven out of 18 participants were classified as highly active, six as moderately active, and one as low active. Regarding motion sickness, 10 out of 18 exhibited symptoms in the last 10 years. Sixteen participants showed low to moderate susceptibility to motion sickness, indicating varied tolerance across different transport. However, a subset of 2 participants consistently reported higher instances of nausea, both in childhood and adulthood, highlighting individual variability in motion sickness susceptibility.

### 4.2 Apparatus

The experiment was conducted on a PC with a 12th Gen Intel(R) Core(TM) i7-12700 2.10 GHz, 32 GB RAM, and an NVIDIA GeForce RTX 3070 graphics card. For the walking method, we used three different combinations of VR HMDs and VR-ODTs, described below.

Figure 3: (A) Kat VR mini treadmill [31], (B) Meta Quest 3 VR Headset (C) Walking-in-place on the treadmill

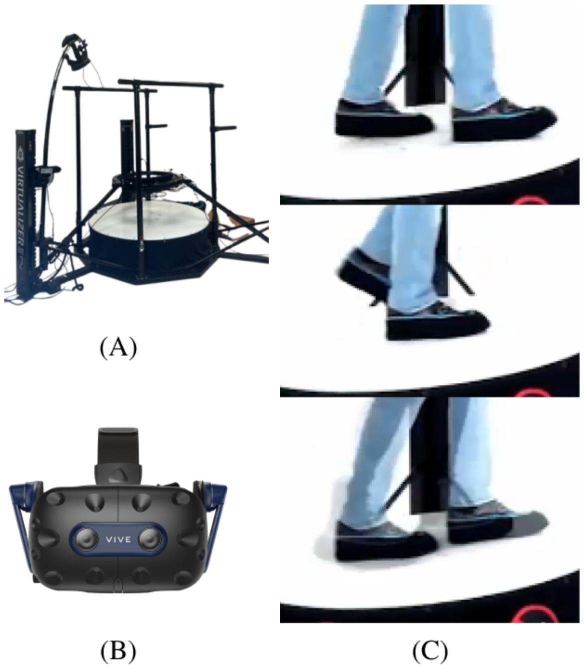

Figure 4: (A) Cyberith Virtualizer ELITE 2 treadmill [7], (B) HTC Vive Pro 2 VR Headset [21] (C) Sliding on the treadmill

- **WALK-IN-PLACE:** Participants used the Kat VR Mini [31] as the VR-ODTs, and the Meta Quest 3 [50] as the VR HMD. We used the official Meta Quest guidelines for setting up the environment and the official Kat VR Mini development kit to connect the VR HMD to the device. See Figure 3 for a picture of the device and the description of the walking method.

- **SLIDING:** Participants used the Cyberith Virtualizer ELITE 2 [7] as the VR-ODTs, and the HTC Vive Pro 2 headsets [21] as the VR HMD. We used the official HTC Vive Pro guidelines for setting up the environment and the official Cyberith Virtualizer ELITE 2 development kit to connect the VR HMD to the device. See Figure 4 for a picture of the device and the description of the walking method.

- **NATURAL WALKING:** Participants used the Meta Quest 3 [50] as the VR HMD. In this condition, we did not have a VR-ODT but used an open space measuring 4.6m by 11.7m room to run the study. The space had no objects participants could collide, and we matched the VE to the room size. See 2 for an overview of the walking method.

For the VE, we created a maze using a random maze generation program [78], which ensured variability and complexity in the design—critical factors for evaluating VR navigation. The maze had a 7x7 grid structure with 35 out of 84 possible internal walls. The shortest path length was 23, providing a challenging yet solvable task within the session's time constraints. Figure 5 shows that the maze design includes a 2D layout and the corresponding 3D model we used. Inside the VE were eight boxes; on every try, we randomly added four spheres into four of those eight boxes using the C# Random function. Changing the sphere position made the VE non-deterministic and was inspired by Nguyen-Vo et al. [52].

The VE for the WALK-IN-PLACE and SLIDING conditions used Unity 2021.3.24f [1] and the VE for walking used Unity 2021.3.26f [2]. We changed Unity versions due to hardware requirements. The Cyberith Virtualizer required Unity 2021.3.24f, also compatible with Kat VR. However, the Quest 3 standalone headset only supported Unity 2021.3.26f or later.

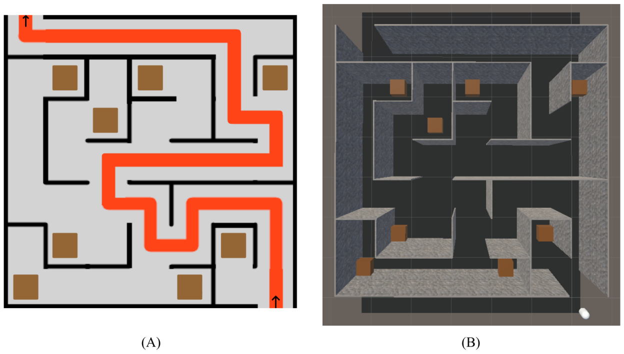

Figure 5: The maze used in our study was developed in Unity. (A) 2D layout showing the exact positions of the boxes and the shortest path to exit. (B) 3D model of the maze with the same box positions.

### 4.3 Procedure

Participants were randomly assigned to one of six groups, each following a different order of the three VR walking techniques to counterbalance learning effects. The order was determined using

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[1] https://unity.com/releases/editor/whats-new/2021.3.24#notes

[2] https://unity.com/releases/editor/whats-new/2021.3.26#notes

a Latin Square design. Each participant engaged in three experimental sessions corresponding to the three different VR walking techniques. The sessions occurred on multiple days; nine participants did the study on three different days, one for each VR walking method, and nine participants on two different days (SLIDING on one day, and WALK-IN-PLACE and NATURAL WALKING on the other, with a one-hour break between sessions).

In the first session, participants began by giving voluntary consent to participate in the experiment and filling out a demographic form. Before the experiment, they completed a demographic questionnaire, the International Physical Activity Questionnaire (IPAQ) [43], and the Motion Sickness Susceptibility Questionnaire (MSSQ) [16]. These surveys gathered information about participants' backgrounds, physical activity levels, and susceptibility to motion sickness. Then, participants watched instructional videos from the treadmill manufacturers to familiarize themselves with the equipment. Following this, we briefed participants on the VR experience, including what they would see and hear and the tasks they needed to perform. We gave specific instructions for those participants in the NATURAL WALKING condition to avoid walking through virtual walls.

Participants navigated the VR maze in each session using the assigned walking method. They were required to collect four randomly placed spheres from eight boxes within the maze. In total, they repeated the maze two times for each walking method. After each session, participants completed the Virtual Reality Sickness Questionnaire (VRSQ) [32], NASA Task Load Index (NASA TLX) [19], System Usability Scale (SUS) [44], and a post-study questionnaire. After the third session, participants completed a post-study questionnaire to provide overall feedback on their experience, including their preferences and reasons for selecting specific VR walking techniques.

### 4.4 Evaluation Metrics

The data collected in this study were analyzed to assess the impact of different VR walking techniques on user performance, spatial navigation, and physical exertion. Below, we describe all the measurements we recorded and analyzed:

- **Trial Duration**: The time taken to complete the VR maze was measured as the duration between entering and exiting the maze. We started the timer when the user crossed the entry and stopped it when they crossed the exit after finding the four hidden spheres.

- **Steps**: Three different methods were used for step counting: Garmin Vivosmart4 smartwatch [15], Ozo Fitness CS1 pedometer [57], and manual counting via the Big Tap Counter app [10] on an iPhone. After evaluating the accuracy of these methods, we chose manual counting as the most reliable method due to frequent inaccuracies compared to the other two devices on the treadmills.

- **Total Maze Cells Traveled**: The number of total maze cells explored by each participant. In total, there were 49 cells, but participants could visit a cell multiple times and, thus, had a higher total maze cell traveled count.

- **Revisited Boxes**: The number of times a participant returns to a box they have previously visited during their navigation task. This measure is used to assess the efficiency of spatial exploration, as higher counts may indicate redundant searching or difficulties in remembering explored areas.

- **Empty Box Visits**: The number of times participants visited boxes within the maze that did not contain a sphere. This metric helps assess the efficiency of the participant's exploration and navigation strategy, as more empty box visits may indicate less effective search patterns or difficulties in spatial memory and navigation.

- **Total Distance Traveled**: The cumulative distance moved by the participant within the maze. We calculate it by measuring the displacement of the participant's head position along the axes of the virtual 3D scene.

- **User Experience:** After using each walking method, our participants filled out the following questionnaires: 1) *NASA TLX* to measure the perceived workload of using that walking method; 2) *SUS* to measure the usability of that walking method. We calculated the SUS score using the Lewis et al. [44] method; and 3) *VRSQ* to measure the motion sickness of the participant after using that walking method.

- **Participants' Preferences:** Participants completed questionnaires about their preferred walking method. After using each walking method, participants were assessed across six areas: Comfort, Control, Orientation, Immersion, Ease of Use, and Physical Exertion. Then, at the end of the last session, participants filled out another questionnaire with open-ended questions. We asked their overall feedback on the experiment, including their preferences and reasons for choosing a particular walking method. We analyzed these data by categorizing the participant's answers by themes using Braun and Clarke thematic analysis methodology [6].

### 4.5 Experimental Design

We performed a one-factor within-subjects user study with three **VR walking techniques** conditions ($3_{techniques}$ = WALK-IN-PLACE, SLIDING, NATURAL WALKING). We measured trial duration (seconds), total maze cells traveled (count), revisited boxes (count), empty box visits (count), distance traveled (m), and steps (count) as dependent variables. We counterbalanced the **techniques** with a Latin Square across participants. Participants repeated the maze two times. In total, each participant performed $3_{techniques} \times 2_{Mazes} = 6$ repetitions. The experiment took a total of three sessions of 60 minutes for each individual.

## 5 RESULTS

Results were analyzed using one-way ANOVA in SPSS Statistics [22] and plotted using JMP Pro 18 software [27]. The normality of the data was assessed using the Shapiro-Wilk Test, followed by a Box-Cox transformation to normalize the metrics. However, *Steps*, *Revisited Box Counts*, and *Total Distance Travelled* remained non-normal despite transformation. The Friedman test was used for these non-normal metrics. The Tukey HSD test was applied to identify interaction effects for normally distributed data, while the Wilcoxon method assessed interaction effects in non-normal data.

### 5.1 User Performance

Results are shown in Table 1, and in Figure 6. There was a significant main difference in **trial duration** for VR walking techniques ($F(2,51) = 35.713$, $p < 0.001$, $\eta^2 = 0.562$). All VR walking techniques differed; NATURAL WALKING was the fastest, followed by SLIDING, and finally WALK-IN-PLACE.

We also found a significant main difference in **steps** between VR walking techniques ($Z = 28.778$, $p < 0.001$, $\eta^2 = 0.266$). Our results show that participants took fewer steps with NATURAL WALKING than with SLIDING and WALK-IN-PLACE, but there is no difference between SLIDING and WALK-IN-PLACE.

There was a significant main difference in **total distance traveled** between the VR walking techniques ($Z = 12.444$, $p = 0.002$, $\eta^2 = 0.115$). Our results show that when using NATURAL WALKING, our participants traveled a shorter distance than when using

SLIDING and WALK-IN-PLACE, but we found no difference between the VR walking techniques used in VR-ODTs.

Finally, we did not find a significant difference for **total maze cells traveled, revisited boxes, and empty box visits**.

### 5.2 User Experience

We found a significant difference between VR walking techniques for **workload (NASA-TLX)**. See Figure 7 and Table 2 for the results. There was a significant main difference between VR walking techniques for four of the factors evaluated: 1) **Mental Demand** ($Z = 14.246$, $p < 0.001$, $\eta^2 = 0.340$), where WALK-IN-PLACE had a higher mental demand than NATURAL WALKING, but there was no difference between WALK-IN-PLACE and SLIDING, nor between SLIDING and NATURAL WALKING; 2) **Physical Demand** ($Z = 10.533$, $p = 0.005$, $\eta^2 = 0.237$), where WALK-IN-PLACE and SLIDING had more physical demand than NATURAL WALKING, but there was no difference between them; 3) **Effort** ($Z = 13.966$, $p < 0.001$, $\eta^2 = 0.333$), where WALK-IN-PLACE required a higher effort than NATURAL WALKING, but there was no difference between WALK-IN-PLACE and SLIDING, nor SLIDING and NATURAL WALKING; 4) **Frustration/Failure** ($Z = 15.954$, $p < 0.001$, $\eta^2 = 0.388$), where WALK-IN-PLACE and SLIDING were more frustrating than NATURAL WALKING, but there was no difference between them. Finally, we did not find significant differences for **Temporal Demand** or **Performance**.

For **motion sickness (VRSQ)**, our results show a statistically significant difference between VR walking techniques. See Figure 8 and Table 3. The eight factors with significant main differences were: 1) **General Discomfort** ($Z = 18.130$, $p < 0.001$, $\eta^2 = 0.448$), where WALK-IN-PLACE and SLIDING had higher participant discomfort over NATURAL WALKING, but there were no differences between them; 2) **Fatigue** ($Z = 13.636$, $p = 0.001$, $\eta^2 = 0.323$), where WALK-IN-PLACE and SLIDING had increased participant fatigue over NATURAL WALKING, but there were no differences between them; 3) **Difficulty Focusing** ($Z = 10.640$, $p = 0.005$, $\eta^2 = 0.240$), where participant had more difficulty focusing with the WALK-IN-PLACE than with the NATURAL WALKING condition, but there were no differences between NATURAL WALKING and SLIDING, nor SLIDING and WALK-IN-PLACE; 4) **Headache** ($Z = 6.067$, $p = 0.048$, $\eta^2 = 0.113$), but none of the pairwise comparisons reached significance after Holm correction; 5) **Fullness of Head** ($Z = 9.500$, $p = 0.009$, $\eta^2 = 0.208$), where participants' rating of fullness of head was worse with WALK-IN-PLACE than NATURAL WALKING, but there were no differences between NATURAL WALKING and SLIDING, nor SLIDING and WALK-IN-PLACE; 6) **Blurred Vision** ($Z = 8.000$, $p = 0.018$, $\eta^2 = 0.167$), where participant's got more blurred vision with SLIDING than with NATURAL WALKING, but there was no difference between NATURAL WALKING and WALK-IN-PLACE nor WALK-IN-PLACE and SLIDING; 7) **Dizzy (Eyes Closed)** ($Z = 10.606$, $p = 0.005$, $\eta^2 = 0.239$), where participants' got more dizzy with WALK-IN-PLACE and SLIDING than with NATURAL WALKING, but there was no difference between them; and 8) **Vertigo** ($Z = 9.250$, $p = 0.010$, $\eta^2 = 0.201$), where SLIDING gave more vertigo to participants than NATURAL WALKING, but there was no difference between NATURAL WALKING and WALK-IN-PLACE nor WALK-IN-PLACE and SLIDING. Finally, we did not find significant differences for **Eyestrain**.

For **usability (SUS)**, NATURAL WALKING had a score of 88.06, equivalent to an A+ grade. For WALK-IN-PLACE, the score was 58.61, equivalent to a D grade. Finally, the score for SLIDING was 72.5, equivalent to a C+ grade.

### 5.3 Participants' Preferences

We analyzed the participants' preferences for walking techniques and open-ended questionnaires together to understand the participant experience while using the different VR walking methods. We found two main themes: (1) Naturalness & Immersion and (2) Comfort, Physical Effort & Safety. Next, we summarize the recurring themes.

Naturalness & Immersion: Overall, participants preferred NATURAL WALKING as the VR walking method, with 14 participants choosing it as the best method due to its applicability to the real world. For example, P2 stated *"Regular walking felt the most natural and immersive. I forgot I was even in VR."* Other participants also highlighted its intuitiveness, with all 18 participants ranking it "Very satisfied" or "Extremely satisfied" for ease of use. P4 also mentioned this intuitiveness in the open-questions: *"It was just like real life; there was no learning curve at all."*.

The second-best method was SLIDING, which received positive feedback, particularly for its immersive experience and the sense of natural movement it provided. For example, two participants ranked it first due to its moderate realism, and P10 stated *"[SLIDING ] closer to actual stepping but still wasn't perfect."* SLIDING also had increased satisfaction in Control and Orientation, as 12 out of 18 participants rated these areas as "Very satisfied" or "Extremely satisfied."

Finally, most participants found WALK-IN-PLACE not natural, with feedback suggesting that it felt less comfortable, which detracted from the overall experience. For example, P3 stated *"hard to walk on and unnatural"*. Participants also showed a lower satisfaction, with 10 out of 18 participants reporting being "Not at all satisfied" or only "Slightly satisfied" for control and orientation.

Comfort, Physical Effort & Safety: Our participants mentioned NATURAL WALKING as a VR walking method that was less physically demanding and comfortable. For example, all 18 participants rated it high for control (movement autonomy). Interestingly, SLIDING was generally viewed as requiring less effort, with P12 saying *"I could move around smoothly without wearing myself out."*. Other participants remarked on the unique appeal of the slider, e.g., P13 said *"Sliding had an amusement-park feel, which was kind of exciting."*. Regarding safety, participants mentioned the harnesses and rails as confining, even if they eliminated the risk of physically bumping into objects.

Interestingly, two participants ranked WALK-IN-PLACE first, mostly due to the reduced risks of real-world collision. For example, P14 said *"I didn't worry about hitting walls when I used the KAT VR mini, so it felt safer."*. Yet, participants also found that it required too much physical effort, like P1, who said *"It felt like a burden; too much energy for too little realism."*

Summary: Our findings indicate a clear preference for NATURAL WALKING due to its ease of use and natural feel. Yet, SLIDING offers a strong alternative due to its ability to mimic natural walking while maintaining a high level of immersion and the less effort required to navigate the VE than NATURAL WALKING. Moreover, SLIDING and WALK-IN-PLACE helped mitigate real-world collisions that might occur with NATURAL WALKING. Still, SLIDING does not match the satisfaction levels of NATURAL WALKING.

## 6 DISCUSSION

This paper evaluated the effectiveness, user experience, and physical exertion of three distinct VR walking techniques: NATURAL WALKING, WALK-IN-PLACE using the Kat VR Mini, and SLIDING using the Cyberith Virtualizer ELITE 2. In a within-subjects user study, nine men and nine women used all three navigation techniques while navigating a non-deterministic virtual maze. By doing a comprehensive evaluation to identify the strengths and limitations of each VR walking technique with a balanced gender population

| | Walking Mean (SD) | WIP Mean (SD) | Sliding Mean (SD) | Statistical Test | p-value | Effect Size ($\eta^2$) |
|---|---|---|---|---|---|---|
| **Experiment Duration** | 90.694(34.325) | 246.611(65.046) | 185.417(62.626) | F(2, 51) = 49.805, | $< 0.001$ | 0.56 |
| **Steps** | 115.611(35.148) | 282.083(82.154) | 234.583(77.384) | Z = 28.778 | $< 0.001$ | 0.266 |
| **Total Cell Traveled in Maze** | 87.000(34.482) | 84.889(16.673) | 85.889(23.683) | F(2, 51) = 0.262 | 0.771 | -0.028 |
| **Revisited Box Count** | 2.083(2.917) | 2.250(2.060) | 2.444(2.394) | Z = 1.2 | 0.549 | 0.011 |
| **Empty Box Visits** | 5.278(3.241) | 5.611(2.104) | 5.583(2.608) | F(2, 51) = 0.708 | 0.497 | -0.011 |
| **Total Distance Traveled** | 43.897(17.427) | 66.912(14.020) | 60.460(15.983) | Z = 12.444 | 0.002 | 0.115 |

Table 1: User Performance Study Results

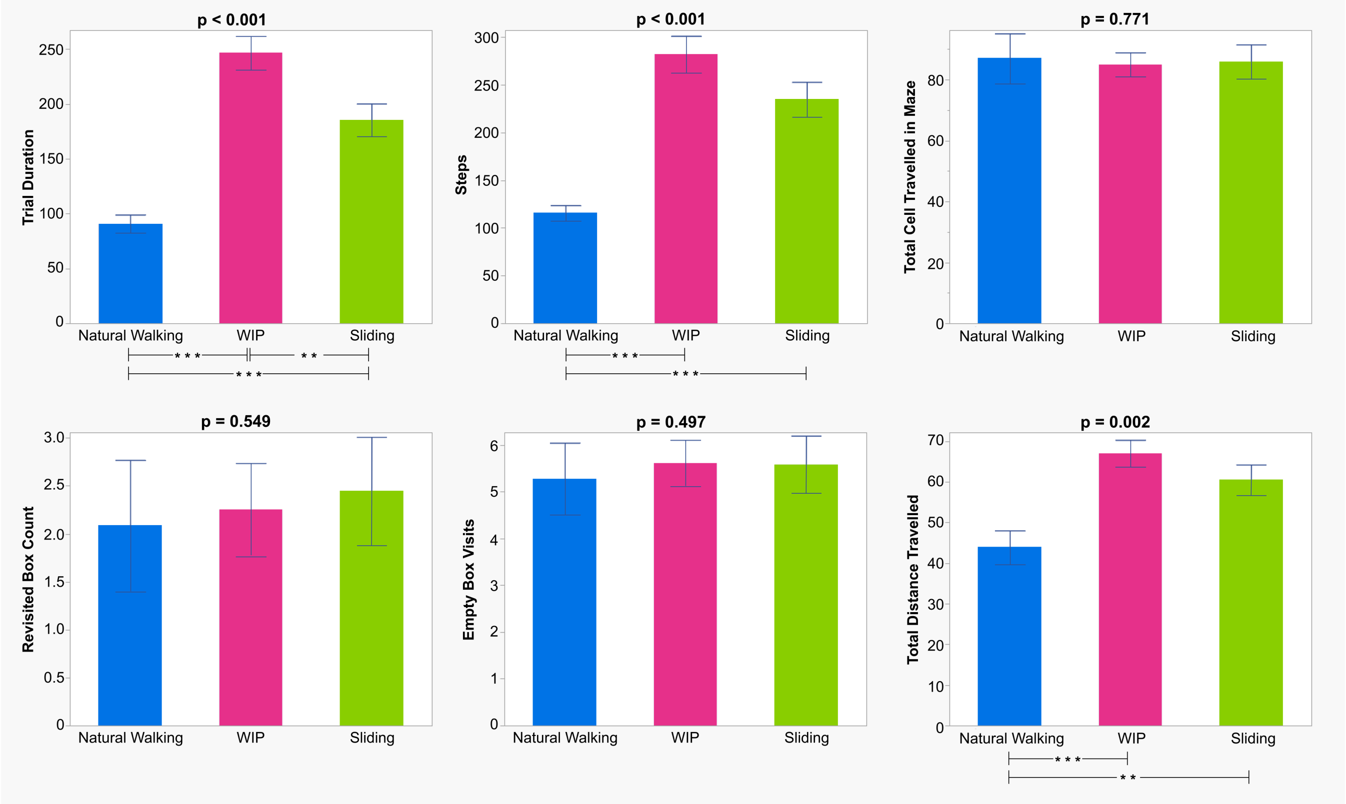

Figure 6: Comparison of natural walking, walking-in-place (Kat VR), and sliding (Cyberith Virtualizer ELITE 2) across six different metrics. The significant results are displayed with * * representing $p < 0.01$ and * * * representing $p < 0.001$.

and non-deterministic VE, our results can generalize to other VR-ODTs that utilize the same VR walking interactions. Moreover, as our focus was not on specific devices, our work can also apply to other VR-ODTs that utilize partial gait (WALK-IN-PLACE) or gait negation techniques (SLIDING) for locomotion in VR. Therefore, our results contribute to optimizing VR-ODTs for enhanced user performance and experience. Next, we discuss how our results answer each of the research questions:

## 6.1 User Performance

The study results about user performance metrics answer **RQ1** by showing that NATURAL WALKING had the best performance of all evaluated VR walking techniques. Overall, participants completed the maze faster, took fewer steps, and traveled shorter distances when using NATURAL WALKING than when using WALK-IN-PLACE and SLIDING. These results are similar to past work that compared VR-ODTs with natural walking [8, 45, 1]. Yet, finding a space large enough for the VE is not always possible. Thus, we will focus our "discussion" on the differences between the VR-ODT walking techniques.

Our results show that SLIDING performed better than WALK-IN-PLACE for the trial duration, as participants finished the maze faster. Interestingly, there was no difference between VR walking techniques for steps and total distance traveled. One possible explanation is that even if not significant, when using WALK-IN-PLACE, participants took more steps on average than when using SLIDING (283 steps versus 234 steps). Similarly, WALK-IN-PLACE had, on average, a higher total distance traveled than SLIDING (66.9m versus 60.4m). This difference means that WALK-IN-PLACE led to less efficient navigation, likely due to the additional physical effort, than SLIDING. Past work findings support this, as WALK-IN-PLACE unnatural movements increase the physical exertion of the user [81, 83].

A possible explanation of the differences in trial duration between WALK-IN-PLACE and SLIDING is the feedback each VR walking technique provides. Past work found that increasing the realism of the technique using multisensory feedback affects user performance [79], as walking involves coordinated inputs from visual, vestibular, and proprioceptive systems [38]. SLIDING is a gait negation technique that allows users to do the full gait cycle, including the forward motion, which provides the correct walking

|  | **Walking Mean (SD)** | **WIP Mean (SD)** | **Sliding Mean (SD)** | **Statistical Test (Z)** | **p-value** | **Effect Size ($\eta^2$)** |
|---|---|---|---|---|---|---|
| **Mental Demand** | 3.389 (2.330) | 5.833 (2.149) | 4.778 (2.861) | 14.246 | <0.001 | 0.34 |
| **Physical Demand** | 2.944 (2.236) | 5.278 (2.024) | 4.722 (2.608) | 10.533 | 0.005 | 0.237 |
| **Temporal Demand** | 4.111 (2.654) | 5.167 (2.007) | 4.944 (2.155) | 0.875 | 0.646 | -0.031 |
| **Performance** | 8.722 (1.320) | 8.222 (1.768) | 8.222 (2.290) | 4.133 | 0.127 | 0.059 |
| **Effort** | 2.278 (1.904) | 4.556 (2.572) | 3.444 (2.706) | 13.966 | <0.001 | 0.333 |
| **Frustration/Failure** | 0.389 (0.608) | 2.278 (2.539) | 1.722 (1.904) | 15.954 | <0.001 | 0.388 |

Table 2: NASA-TLX Results

|  | **Walking Mean (SD)** | **WIP Mean (SD)** | **Sliding Mean (SD)** | **Statistical Test (Z)** | **p-value** | **Effect Size ($\eta^2$)** |
|---|---|---|---|---|---|---|
| **General Discomfort** | 0.056 (0.236) | 0.833 (0.924) | 1.056 (0.873) | 18.130 | <0.001 | 0.488 |
| **Fatigue** | 0.111 (0.323) | 0.444 (0.616) | 0.833 (0.985) | 13.636 | 0.001 | 0.323 |
| **Eyestrain** | 0.222 (0.428) | 0.500 (0.618) | 0.611 (0.850) | 4.522 | 0.104 | 0.104 |
| **Difficulty Focusing** | 0.167 (0.383) | 0.278 (0.461) | 0.778 (1.003) | 10.6400 | 0.005 | 0.240 |
| **Headache** | 0.222 (0.428) | 0.500 (0.618) | 0.833 (1.043) | 6.067 | 0.048 | 0.113 |
| **Fullness of Head** | 0.000 (0.000) | 0.500 (0.786) | 0.667 (0.907) | 9.500 | 0.009 | 0.208 |
| **Blurred Vision** | 0.167 (0.383) | 0.667 (0.767) | 0.444 (0.784) | 8.000 | 0.018 | 0.167 |
| **Dizzy (Eyes Closed)** | 0.056 (0.236) | 0.667 (0.907) | 0.667 (1.029) | 10.606 | 0.005 | 0.239 |
| **Vertigo** | 0.056 (0.236) | 0.500 (0.618) | 0.722 (1.179) | 9.250 | 0.010 | 0.201 |
| **Total VRSQ Score** | 0.167 (0.383) | 0.722 (0.752) | 0.778 (0.808) | 9.435 | 0.090 | 0.207 |

Table 3: VRSQ Results

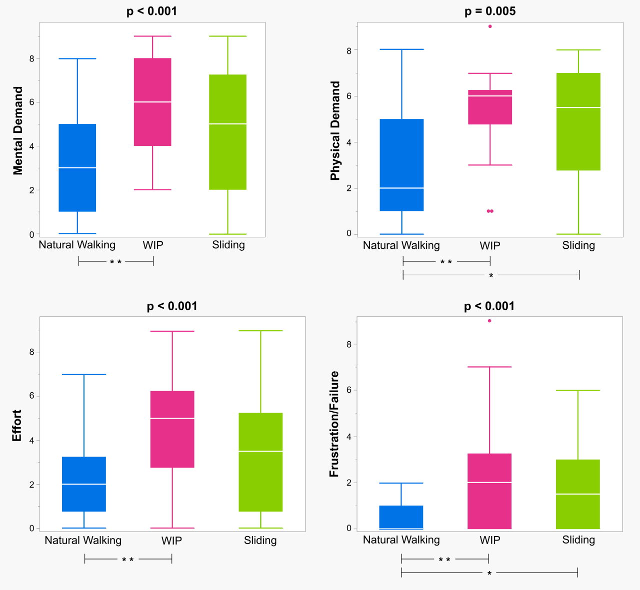

Figure 7: Nasa-TLX questionnaire results. The significant results are displayed with * representing $p < 0.05$, and * * representing $p < 0.01$.

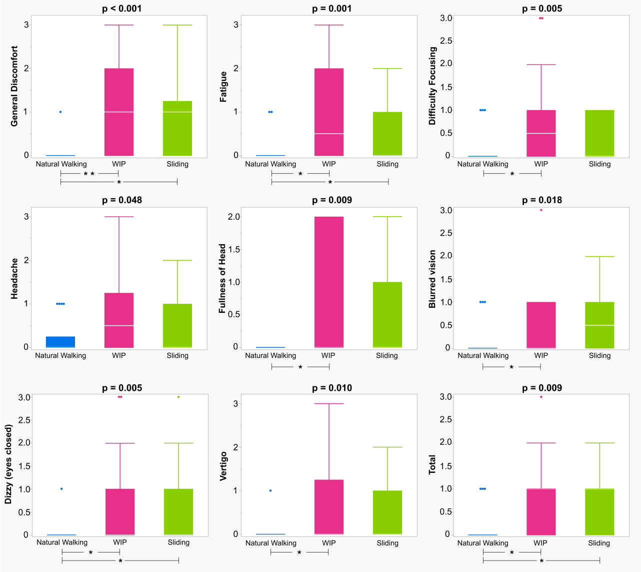

Figure 8: VRSQ questionnaire results. The significant results are displayed with * representing $p < 0.05$, and * * representing $p < 0.01$.

feedback. In opposition, WALK-IN-PLACE is a partial gait technique that breaks the gait cycle, which might provide diminished feedback to the user, thus affecting performance. Yet, as we did not collect data about the feedback participants receive for each step, future studies are needed to identify the differences in feedback between VR walking methods and their effect on user performance.

Moreover, the two VR walking interactions use different devices; WALK-IN-PLACE uses a low friction surface VR-ODTs, e.g., the KAT VR [31], and SLIDING uses an active VR-ODTs, e.g., the Cyberith Virtualizer [7]. The difference in technology affects the physical movement users do, as low friction surface VR-ODTs require more effort from the user due to the lack of mechanical parts. Past work already found that higher physical movements induce greater cognitive loads [35] and thus might reduce user performance. The difference in technology also affected the motion sickness results, with WALK-IN-PLACE inducing more motion sickness than NATURAL WALKING. Yet, future studies need to evaluate other VR-ODTs to identify the effect of VR-ODT technology on user performance.

Finally, our results show that NATURAL WALKING is the most efficient method in terms of performance. Yet, SLIDING using the Cyberith Virtualizer ELITE 2 provides a reasonable alternative with some reduction in efficiency. WALK-IN-PLACE with the Kat VR Mini introduces factors that affect the user performance and may lead to less efficient navigation, likely due to the additional physical effort. However, other exploration-related metrics, such as revisited box counts, total cell traveled, and empty box visits, did not show significant differences, indicating that participants' ability to explore and navigate the virtual environment remained relatively consistent across all techniques.

### 6.2 User Experience

The post-study questionnaire results answer **RQ2** by showing that our participants considered naturalness and immersion as the main properties of a VR walking technique. From their point of view, they ranked NATURAL WALKING as the most natural and immersive technique, primarily noting its intuitive feel and resemblance to real-life walking. These results extend past work identifying immersion, comfort, and perceived usability [4, 68] as factors that influence the overall user satisfaction with navigation and VR walking techniques.

When looking at the walking techniques employed with VR-ODTs, our participants identified that SLIDING provided a highly immersive experience, with participants finding it like natural walking. The SUS results further confirmed these findings, with SLIDING obtaining a C+ grade. In opposition, WALK-IN-PLACE received the lowest satisfaction scores, primarily due to the unnatural movement and low usability (D grade). These results show that the multisensory feedback from the SLIDING full gait cycle increases user immersion and extends past work to VR walking interactions [79].

Finally, participants found that SLIDING and WALK-IN-PLACE helped mitigate real-world collisions that might occur with NATURAL WALKING. Yet, participants did not see the rails used in the Cyberith Virtualizer as an advantage over the KAT VR's lack of rails. These results show that security is important for users and that future work on rehabilitation and training applications that use VR-ODTs should consider the user perceptions of safety.

### 6.3 Physical Exertion and Movement Efficiency

The NASA-TLX results and the user comments answer **RQ3**. Here, our results show that NATURAL WALKING has lower mental and physical demands and requires less effort than the VR walking interactions. These results verify past work that walking requires less effort than using VR-ODTs to walk in VR [45, 8].

Yet, the open-ended preferences questionnaire results show that participants felt SLIDING as requiring less physical effort than NATURAL WALKING. Past work by Kang et al. [29] highlighted differences in distance perception between VR-ODTs and real-world locomotion, emphasizing that excessive physical demands can detract from the overall VR experience. Our results extend these results by showing that, even with ample space, SLIDING might be an option for VR walking interaction due to user perception of physical effort. The user performance results support this, as NATURAL WALKING did not significantly improve spatial navigation understanding over SLIDING, as comparable total maze cells traveled and revisited box counts were found, demonstrating SLIDING as an option for exploring VEs. Yet, more work is needed to understand better how user perception influences user performance in specific training and rehabilitation applications.

In opposition to SLIDING, WALK-IN-PLACE was associated with the highest levels of physical exertion, as evidenced by the steps taken, the participant's opinions, and the NASA-TLX results. Yet, past work identified that variations in the WIP implementation could lead to different user experiences and performance outcomes in VR environments [36]. Thus, future work might want to evaluate different WALK-IN-PLACE implementations using VR-ODTs.

## 7 LIMITATIONS

The main limitation of this work is that the VR walking interactions evaluated highly depended on the implementation of the interaction technique and the VR-ODTs chosen. For example, past work has suggested that WALK-IN-PLACE implementation can reduce physical exertion [55]. Moreover, the same interaction technique used in two different VR-ODTs might have a different effect on user performance and preference, as past work has found that factors like the walking surface and step feedback influence the user [80]. Future work should run similar user studies with other VR-ODTs to verify our results.

Another limitation is the relatively low sample size (n=18), which limits our results' generability. Yet, we took care in finding a diverse participant population that included a balanced gender ratio, different levels of experience with VR and VR-ODTs, and fitness levels. Another limitation is how we counted the steps (using a Garmin Vivosmart4, Ozo Fitness CS1 pedometer, and an iPhone application), as each of these methods provided different counts depending on the VR-ODTs used. Future work should use a different method to count steps, like shoes, which are more reliable in their data between devices.

## 8 CONCLUSION

This study evaluated and compared the effectiveness, user experience, and physical exertion of three distinct VR walking techniques: NATURAL WALKING, WALK-IN-PLACE using the Kat VR Mini, and SLIDING using the Cyberith Virtualizer ELITE 2. We analyzed how each method impacted user performance, movement efficiency, and physical demands in a virtual maze navigation task through a comprehensive within-subjects user study.

Our findings demonstrated that NATURAL WALKING was the most efficient and intuitive method. Participants completed tasks faster and reported higher satisfaction than omnidirectional VR treadmill-based methods. Natural walking also requires moderate physical exertion, making it a balanced option for VR applications where natural movement and ease of use are priorities.

In contrast, the Kat VR Mini that uses the WALK-IN-PLACE technique imposed the highest physical exertion, as participants took the most steps and covered the greatest distance. While this method maintained realism through its walking-in-place mechanism, the higher physical effort required resulted in slower experiment duration time and lower user satisfaction.

The Cyberith Virtualizer ELITE 2, which uses the SLIDING technique, offered a balanced experience, combining moderate physical exertion with a relatively immersive experience. Participants appreciated the sliding mechanism's ability to simulate movement more naturally than walking-in-place, though it still fell short of the ease and efficiency of natural walking.

Overall, each navigation method presented distinct advantages and drawbacks depending on the application. Natural walking appears to be the most effective option for VR applications that prioritize task efficiency and user comfort but is limited to VE smaller than the physical space. Walking-in-place may be suitable for tasks requiring higher physical involvement. At the same time, sliding offers a middle ground for users seeking a more immersive experience without overwhelming physical demands. The Cyberith Virtualizer ELITE 2 also offers the option to add a safety harness and a fixed ring around the user, which might be necessary for scenarios like rehabilitation. These findings provide valuable insights for developers and researchers aiming to optimize VR locomotion systems, emphasizing the importance of selecting a navigation method that aligns with a VR application's specific goals and user needs.

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