Evaluating the Impact of Lower-Body Tracking on Immersion in a VR Hiking Game

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Abstract

Interaction methods in VR environments is a very potent area for researchers. Lower-body tracking has the potential to increase embodiment and immersion in virtual reality applications. It does so by enabling movement that is more natural. Yet, its impact within educational VR contexts remains underexplored. This paper presents a controlled experimental study comparing lower-body tracking based locomotion using HTC Vive 3.0 trackers with conventional joystick based locomotion. The study was conducted during the creation of VR Trebević, an educational VR hiking game designed to teach basic hiking skills through task based learning. These tasks include correct packing, orientation and basic safety procedures. Alongside this game, an additional application is created which features a similar environment and mechanics for different ways of moving through space and participants were instructed to try out both. User experience is evaluated using a Likert scale questionnaire focusing on perceived immersion related to experience and comfort. This study aims to provide insights on how lower-body tracking influences user perceived immersion in educational VR environments and to support the design of future VR learning applications that rely on embodied movement mechanics.

Keywords: Virtual Reality, Lower-Body Tracking, Locomotion Methods, User Experience Evaluation, Experiential Learning, Serious Games

1 Introduction

Virtual reality has become a useful tool for interactive learning. Many educational environments are now explored through immersive systems. A strong sense of presence, the feeling of “being there” inside a virtual environment, is often expected from such systems. This perception is strongly affected by movement mechanics. Movement in virtual reality has always been a design challenge. Natural walking can’t always be used because of physical space limits, so most users interact inside small indoor areas. For this reason, artificial locomotion methods are often applied. These methods attempt to simulate movement without requiring large real-life spaces.

Several common locomotion techniques are used in VR applications, typically categorized by their interaction style. Existing VR locomotion typologies classify techniques as motion-based, room-scale, controller-based and teleportation-based. However, recent work has introduced a new type, motion-based teleporting, to capture hybrid locomotion methods [1]. While teleportation has traditionally been a standard choice due to its ability to reduce motion sickness, the sudden change in position can interrupt the sense of natural movement. An analysis of 330 commercial VR applications shows a decline in teleportation usage and an increase in arm-tracked locomotion techniques, highlighting differences in locomotion adoption between industry practice and academic research [2]. These trends suggest a growing interest in movement methods that prioritize physical engagement. Another frequent technique is joystick locomotion. This method is similar to movement in traditional video games. The user pushes a controller stick to move forward or change direction. The approach is simple and familiar. The body remains mostly still while the environment moves around the user and this mismatch between physical and virtual movement can cause discomfort to the player.

Researchers have also explored physical locomotion techniques. These methods attempt to map real body movement to virtual movement. Examples include treadmill walking or arm swing locomotion. Arm swing locomotion detects rhythmic hand movement and translates it into forward motion, that way the user feels more physically involved. Still, this movement method doesn’t fully reflect natural walking patterns. Lower-body tracking has recently gained attention as another possible solution. This technique uses trackers attached to the legs or feet. Movements of the lower-body are detected in real time. The system translates those movements into actions inside the virtual world. That way a stronger link between physical effort and virtual movement can be created. Because of this,

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immersion may increase. However, several challenges are also present. Extra hardware is required for lower-body tracking, setup time may become longer, calibration errors can affect accuracy etc. These limitations raise questions about practicality. It is not yet clear whether the benefits outweigh the extra complexity. Educational VR environments provide an interesting context for this question. Learning experiences often depend on engagement and exploration. When users move in a natural way, attention may remain focused on the environment and its content. This idea is related to the theory that learning is influenced by bodily interaction with the environment.

The study was conducted during the development of VRTrebević, an educational VR hiking game inspired by Trebević Mountain. VRTrebević was developed specifically as a research instrument for this study and is currently an unpublished application. The game was designed to teach basic hiking skills through task based learning. Several short tasks were included. These tasks focus on correct backpack packing, trail orientation and basic safety procedures that hikers should know when in nature. Hiking is strongly connected to physical motion. Because of this, the way a user moves through the environment can affect the overall experience. A natural walking rhythm may increase immersion. For this reason, an additional application that uses a similar environment was developed alongside the main game. Each version uses a different movement approach. One method uses traditional controller based locomotion, while the other one uses lower-body tracking.

The main purpose of this research is to evaluate how different locomotion methods affect immersion. Immersion describes the degree to which a user feels absorbed in a virtual environment. A higher level of immersion may improve engagement and learning outcomes. However, increased physical demand may also influence user comfort. The results of this study aim to support better design decisions for future educational VR experiences.

2 Related work

The use of virtual reality in education is changing as the technology gets better. At first, the focus was on making the graphics and sound look real. Now, there is much more interest in how the player's physical body affects the experience. Bailenson [3] argues that VR is used best when it allows us to do things that would otherwise be dangerous, impossible, counterproductive or expensive (DICE). For many, a hike fits some of these criteria. Using games in VR has shown a lot of promise for teaching. A study by Lampropoulos and Kinshuk [4] found that gamified VR environments help students feel more motivated to learn. However, the success of these tools depends on how immersed the student feels, which is often tied to how they move in the virtual world.

When it comes to VR locomotion and body tracking, research shows that embodied interaction has a big impact on players' sense of immersion. Lanier [5] suggests that the VR's magic comes from the brain's ability to accept a new body, a concept known as homuncular flexibility. A study by Caserman et al. [6] using Vive trackers showed that tracking a user's limbs makes the virtual environment feel much more real. Furthermore, research into wearable electronics has shown that a recent wearable leg movement monitoring system enables accurate, real-time assessment of locomotion speed and motion state [7], suggesting that educational VR games that combine realistic movement with interactive elements keep players more interested. Still, there is a gap in the current research. Not many studies have looked at how lower-body tracking compares to using a joystick for movement, when it comes to immersion and physical comfort.

The context of hiking in VR provides a unique way to study this. Research by Haliburton et al. [8], on a VR hiking system found that moving the body leads to higher levels of mindfulness and positive emotions compared to passive movement. Meaning that the effort of hiking is not just a gameplay mechanic, but also a way to improve the user's emotional state and connection to the environment. This aligns with the design principles outlined by Jerald [9], where he emphasizes that the most effective VR experiences are those that respect the user's biological expectations of movement.

A major part of any VR experience is presence, and that feeling of actually "being there". Jerald [9] explains that presence happens when a place feels real and believable. In a hiking game, this feeling is easily broken. If the camera moves forward while the player's legs are standing still, the brain will get confused. This mismatch is the main cause of motion sickness and often results in a break in presence, where the player remembers they are in a room wearing a headset. By using lower-body tracking the experience can be made to feel more grounded.

The body's internal sense of its own movement called proprioception, is very important here. Research by Bayramova et al. [10] shows that the brain understands movement better when physical motion and visual cues match up. When the way you move in the game mirrors how you move in real life, like the walking in place systems studied by Lee et al. [11], the sense of presence is much stronger. This suggests that moving your legs gives the brain the physical feedback it expects when it sees the scenery moving. In a hiking game, the effort of moving your legs makes the task feel more authentic.

Adding physical movement also helps with learning through a theory called embodied cognition. This is the idea that our bodies and our minds are closely linked. Basically, we learn better when our bodies are involved in the process. Johnson-Glenberg [12] argues for high embodiment VR, where physical actions are related to what is being learned. In a hiking game, the act of walking is a high embodiment action. The physical effort of following a trail makes the lesson more memorable than watching a video.

Even with these findings, there is still a gap in research about how lower-body tracking specifically affects comfort and immersion compared to using a standard controller, especially in educational games. This project will look at how leg tracking specifically changes the experience for players in a virtual mountain environment.

3 Case study

This section describes the development of VRTrebević. To study the issue of hiking and physical motion, two versions of the application were created. Participants were asked to experience both movement systems and their impressions and responses were later evaluated.

3.1 Application design and structure

The structure of VRTrebević follows a simple progression along a forest trail. Users begin at a starting point and gradually move through the environment. A forest path, natural terrain and hiking markers and signs were included in the design to help create a believable outdoor setting. The experience encourages users to gain knowledge by completing practical actions rather than passively receiving information [13]. Instead of reading instructions, users interact with objects and situations that represent real hiking scenarios. At the beginning of the experience, users encounter a preparation task (see Figure 1). After completing the preparation task, the user continues along the trail, where the navigation becomes the next learning element. Trail signs and environmental cues guide the user toward the correct direction. Navigation is not solved through explicit instructions. Instead, environmental observation becomes part of the learning process.

The structure of the application remains intentionally simple. The experience focuses on exploration and interaction rather than storytelling.

Figure 1: Preparation task

3.2 Implementation

VRTrebević was implemented using Unreal Engine 5 [14]. This development platform is widely used for games and virtual reality experiences. The engine provides tools for environment creation, interaction design and VR integration. In VR apps high frame rates must be maintained to prevent discomfort and simulator sickness [15]. Because of this requirement, optimization techniques were applied during development. One important technique involves the use of level of detail (LOD) models. LOD refers to simplified versions of 3D models that appear when objects are far from the user. This method reduces rendering cost and improves performance. In addition, distance based culling was applied, where objects beyond a certain range are hidden entirely, further lowering rendering cost to help maintain high frame rates in VR. The app supports standard VR headsets that use controllers and head tracking. Head tracking allows the user to look around naturally inside the virtual space, while controller input is used for object interaction and navigation.

For the locomotion experiment, two navigation systems were developed. The first system uses controller based locomotion, in which the user pushes the joystick on the controller to move forward through the environment. This approach is commonly used in VR applications, as it allows smooth movement and requires minimal physical effort. The basic locomotion system was implemented in the original version while the lower-body tracking system was implemented in the experimental version of the application developed in Unity Engine [16]. The second locomotion system uses lower-body tracking where external trackers are attached to the user's legs. These devices capture leg movement during stepping actions. Tracking data is transmitted to the application in real time, where the system analyzes this movement pattern. When stepping motion is detected, forward movement is activated inside the virtual environment. This method attempts to simulate natural walking behavior. The user performs stepping motions while remaining in a small physical area and the in-game character moves forward along the hiking trail. Although the user does not physically travel through space, the body still participates in the locomotion process. This interaction may strengthen the sense of embodiment, the perception that the virtual body belongs to the user. A stronger connection between physical and virtual action may increase immersion. But, at the same time, physical movement may introduce fatigue during longer sessions.

A custom walking in place mechanism was developed in Unity. The hardware interface consists of two HTC Vive 3.0 trackers. These sensors are secured to the user's lower limbs, specifically positioned slightly above the ankles using velcro straps (see Figure 2). This placement is due to the need to capture the maximum vertical displacement of the leg. The trackers connect to the computer using 2.4 GHz Vive wireless dongles, providing low latency that keeps real and virtual movements aligned. In addition to the trackers and dongles, two HTC Base Stations are positioned in the corners of the play area. These base stations act as reference points for the system by covering the room with infrared lasers, which the trackers use to calculate their exact position and orientation in 3D space (see Figure 3).

Figure 2: HTC Vive trackers attached to users' legs

Figure 3: HTC Vive 3.0 Tracker, HTC Base Station and HTC Vive Wireless Dongle [17]

The signal processing and mapping of raw sensor data are handled through a multi stage pipeline. First, the raw vertical displacement (Y-axis) is processed using a function with a smoothing time of 0.05s. This filter is necessary to ensure the stability of the signal and to remove "jitter" or sensor noise that could cause unintended movements in the virtual environment.

The system defines the tracked motion pattern as a rhythmic stepping cycle. Recognition of this pattern is achieved when movement speed exceeds a set limit. A step is officially registered when the filtered vertical velocity exceeds a threshold of 0.03m. To keep the system stable, the system uses a "cooldown" period and a "step landing" check. Once a foot lift is registered and returns towards the floor (deltaY<0), the system calculates the resulting movement speed based on two metrics: StepFrequency (the inverse of the time interval between the current and last registered step) and StepHeight (the magnitude of the vertical lift). These values are combined using a linear scaling factor to determine the character's final velocity, which is fixed between a minimum of 0.5m/s and a maximum of 4m/s. The virtual forward vector, derived from the headset's orientation, is projected onto the virtual terrain using a downward raycast. This allows the character to maintain a consistent height relative to the slope. While alternative hardware could be used, the Vive system was selected for its better stability. The HTC Vive Trackers demonstrate sufficient precision for capturing human movements across a variety of dynamic conditions, making it a versatile option for motion tracking both inside and outside of VR environments [18].

3.3 Interaction design

Interaction design plays an important role in VR experiences. VRTrebević focuses on simple interactions that do not distract from learning during the hike. Most interactions are based on direct object manipulation. Direct manipulation refers to interacting with objects using natural hand movements. Users reach toward virtual objects and grab them using controller grab buttons. Additionally, users can access an in-game guide on how to use the controllers by pressing the button Y, providing instructions for proper interaction (see Figure 4).

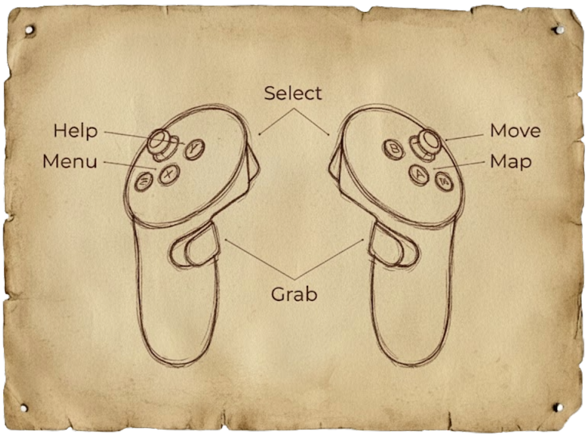

Figure 4: Controller guide

Menus are also integrated into the VR experience to support navigation. The main menu can be accessed via the controller, by pressing the button X, and allows users easy access to navigation options. Menus appear within the virtual environment to maintain immersion. Human-Computer Interaction principles guided the design, ensuring that interface behavior matches user expectations, making navigation intuitive and reducing confusion [19]. A visual representation of the in-game menu is shown in Figure 5.

Navigation interaction is handled through environmental exploration. Trail markers guide users along the cor-

Figure 5: Main menu

rect path, which is why they should pay attention to these markers while hiking through the forest. Visual cues along the trail encourage users to think about their navigation choices.

4 Methodology

This study evaluates how lower-body tracking influences immersion in a virtual hiking experience. The evaluation was conducted using a user study with a questionnaire based approach. Participants were asked to complete the VR experience and later report their impressions through survey responses. Both scaled questions and open-ended questions were included.

The study was conducted using VRTrebević. Two locomotion methods were tested during the experiment. The first method used traditional controller based movement. Participants moved through the environment using a joystick on the VR controller. The second method used lower-body tracking. In this case, stepping motion was detected through the trackers attached to the users' legs. During the sessions, participants explored the environment and completed short tasks. While performing these tasks, users navigated the trail using the locomotion method assigned to their group. Each session lasted approximately fifteen minutes. After completing the experience, participants filled out a questionnaire. The survey measured several aspects of the interaction. These included ease of movement, perceived immersion, physical effort and overall comfort. Participants were also asked to provide written comments about their experience.

The study was conducted in the VR lab at University SSST, where a dedicated play area was prepared to allow safe use of the Meta Quest 3 [20] headset and tracking equipment. Environmental distractions were minimized so participants could focus on the virtual environment. Before each session began, participants were given a short explanation of the controls and interaction mechanics. They were also informed about the purpose of the study. Participants were reminded that they could stop the session at any moment if they experienced discomfort.

Through this evaluation process, the goal was to examine how different locomotion systems influence immersion in an educational VR hiking environment.

4.1 Participants

Participants were divided into three testing groups. Each group experienced a different locomotion setup. This separation allowed the movement methods to be observed independently.

The first two groups consisted of 33 participants all together. Among them, 60.6% of participants were female, while 39.4% were male. Their ages ranged from 19 to 50 years old. Most participants had little or no prior experience with VR. Because of this, their responses provide insight into how new users adapt to VR locomotion mechanics. Participants also reported different levels of hiking experience. Some were familiar with hiking, while others had limited experience, which allowed observing how users with different backgrounds interpret a virtual hiking environment.

The third group included 6 additional participants who performed a comparative test of both locomotion systems. Participants in this group completed the experience twice, once with joystick movement and once using lower-body tracking. By experiencing both methods in a single session, these participants were able to provide direct comparative feedback. This allowed for an evaluation of how the same user perceives immersion and comfort when switching between traditional and lower-body tracking based movement.

4.2 Survey design

The survey was designed to evaluate the user perception of locomotion mechanics. In particular, the survey examined how different movement methods influenced immersion and comfort. Both quantitative and qualitative questions were included in the survey, which allowed the collection of ratings and personal feedback.

The quantitative section of the questionnaire used a Likert scale. A Likert scale is a common survey method where participants rate their agreement with a statement. In this study, a five point scale was used. Responses ranged from "Strongly Agree" to "Strongly Disagree". Participants were asked to evaluate several aspects of the VR interaction, with focus on ease of movement. Additional questions examined physical comfort during movement and the overall sense of immersion in the environment.

The survey also included open-ended questions. These questions allowed participants to explain what aspects of the movement system felt natural or difficult. They were also asked to suggest possible improvements. This combination allowed for a more complete understanding of their experience.

4.3 Data collection

The survey was provided to participants through a Google Forms link. Participants completed the questionnaire immediately after finishing the VR session. The survey was filled out on site so that assistance could be provided if needed. This allowed for responses to be collected while the experience was still fresh in the participants' memory. As a result, the feedback was their immediate impressions of the locomotion system. Conducting the survey in the same controlled environment also made sure that all participants had equal access to any guidance during the evaluation process.

5 User experience evaluation

The study recruited participants that navigated the trail and completed tasks designed to simulate real hiking activities. The following sections present the analysis of participant responses, highlighting key insights and areas for improvement in the experience.

5.1 Results

In this section, the results from the participant groups are presented. Each group tested a different locomotion setup, to allow comparison of user experiences with joystick movement and lower-body tracking. Feedback on comfort, immersion and interaction is summarized to highlight areas for improvement.

In the first group, which tested joystick based locomotion, most participants reported a generally positive experience of the game. However, some discomfort was associated specifically with movement, with 12.5% of participants experiencing general discomfort and 37.5% reporting occasional discomfort during locomotion. Additionally, 56.25% reported feeling dizzy at some point while navigating the virtual trail, which is not unexpected given that most participants were new to VR and used joystick-based movement (see Figure 6). These findings suggest that even with familiar controller-based movement, some users experienced mild physical strain or disorientation. The data highlight the importance of monitoring comfort and vestibular effects when designing VR hiking experiences, even for joystick-based locomotion.

The results for the second group, which used lower-body tracking, showed a high level of engagement. Participants reported that the stepping based movement increased their sense of physical involvement (Figure 8). Because the virtual movement matched their leg actions, many users noted that the experience felt more authentic. This is supported by the survey results, where 94.1% of participants agreed that moving in the VR environment was easy and 76.4% reported feeling physically comfortable during the experience and indicated that the movement method didn't cause them discomfort or nausea (see Figure 7).

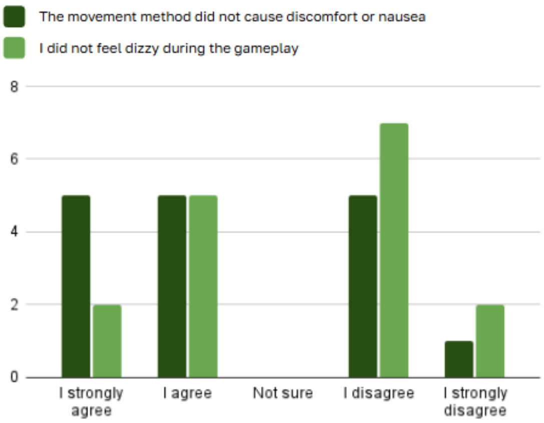

Figure 6: User experience using joystick movement

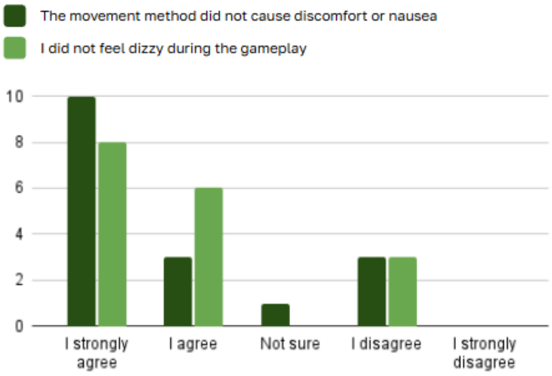

Figure 7: User experience using lower-body tracking

However, a clear trade-off between immersion and physical exertion was observed. While participants reported a strong sense of presence, they also experienced physical fatigue. This suggests that while lower-body tracking increases the realism of the hike, the increased physical demand may limit the duration of a single educational session compared to traditional locomotion methods. Participants also provided specific feedback for technical improvement. It was noted that the accuracy of foot detection could be further refined to make the locomotion feel smoother. While users felt the physical effort was high, the majority of users really liked the level of immersion provided by the leg trackers. With a sample size of 17 participants, the data indicates that lower-body tracking is a viable alternative for educational VR applications where high embodiment is required.

5.2 Comparative Analysis

The third group served as a control group, in which participants tried both locomotion methods. Six participants took part in this comparison. A significant majority of participants reported that the sense of presence was higher

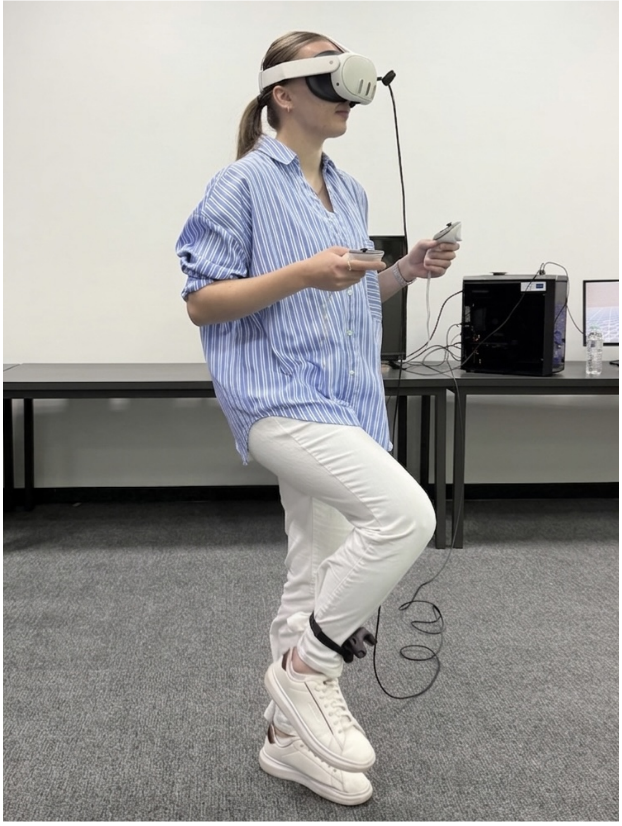

Figure 8: Participant using lower-body tracking

when using lower-body tracking compared to the joystick. While the joystick was considered more efficient for traveling long distances, the stepping motion was favored for the tasks requiring a stronger feeling of “being in nature”.

Survey results support these observations, with all participants agreeing that lower-body tracking felt more immersive and comfortable. 83.3% of participants reported that it gave them better control over movement and indicated that joystick locomotion caused more dizziness, while it required almost no physical effort. However, a more critical look at the data reveals clear technical limitations. While participants enjoyed the immersion, the precision of the leg-tracking system was not always consistent. Occasional jitter or latency in the Vive trackers sometimes made the movement feel less responsive than the joystick. Furthermore, the physical nature of the system presents a challenge for accessibility. Although only 16.7% of participants reported immediate physical strain, with 66.7% remaining neutral due to short session lengths (see Figure 9), participants noted in the open-ended feedback that they would expect to become significantly fatigued during longer sessions.

Overall, 83.3% of participants preferred lower-body tracking, reporting that it felt more natural and, in some cases, even more fun. Nevertheless, the reliance on wearable hardware adds a layer of complexity. If the sensors are not calibrated perfectly or if they shift slightly on the ankle, the locomotion can become clunky and frustrating. This suggests that the system currently lacks the effortless reliability of traditional controller-based movement.

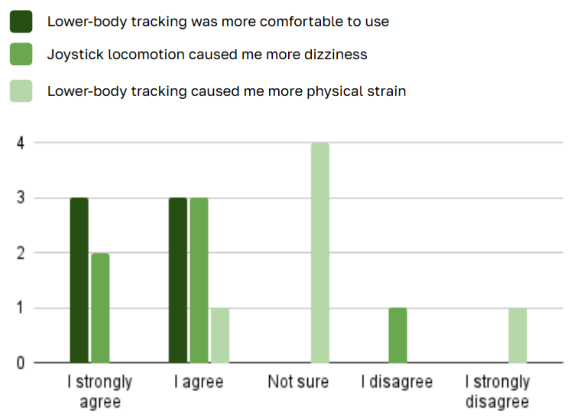

Figure 9: User experience comparison

6 Conclusion and future work

This study investigated the impact of locomotion mechanics on immersion and user experience in VRTrebević. The research focused on how lower-body tracking may influence engagement and comfort during virtual hiking. Participants explored different locomotion systems, including joystick-based movement and stepping-based movement, allowing for a comparison of user experience, physical strain, and presence between the two methods.

Results from the first group, which consisted of 16 participant that tested joystick movement, showed that participants generally reported a positive experience of the game, though some discomfort was associated specifically with movement, where 37.5% reported occasional discomfort and 56.25% felt dizzy at some point.

The second group, which tested lower-body tracking, reported that stepping-based movement increased physical involvement and enhanced the sense of presence, though it also introduced physical fatigue not observed with joystick-based locomotion. Survey results indicated that participants felt the system was immersive and comfortable and only 16.7% experienced physical strain, with 66.7% remaining neutral though they noted in feedback that longer sessions could increase fatigue. Participants also suggested refinements in foot detection and smoother movement calibration to improve the experience.

The third control group, which tested both methods, confirmed that lower-body tracking was preferred by 83.3% of participants. It was reported to feel more natural and provided a higher sense of presence, while joystick movement was more efficient for long distances and caused more dizziness but required minimal physical effort. However, this increased immersion comes with technical and physical trade-offs. While the majority of users preferred the tracking system, it was observed that the precision of the sensors can be inconsistent. Issues such as minor tracking inaccuracies or the need for perfect calibration can make the movement feel clunky compared to the reliability of a joystick. Furthermore, the physical effort required for stepping in place can lead to significant fatigue in larger applications or longer sessions. In the future, these issues must be considered, as user exhaustion and sensor reliability are critical factors for making long VR experiences.

Overall, the study indicates that incorporating lower-body tracking can enhance immersion and presence in VR hiking, though attention to physical strain and session length is critical. Comfort and naturalness of movement are central to engagement, and even subtle inaccuracies in motion detection or delayed responsiveness can disrupt immersion. Future iterations of VRTrebević should focus on refining lower-body tracking. Potential improvements smoother calibration of leg trackers and options to adjust to individual user preferences.

Finally, by collecting detailed participant feedback and incorporating both qualitative and quantitative data, developers can refine locomotion mechanics and reduce discomfort while maintaining immersion. This way VRTrebević can also serve as a tool for promoting outdoor skills and education with VR.

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