A Study on Usability and Motion Sickness of Locomotion Techniques for Virtual Reality

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ABSTRACT: Virtual Reality (VR) is widely used today in both research and entertainment. The continuous growth of this technology makes VR consumer hardware now available for the masses. The new trend in the next generation of VR devices is a VR headset and con- trollers with inside-out technology. These VR devices will become an important basis for the future of VR applications. Virtual travel or locomotion inside VR experiences is an important part in an VR application development, which affects users preferences. The goal of this research was to study the differences in lo- comotion techniques for VR with new device trends consisting of a VR headset and controllers without using other accessories. Three locomotion techniques have been analyzed for their differences: controller-based, motion-based and teleportation-based tech- nique. A VR scene with virtual environments was created to use in this experiment, where users had to move with different locomotion techniques. The Us- ability Questionnaire (UQ) was used to evaluate the usability value of each locomotion technique, while the Simulator Sickness Questionnaire (SSQ) was used to assess the motion sickness value. The results showed that usability (p-value=0.02007) and motion sickness (p-value=0.00014) of all locomotion tech- niques were different, and usability affected user pref- erence. The conclusions of this VR locomotion study were discussed along with the limitations of the study and future suggestions for this research.

Keywords: Virtual Reality, Human Computer In- teraction, Locomotion, Motion Sickness

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1. INTRODUCTION

VR technologies are used extensively in research and entertainment media. The Head Mounted Display (HMD) device is currently being developed substantially. It is quite different from the past, where HMD devices consisted of a large headset, low resolution display, and poor tracking. The changing technology of display and tracking makes it easier to detect and interact in a limited space. The 6 degrees of freedom (6DoF) movement tracking via built-in internal sensors used for VR headsets is called inside-out tracking [1]. Inside-out tracking is a method of positional tracking commonly used in VR technologies. Many VR headsets and motion controller accessories have applied this technology for tracking position instead of using additional sensors in a stationary position, which are used to determine the position of an object in spaces [2]. There is no need to install sensors in spaces to detect devices, and a guardian for setting the boundary is used instead. It differs from outside-in tracking where the location of the camera or other sensors are placed in a stationary location, whereas the camera or sensors of inside-out positional tracking are located on the HMD device that is being tracked [3]. Internal sensors within a VR headset look out to determine how their position changes in relation to the environment. When the headset moves, the sensors readjust their place in the room and the virtual environment responds accordingly in real time. Hand-held controllers usually come with the headset to enhance user interaction with the VR application [4]. There are two controllers for the left and right hand, where both have a thumbstick, trigger, buttons, and also a trackpad. The controllers are recognized by the HMD headset, as well as the finger position detection on the controller, which allows for more interaction between users and the virtual environment

The new standard for VR devices usually consists

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of the HMD device with left and right controllers. Therefore, VR application should be designed with regard to the interaction with these devices. One of the interesting interactions that have been used with many VR applications is the interaction technique for locomotion, where the movement in VR is designed according to the devices [5]. At the beginning of HMD device design, there was only a VR headset and we had to interact with the virtual environment directly from the HMD device by gazing[6, 7]. We needed to connect additional devices, such as joystick or Leap Motion for hand gestures to enable the control of movements in VR [8]. Therefore, many different locomotion techniques were designed, and each of them affected each user differently. Usability is evaluated depending on the design of the locomotion techniques [9]. Another issue that affects the user is motion sickness caused by locomotion in VR. Motion sickness occurs when users move in VR [10], which can also be caused by VR locomotion. This is the effect of motion images that do not correspond to the actual movement. Users need a locomotion technique without side effects or any health problems.

In this research, we studied different ways of using VR locomotion. The study was divided into two parts: 1) the usability of interaction and 2) the effects of various symptoms caused by motion sickness. The locomotion techniques used in the experiment were designed according to the characteristics of inside-out technology, the new generation of VR devices that will be the trend of VR application for the future. The experimental results will support VR developers to understand the usage and the design of locomotion more efficiently.

2. VR HEADSET TREND

There are many VR devices in the market and they are divided into two categories: desktop-based VR and mobile-based VR. When considering the interaction, mobile-based VR is less effective than desktop-based VR due to the sensors and controllers. Moreover, mobile-based VR can cause more adverse effects than desktop-based applications [11]. Therefore, we focused on desktop-based devices for locomotion in VR. VR interactions are enhanced when a VR headset comes with controllers. When considering the various commercial products with controllers that have been developed since 2016, we found that Oculus, HTC, and Windows Mixed Reality (WMR) were the advanced products that technology vendors were creating in this market. The Steam Hardware Survey results for April 2020 [12] showed that Oculus (44.68%), HTC (30.34%), WMR (8.54%) and others (16.44%) were active HMD devices on the Steam.

The Oculus Rift CV1 is the first consumer model with constellation outside-in technology. The motion controller Oculus Touch is available for more interactions in VR. The Oculus Go is the first standalone VR headset of Oculus. It contains its own dedicated display and mobile computing hardware including a hand-held controller using relative motion tracking. However, The Oculus Go is a non-positional 3DoF tracking. The Oculus Rift S and Oculus Quest were released in March, 2019. They used Oculus Insight technology for motion tracking bundled with an iteration of the Oculus Touch controllers, which were slightly redesigned. The Oculus Quest is proposed to be a standalone device, whereas the Rift S is still PC-tethered with more performance [13, 14]. Hand Tracking is the new feature of the Oculus Quest using on-board cameras to identify the movements of fingers and hands without hand-held controllers [15].

The HTC Vive uses room-scale tracking technology with Lighthouse 1.0 base stations, allowing the user to move in a 3D space and use motion-tracked handheld controllers to interact. The HTC Vive Pro is an upgrade in resolution display with Lighthouse 2.0 base stations, allowing an increase in space to 10m $\times$ 10m. The Vive Trackers are included to have more interactions. The HTC Vive Focus+ is the first standalone VR headset of HTC with inside-out track- ing technology. Gaze and hand tracking are integrated through the Vive Wave and Hand Tracking SDK. The controller is redesigned to use 6DoF ultrasonic tracking. The HTC Vive Cosmos is also a standalone device with refined inside-out tracking with six camera sensors. The controller is upgraded from the HTC Vive Focus with precision joysticks. Although the HTC Vive Cosmos is a standalone headset, the Lighthouse tracking is also supported for more precision tracking [16, 17].

WMR is a mixed reality platform introduced as part of the Windows 10 operating system providing VR experiences with compatible HMD devices from Acer, Dell, HP, Lenovo, and Asus [18, 19]. Most of them have the same specifications except for the LCD resolution and FOV, which are slightly different. All headsets are PC-tethered and feature integrated inside-out motion tracking and also contain cameras used to track handheld motion controllers, which are compatible with the Xbox One controller. There are also many other VR headsets available on the market that should be considered as part of the trend. The Samsung Odyssey+ is compatible with the WMR and SteamVR platform. The Anti-SDE (Screen-Door Effect) filter is applied to the display and also has a slightly different controller design, which makes it different from the other WMR headsets [20]. The Valve Index is a high-end HMD device compatible with the SteamVR platform. The headset uses an improved version of the Lighthouse tracking system. The Knuckles controllers come up with all fingers trackable which is the best one in regard to VR controllers [21]. The Pimax is a HMD device with outside-in technology. This product focuses on a wide range of displays and there are many versions of

Table 1: *Hardware and technology comparison of VR headsets using inside-out tracking.*

Device	WMR	Samsung Odyssey+	HTC Vive Focus+	HTC Vive Cosmos	Oculus Rift S	Oculus Quest
Release date	2017-10-4	2018-10-22	2018-11	2019-02-19	2019-05-21	2019-05-21
Type	PC-tethered	PC-tethered	Standalone	Standalone	PC-tethered	Standalone
Price	399$	500$	599$	699$	399$	399$
Display and resolution	LCD (RGB subpixel) 1440x1440, 110° FOV	AMOLED 1440x1600, 110° FOV	AMOLED 1440x1600, 110° FOV	LCD 1440x1700, 110° FOV	Dual fast-switch LCD 1280x1440, 90° FOV	OLED 1440x1600, 100° FOV
Refresh rate	90Hz	60Hz/90Hz	75Hz	90Hz	80Hz	72Hz
Tracking technology	2xCameras-based, Accelerometer, Gyro sensor, Magnetometer, Proximity	2xCameras-based, Gyroscope, 3-Axis Compass, Proximity sensor, IPD Sensor	2xCameras-based, G-sensor, Gyroscope, VIVE Wave, Hand Tracking SDK	6xCameras-based, G-sensor, Gyroscope, IPD sensor, Eye tracking	5xCameras-based, Insight tracking, Accelerometer, Gyroscope, Magnetometer	4xCameras-based, Insight tracking, Accelerometer, Gyroscope, Magnetometer
Controller	6DOF controller with haptic feedback, thumb stick, touchpad, analog trigger, grap button, Windows and menu button, compatible with Xbox One Controller	6DoF dual controllers tracked by HMD and also compatible with Xbox One Controller	Dual 6DoF controllers with ultrasonic tracking, 2 trigger buttons, a trackpad, 2 face buttons	Dual 6DoF controllers with system buttons, 2 app buttons, a trigger, a bumper, a grip button and a joystick	2nd generation Oculus Touch motion tracked controllers with 6DOF Inside-out with a system button, 2 app buttons, a trigger, a grip button and a joystick	2nd generation Oculus Touch motion tracked controllers with 6DOF Inside-out with a system button, 2 app buttons, a trigger, a grip button and a joystick

the displays: 4k, 5k, and 8k. However, no controllers or tracking base stations are included.

Considering the trend, it can be seen that the development of the VR device from most market shares like Oculus and HTC is going the direction of the standalone device. However, the PC-tethered device is still more efficient because it uses the PC resources for processing. WMR is still focusing on a cheaper PC-tethered version rather than competing with Oculus and HTC. Sumsung and Valve have developed higher efficiency VR headsets than WMR, but they are sold at a higher price as well. All companies that make VR devices now focus on using inside-out technology due to it being user friendly and easier to install, as well as being compatible with controllers. The controllers also have tracking improvements that can be used to interact with the virtual environment even more. With the development of Hand Tracking, using cameras on headset allows users to interact with the virtual environment with their bare hands. This is a new standard of VR devices and the development of VR applications should be based on this trend. Furthermore, the development of locomotion techniques on these VR devices is an important basis for appropriate design of movement in VR.

3. VR LOCOMOTION AND RELATED WORKS

This research was related to various issues including VR locomotion, motion sickness, and locomotion studies. VR locomotion is considered as the classification of movement in VR applications. Motion sickness is in regard to the measurement of various symptoms caused by inconsistent movement with the user body. Locomotion studies are in regard to interaction techniques of VR locomotion and the comparison with locomotion in the past.

3.1 VR locomotion

Because there are many different types of locomotion, this research would like to compare three different types of VR locomotion. The usage of VR locomotion is different in relation to usability and motion sickness, which is the consistency between movement and viewing in VR during interaction. VR locomotion techniques can be divided by interaction, motion, space, and devices. The classification of locomotion techniques are defined as follows:

3.1.1 Motion-based technique

The motion-based technique is characterized by the physical interaction of the user's movement, which is a continuous form that results in unlimited locomotion in the VR space [5]. Walking-in-place (WIP) is the technique to simulate as close as possible the manner of walking through the real world, where feet movement is tracked and then translated to movement in the virtual environment based on room-scale tracking. However, the WIP locomotion technique requires using additional hardware and the interaction area is limited by the room size [22, 23]. Guardian-based tracking also relies on the motion-based technique, but it uses limited guardian and focuses on stationary interaction instead of moving based on room-scale tracking. Arm-Swinging is one of techniques that lets the user move forward when they move their arms while in a stationary position. This technique has many different approaches. Some research use the Myo Armband, a forearm tracking device with various features [23–25]. The direction of the armband is tracked to check whether the user moves their arm or not, which is used for movement tracking. Gesture-based tracking is the technique using hand gestures to control user movement in VR. Some VR headsets don't have a hand tracking system and an additional device is required. The Leap Motion device has been adapted to allow users to use hand gestures for moving. The movement is dependent on hand gesture configurations, where postures were defined before [26, 27].

3.1.2 Controller-based technique

This VR locomotion technique is an artificial interaction style using controllers to move the user in the VR environment. The VR interaction space is open, and the motion is continuous. This technique is simple to use and can be applied by the controller consisting of a joystick, thumbstick, or trackpad [28]. This technique is a good baseline for locomotion testing because movement is directly controlled from the controllers. However, this locomotion technique is prone to induce motion sickness.

3.1.3 Teleportation-based technique

This VR locomotion technique uses an artificial interaction in open VR spaces with discontinuous movement. The teleportation technique uses the controller to point towards a position in the virtual environment and then instantly moves to it, resulting in a teleportation effect. Teleportation is one of the most common locomotion techniques in modern VR games [5]. This technique is popular among users because it induces less motion sickness [29, 30]. However, the teleportation technique is likely to disorient the user, and some studies have found that this technique is frustrating for the user [31, 32].

When considering different types of VR locomotion, some research [5, 33, 34] separated room scale-based technique from motion-based techniques because it is a limited area motion for WIP. And when we considered using HMD devices with inside-out tracking, we can see that the room scale-based is a type of motion-based technique that uses guardian setting to set the movement area. Therefore, this research divided VR locomotion into three types which were motion-based technique, controller-based technique, and teleportation-based technique according to HMD devices with inside-out tracking.

3.2 VR sickness

The VR experience has the opportunity to make users uncomfortable during using VR applications. The side effects of using VR applications may include any symptoms that are not ordinarily associated with sickness, such as fatigue, sweating, difficulty focusing, etc. VR technologies are advance in hardware including display, tracking, and processing, which cause less side effects to users [35]. In order to reduce side effects from the hardware, the responsibility is in the locomotion design. In addition, the classification of VR sickness is complicated due to many factors: difficulty in measuring symptoms, rapidly changing technology, and sensitivity depending on the content [36, 37]. Therefore, it's important for VR developers to understand these side effects in order to reduce or eliminate them for users. The theories of occurred VR sickness are related to motion sickness and simulator sickness.

Motion sickness is a common problem in the VR experience due to a difference between actual and expected motion, while VR sickness occurs when exposure to a virtual environment causes symptoms similar to motion sickness symptoms [38, 39]. VR sickness is different from motion sickness because it can be caused by the visually-induced perception of self-motion, while the real self-motion is not needed. Sensory conflict points out that sickness will occur when a user's perception of self-motion is based on incongruent sensory inputs from the visual system, vestibular system, and non-vestibular proprioceptors with the user's expectation based on prior experience [38]. Sensory conflict provides a framework for understanding motion sickness that can be applied to VR applications. The most common symptoms of motion sickness are general discomfort, headache, stomach awareness, nausea, vomiting, pallor, sweating, fatigue, drowsiness, disorientation, and apathy [40]. Many locomotion techniques have been evaluated in order to find out the optimal interaction with less motion sickness. In order to improve the VR system and experience, we should correctly compare adverse side effects and quantify the symptoms that occur. The Simulator Sickness Questionnaire (SSQ) was designed for simulator sickness studies and to evaluate symptoms of motion sickness in VR [41–43].

3.3 Locomotion studies

From the literature review, there are many studies and trials on locomotion studies. In general, they focused on common issues which included usability, satisfaction, immersion, fatigue, motion sickness, and user experience in using different locomotion techniques. These issues were evaluated to compare on scenario use by case. The locomotion techniques that were most involved in their experiments were the teleportation-based and controller-based techniques. Furthermore, motion-based techniques such as walking-in-place or arm-swinging were tested to assess sickness of locomotion techniques.

Lee et al. [44] analyzed methods to enhance the interaction focusing on walking among various interactions required for VR applications to increase immersion and reduce VR sickness. Three interactions were constructed in a process of controlling walking methods: using a gamepad, using hands, and walking-in-place. The results showed that a higher immersion was achieved when interactions were close to real walking with satisfactory presence and minimal VR sickness. Then the VR sickness was evaluated using the SSQ, and this confirmed that walking-in-place can prevent VR sickness.

Albert [45] proposed the User-Centric Classification (UCC) framework, a common language to classify VR locomotion according to three metrics (sickness, presence, and fatigue), where each metric was determined by the locomotion method to address the corresponding challenge. Sickness occurs when there is a conflict between a user's vestibular and visual senses. Presence is when users feel that they are in the virtual world. Fatigue occurs when users expend muscular energy for a sustained period. He designed the testbed to expose users to the three VR locomotion methods of controller, teleport, and walking in order to capture the user experience. The results showed no difference between these implementations of walk- ing and controller and also of walking and teleport in the context of inducing sickness, while the others were different. Comparing all locomotion techniques related to the metrics provided support for us to understand different methods in meaningful ways and to search for an ideal locomotion method.

Vestibular conflict is one of the principal causes of motion sickness affecting VR locomotion. Continuous motion is a problem for stationary users, and teleportation has become a common method providing accessible locomotion. However, teleportation increases disorientation and decreases a sense of presence within the virtual environment. Habgood et al. [32] proposed an alternative locomotion technique using a node-based navigation system, which allows the user to move between predefined node positions. Evaluation was undertaken to compare this technique with the teleportation-based and continuous walking approaches. In this study, 36 participants were enrolled to examine motion sickness and its presence for each technique. The results showed that rapid movement speeds reduces the motion sickness of users as compared to continuous movement, while there was no difference of presence with the teleportation-based technique.

Boletsis and Cedergren [46] proposed a comparative study of the empirical evaluation of VR locomotion techniques and examined user experience (UX). Based on their literature review, walking-in-place, controller/joystick, and teleportation techniques are identified as the prevalent VR locomotion techniques. In the study, 26 participants were enrolled to perform a game-like task using the techniques focused on issues of immersion, ease-of-use, competence, and psychophysical discomfort. The results indicated that the walking-in-place technique provide the highest immersion, but also showed a high level of discomfort. The controller/joystick technique was perceived to be easy to use because users were familiar with it. The teleportation transmission technique was considered effective due to fast navigation, but provided less immersion because of the jumping effect.

Aldaba and Moussavi [47] found that a few studies investigated the effects of different VR locomotion and gender. They examined the effects of a combination of different motion stimuli and users' neck movement through experiments in a gender balanced group. Separated sessions including the TiltChair, omni-directional treadmill, VRNChair, and joystick were used with a HMD device. The same VR navigation task was implemented to measure along with the Simulator Sickness Questionnaire and postural sway. The participants had significantly shorter traversed distances and execution times when they utilized the TiltChair and joystick respectively, while significantly longer execution times resulted when using the omni-directional treadmill. In addition, female participants can easily use the TiltChair and omni-directional treadmills because they explored shorter distances than male participants.

Considering the new trend of VR devices based on HMD tracking and controllers, there is less support for large space room-scale tracking due to a change in technology to inside-out tracking. Therefore, it is interesting to design and assess VR locomotion techniques on these devices in regard to the new technology.

4. LOCOMOTION TECHNIQUES IMPLEMENTATION

We classified VR locomotion techniques into three cases: controller-based, motion-based, and teleportation-based technique. The design of the interaction technique is based on the Oculus Rift S with Touch controllers as a representation of inside-out tracking technology for VR devices. Here, the implementation using OVRinput on Unity3D (Figure 1) of our VR locomotion techniques are defined with the details as follows:

4.1 Locomotion with the Gamepad (controller-based technique)

This is a movement control with a thumbstick on the touch controller. LThumbstick controls translation movement: forward, backward, left, and right. RThumbstick is used to turn for more angles of view with less body movement. However, using Rthumb-

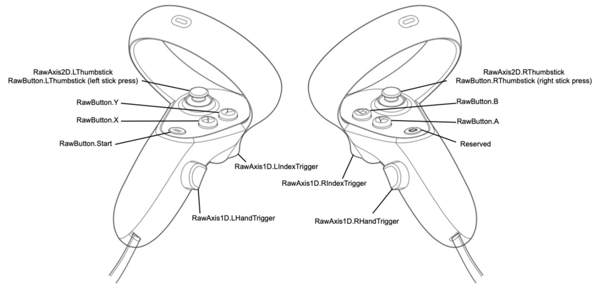

Fig.1: *The Oculus Touch controller from the Oculus developer center [48].*

stick may result in motion sickness because the Oculus Rift S has a guardian setting and head tracking, where the direction and perspective of the user are recognized through the headset. Therefore, pushing the LThumbstick forward leads to moving forward in the direction that the user is facing, which is detected by head tracking. When the user moves the LThumbstick forward along with changing the view point, it changes the direction of movement in that direction.

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The locomotion with this method is in a standard format. The advantage of this technique is that it allows for quickly changing the movement direction, but the disadvantage is that it is not possible for users to look at their surrounding while moving at the same time. This is because changing the perspective changes the direction of movement as well. However, users can look around in this locomotion technique by stopping their movement first for observation and then continue moving.

4.3 Locomotion with the Armswing (motion-based technique)

This is the control of movement by swinging the arms. This locomotion technique begins when the user presses both the LHandTrigger and RHandTrigger buttons simultaneously, imitating the running motion. The speed depends on the arm swinging motion. The avatar moves slowly if swinging arms for a short distance, whereas swinging arms for a longer distance increases the speed following the distance. The user's hand position also affects the speed. If the user's hand is swinging around the abdominal area, the speed is set to default. If the position of the hand is raised higher, then the speed increases more.

Side step turning is enabled when the hand stops forward swinging and starts side swinging to move sideways. The direction of movement is calculated from the average position of both hands. Because of this reason, head direction is independent from the movement. Therefore, users are able to view the surrounding environment freely at any time.

4.4 Locomotion with the Teleportation (teleportation-based technique)

This locomotion is a discontinuous movement by locating the position on the ground and then moving the avatar onto that position. In order to enable this technique, the user needs to press and hold the RIndexTrigger button to specify the teleportation anchor (the blue anchor zone in Figure 4c) to determine where to move. Then, a direction controller appears and can be aimed in a direction using the RThumbstick. The direction controller is from where the position of the RController points to the ground with a falling parabolic curve and the user then moves to that position.

Therefore, the change in movement is dependent on the position and direction of the RController. When the RIndexTrigger button is released, the avatar teleports to the specified position and direction.

5. EXPERIMENT

5.1 Scene design

In our experiment, scenes were designed to test the locomotion techniques, which included the Gamepad, Armswing, and Teleportation. The participants had to answer a usability and motion sickness questionnaire, which provided the results of using different locomotion techniques. The results of the experiment showed the satisfaction for each locomotion, including which type was suitable for use. The design focused on the VR application, where locomotion was used to explore the virtual environment. The design of the experiment, therefore, focused on the scene design that was a walkway to see the surroundings while moving. There were two scenes used in the experiment as follows:

5.1.1 Test scene

This scene was the beginning of the experiment to enable the user to understand and know each type of locomotion technique. The setup scene was a simple scene designed with a few obstacles in order to allow user to be aware of the control of movement by avoiding those obstacles.

In the scene, there were three red boxes at the height of the user's chest, one at the front, one on the left, and one on the right. The positions of the boxes were not too far to prevent the user from moving forward continuously, but only to turn left or right or rotate the view to change the direction of movement.

5.1.2 Experimental scene

This scene was used for evaluation after the participants became familiar with how to move with the various locomotion techniques. The design focused on creating a path to explore the environment, and the scene was therefore a loop that was not direct. The route was limited in terms of area, where users could not walk outside of the path in order to prevent them from getting lost and to stay on the same route. The atmosphere around the path was natural, and surrounded by trees, and in the middle there was a large pond with a large bridge that was set as a target for traveling with locomotion. This scene was downloaded for free via the asset store in Unity Game Engine [49]. Some elements had been adapted to suit the VR experience for our experiment.

5.1.3 Menu and operation

The Oculus Rift S with Touch controllers was used as a device in this experiment, and we designed the commands from the controllers with the user interface on the virtual left hand. When entering the experiment, a user's avatar appeared in the virtual environment and they can see their virtual hand. The virtual hand moved according to the position of the Touch controller. The user could open the menu window by pressing the Y button on the left controller. If the menu was open, user can press the button Y again to close it. The ray-cast appeared on the right controller for command selections on the left menu. The RIndexTrigger button was used to select commands and when the menu window was closed, the ray-cast disappeared. When the menu window was displayed, there were two buttons: Test and Start.

Pressing the Test button reset the test scene and returned the user to the starting position again. When trying different locomotion techniques, the user might move far away from the starting point. The user could press the Test button to go back to the initial position.

Pressing the Start button started the experiment. When the user understood how to use the different locomotion techniques, then they could skip to the experimental scene for assessment.

In the menu window there were three check boxes to choose as follows:

Gamepad is to control the movement by using the thumbstick on the Touch controller to make the avatar move according to the direction of the thumbstick.

Armswing is to control the movement by swinging the arms to simulate running.

Teleportation is to control the movement by specifying the warp position on the ground.

Each locomotion had a slider to adjust the movement speed, but it was disabled in this experiment because the speed of movement was a control variable affecting the results. Therefore, the speed of each movement was set to default with the same distance when moving with the same time.

5.2 Questionnaires and research protocol

The objective of this research was to evaluate each locomotion divided into three types (controller-based, motion-based, and teleportation-based), and we designed three different locomotion techniques to represent each type. There were two issues to be evaluated: usability and motion sickness. Both results were used to analyze the advantages and disadvantages of each locomotion technique for the virtual environment scene. This experiment was focused on the VR application, which required environmental exploration and constant moving.

5.2.1 Questionnaires

The Usability Questionnaire was used to evaluate the quality of the locomotion technique implementation. It was a Likert scale questionnaire containing 4 items for users to score by telling how much they agreed with each item between 1-7 points. “1 point” was strongly disagreed and “7 points” was strongly agreed. The questionnaire to assess usability [30, 50] is detailed as follows:

Satisfaction: the usage of the locomotion technique was satisfied.

Understanding: the user understood how to control movement.

Corresponding: movement and control were consistent.

Immersion: the user was immersed during movement.

The motion sickness questionnaire in terms of SSQ was used to assess various symptoms during locomotion usage, which affected user preference. The user provided a score by telling how much they felt in regard to each symptom on a Likert scale between 1-7 points. “1 point” was strongly severe, and “7 points” was no symptoms. The SSQ was divided into different subscales [41, 51] and the details are as follows:

Comfortable: the overall sensation of the user during usage.

Nausea: symptoms such as increased salivation, sweating, stomach awareness, and burping.

Oculomotor: symptoms such as fatigue, headache, eyestrain, and difficulty focusing.

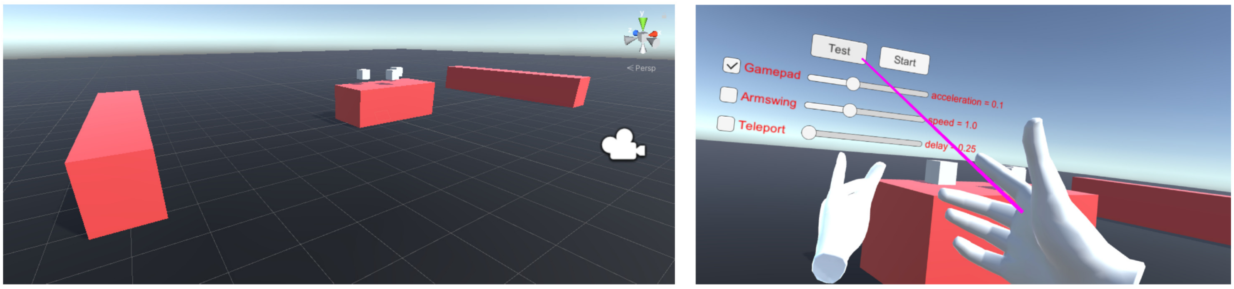


Fig.2: *Test scene with a wide space and three red boxes.*

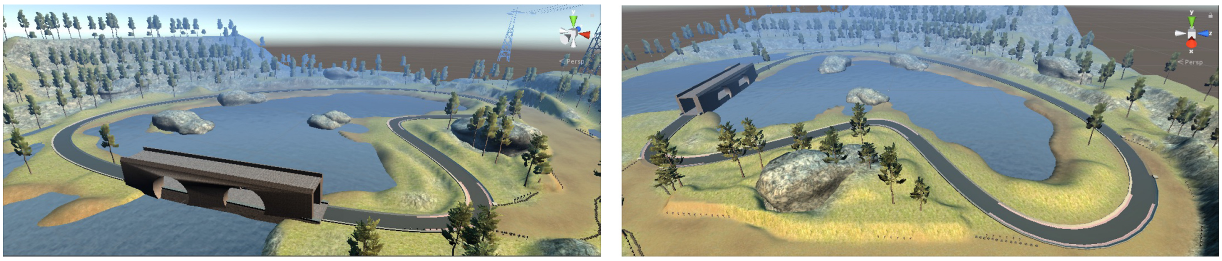
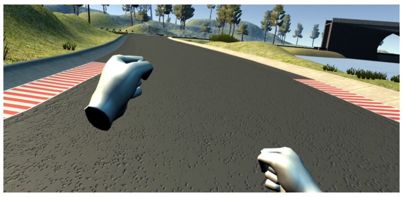
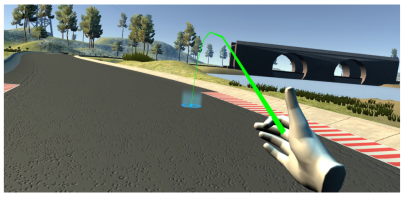


Fig.3: *Experimental scene using an adapted racing map [49].*

(a) Locomotion with Gamepad



(b) Locomotion with Armswing



(c) Locomotion with Teleportation

Fig.4: *Different locomotion techniques in the experimental scene.*

Disorientation: symptoms such as vertigo, dizziness, and blurred vision.

5.2.2 Hypotheses and research protocol

Our hypotheses of the experiment were defined to provide guidance in order to assess the following issues:

H1 Usability hypothesis: Participants have different performance on different locomotion techniques.

H2 Motion sickness hypothesis: Participants have different symptoms when using different locomotion techniques.

H3 Preference hypothesis: User preference on locomotion technique is based on both usability and motion sickness.

In the experiment, 30 participants were enrolled and the experiment was explained to them step-by-step. At the beginning, an introduction and the importance of the research were explained, and they were also informed on how to assess user feeling after each experiment. The participants were notified that using the Oculus Rift S with controllers may cause various symptoms during the experiment, and they can stop the experiment at any time. Then the experiment was started with the Test scene in order to let the participants try out all locomotion techniques: Gamepad, Armswing, and Teleportation. The participants had been provided with a description of the UI operations and system menus, including modifications of locomotion. The time spent on this process was approximately five minutes.

Since each participant was required to assess all three locomotion techniques, the sequence in the experiment affected the evaluation. Therefore, all participants were divided into six groups with five participants for each group according to the permutation of $3! = 3 \times 2 \times 1 = 6$ method as shown in Figure 6.

All groups were tested three times with a different sequence of locomotion techniques. After each experiment, the participants must remove the HMD device and complete the post-test evaluations (UQ and SSQ), and then test on the next system until they finished all three systems. Finally, the participants needed to rank their favorite locomotion techniques.

Fig.5: *Participants during experiment testing.*

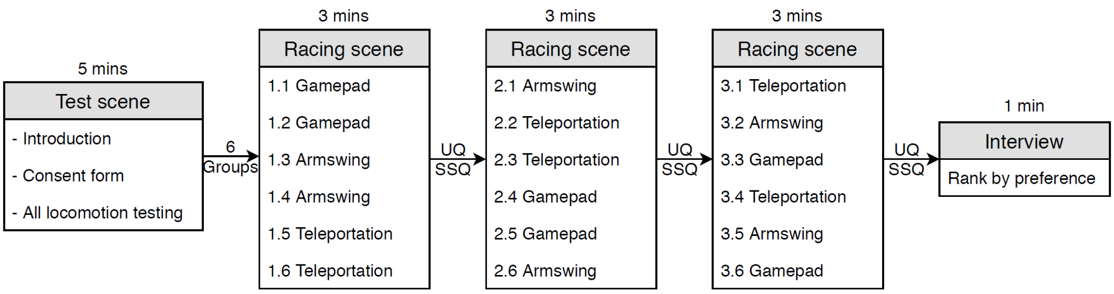


Fig.6: *Research protocol with six separate groups of participants in the experiment.*

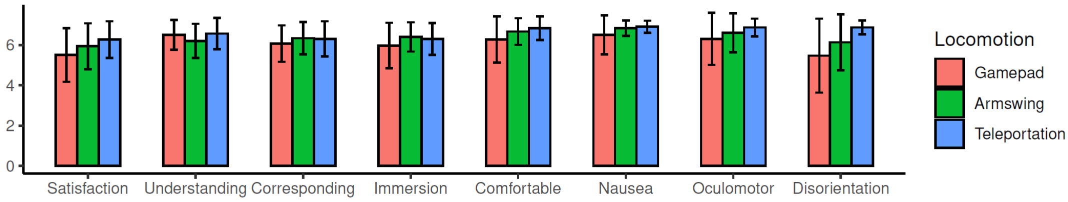


Fig.7: *Comparison of the average (Max=7) usability and motion sickness values (the greater the value, the lesser the symptoms) for each locomotion technique based on the UQ and SSQ.*

Table 2: *Friedman test result of the Usability Questionnaire (UQ) for all locomotion techniques (* significant p<0.05, ** highly significant p¡0.01).*

	Satisfaction	Understanding	Corresponding	Immersion
Gamepad	5.5	6.5	6.07	5.97
Armswing	5.93	6.2	6.33	6.4
Teleportation	6.27	6.57	6.3	6.36
χ_r^2	7.7167	3.35	1.25	3.0167
p-value	0.0211	0.18731	0.53526	0.22128
Significant	*			

6. RESULTS AND DISCUSSION

The results were collected from 30 participants consisting of 16 men and 14 women. The average age of all participants was 22.53 years old. The 7-points Likert scale was used for all questionnaires. The Usability Questionnaire (UQ) was the first part of the questions. The participants were asked about interaction, which included satisfaction, understanding, corresponding, and immersion. The Simulator Sickness Questionnaire (SSQ) was the second part of the questions. Participants were asked about symptoms after using the locomotion techniques, which included comfortable, nausea, oculomotor, and disorientation. After using each locomotion technique, they were asked about the UQ and SSQ. The data of the UQ and SSQ from the 30 participants are showed in Figure 7. The data distribution was non-parametric data. There were three types of locomotion techniques; therefore, the Friedman test [52] was used to analyze the differences between the locomotion techniques.

6.1 Usability result

When examining the results of the UQ (Table 2), we found that only the satisfaction value was different (p-value=0.02111<0.05), whereas understanding, corresponding and immersion were not different. We can, therefore, conclude that the users had the same understanding of the controls, the same sense that the movement and control were consist, and the same immersion level for all locomotion techniques. In contrast, the satisfaction of using each locomotion technique was different. Locomotion with the Gamepad, Armswing, and Teleportation techniques had an average usability score of 6.01, 6.22, and 6.36, respectively. Hence, locomotion with the Teleportation technique had the highest usability score, which meant that users preferred locomotion by the teleportation-based technique more than the other techniques.

In terms of satisfaction, the Gamepad technique had the lowest satisfaction with an average of 5.5, whereas the Teleportation technique had the highest value of 6.27. When using post-hoc analysis [52], we found that the Armswing technique satisfaction at 5.93 was no different from both Gamepad and Teleportation. However, the difference in satisfaction was between the Gamepad and Teleportation techniques, which meant that different locomotion techniques affected user satisfaction.

In terms of understanding, the Armswing technique had the lowest understanding with an average of 6.2, whereas and the Teleportation technique had the highest value of 6.57 which was not much different based on the Friedman test (p-value=0.18731>0.05). It was implied that user understanding was not different for all three locomotion techniques, which meant that the interaction design was easy to learn and use. In particular, the Armswing technique had to design controls that were consistent with body movements combined with using controllers, which was more difficult than the other systems. However, the understanding score of the Armswing technique was not much different from the other techniques.

In terms of corresponding, the Gamepad technique had the lowest corresponding score with an average of 6.07, whereas the Armswing technique had the highest value of 6.33, which was not much different (p-value=0.53526>0.05). This meant that the corresponding factor between the movement in VR and in reality was not different even for users when using different locomotion techniques. However, the lower score of the Gamepad technique might be from controlling the direction of movement. Users needed to turn to their desired direction to move, and sometimes the movement might not have corresponded with the controls.

In terms of immersion, the Gamepad technique had the lowest immersion score with an average of 5.97, whereas the Armswing technique had the highest value of 6.4, which was not much different (p-value=0.22128>0.05). We found that the Gamepad technique was the lowest because the user's perspective affected movement, and the perspective during movement was limited. In contrast, the direction of movement for the Armswing technique depended on the arm position, allowing independent perspective to see the virtual environment.

Table 3: *Friedman test result of the Simulator Sickness Questionnaire (SSQ) for all locomotion techniques (* significant p¡0.05, ** highly significant p<0.01).*

	Comfortable	Nausea	Oculomotor	Disorientation
Gamepad	6.27	6.5	6.3	5.47
Armswing	6.67	6.83	6.6	6.13
Teleportation	6.83	6.9	6.87	6.87
χ_r^2	4.1167	2.6	4.55	9.3167
p-value	0.12767	0.27253	0.1028	0.00948
Significant				**

Table 4: *Friedman test result of average usability and motion sickness (* significant p¡0.05, ** highly significant p<0.01).*

	Usability	Motion sickness
Gamepad	6.01	6.13
Armswing	6.22	6.56
Teleportation	6.36	6.87
χ_r^2	7.8167	17.7167
p-value	0.02007	0.00014
Significant	*	**

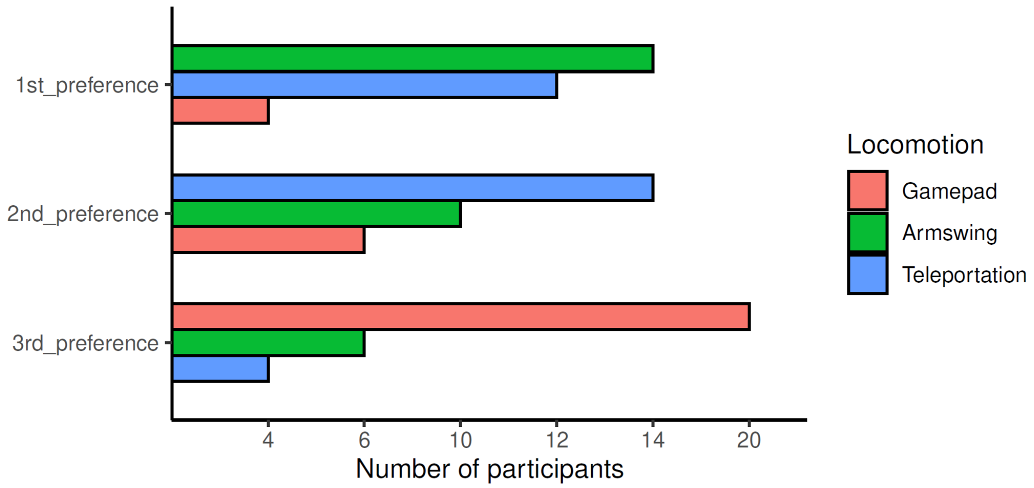


Fig.8: *Comparison of user preference for each locomotion technique by rank.*

Table 5: *Pearson correlation coefficient between user preference with usability and motion sickness (* significant p<0.05, ** highly significant p<0.01).*

	Usability - Preference	Motion sickness - Preference
R	0.4254	0.2972
p-value	0.0191	0.110726
Significant	*	

6.2 Motion sickness result

When considering the results of the SSQ (Table 3), we found that only disorientation was different with a high significance (p-value=0.00948<0.01), whereas the comfortable, nausea and oculomotor values were not different. This meant that the symptoms related to disorientation made each locomotion technique different. When using post-hoc analysis, we found that the disorientation of all locomotion techniques was different. Considering the overview of various symptoms from usage, the Gamepad, Armswing, and Teleportation technique had an average motion sickness score of 6.13, 6.58, and 6.87, respectively. The Teleportation technique had the highest motion sickness score, which meant that when using the Teleportation technique the users had less motion sickness symptoms than the other locomotion techniques.

Considering all symptoms, the Teleportation technique had the highest average value of all symptoms close to 7. This meant that the users had almost no symptoms of motion sickness when using locomotion with the teleportation-based technique. Considering the Gamepad technique, we found that this locomotion resulted in more motion sickness than the other techniques, especially in regard to disorientation. Considering the Armswing technique, we found that this locomotion resulted in less motion sickness than the Gamepad technique, but more than the Teleportation technique. However, we found that the values of comfortable, nausea and oculomotor were close to the Teleportation technique. Only the disorientation value was significantly different, and the Teleportation technique was better than the other techniques in this value.

6.3 Hypotheses testing

The UQ and SSQ results were used to analyze the differences between all three locomotion techniques (Table 4), where the average usability values were significantly different (p-value=0.02007<0.05) and the average motion sickness values were high significantly different (p-value=0.00014<0.01). Therefore, we accepted H1 and H2, which stated that participants have different performance and symptoms when using different locomotion techniques.

The Pearson correlation coefficient [53, 54] was used to measure the strength of a linear association and the direction of the relationship between variables. We measured the linear correlation between the usability and motion sickness scores to user preference from the interview (Figure 8) with the Pearson correlation coefficient. The results are shown in Table 5, and we concluded that the correlation between usability and user preference was significant with R=0.4254 and p-value=0.0191. In contrast, the correlation between motion sickness and user preference was not significant with R=0.2972 and p-value=0.110726. Therefore, by the significance level of p<0.05, the association between usability and user preference would be considered statistically significant. However, we rejected H3, which stated that user preference is based on only usability and not motion sickness.

7. CONCLUSION

The Teleportation technique is a teleportation-based locomotion that many users complain of using.

However, our study showed that this locomotion was the best technique with less motion sickness. That's why many VR applications still use this technique. Even though many users do not prefer it, this technique is still a good locomotion technique for user movement in VR.

The Gamepad technique is a controller-based locomotion, another form that is widely used. Especially with the VR applications in the form of a shooting or RPG game, the Gamepad technique focuses on the movement of the avatar and controlling it with the user's body and head. The thumbstick is used to control the avatar to move in a specified direction, but many users tend to have motion sickness symptoms. However, this technique is easy to understand for novice users.

The Armswing technique is a motion-based locomotion developed by imitating walking and running postures. When moving in VR, hands and arms swing according to the walking or running behavior to reduce motion sickness. However, users felt that it was more difficult to learn than the Gamepad and Teleportation techniques. The results showed that although the understanding for the Armswing technique was the lowest at 6.20, it was not much different when compared to the Gamepad and Teleportation techniques. This meant that users could learn to use it without much difference from other locomotion techniques. Moreover, another advantage of this locomotion was that the immersion value was equal to 6.4, which was better than the other locomotion techniques.

From our results, we found that participants responded with different performance and symptoms when using different locomotion techniques. User preference was based only on usability and not motion sickness, which implied that user preference relied solely on usability. When allowing users to rank preferences, some of them chose locomotion techniques that caused motion sickness. They preferred usability in term of a well-designed technique rather than less motion sickness. However, based on the interviews, users still chose techniques with acceptable levels of motion sickness. For instance, the Armswing technique had been ranked first o among users even though the Teleportation technique had less motion sickness. This implied that usability in terms of the design of the locomotion technique should be considered rather than just focusing only on motion sickness.

The new trend of VR headsets with controllers applies inside-out tracking with a specified guardian boundary. The use of different forms of locomotion is more versatile, which is suitable for all three types of locomotion techniques in this experiment. However, there are many ways to customize locomotion techniques depending on the purpose of the VR application. In particular, motion-based locomotion monitors body movements according to the movement and perspective of the users. In addition, immersion is also added when using motion-based locomotion. VR applications should have different locomotion techniques for users because each locomotion has advantages and disadvantages depending on each user's preferences. For future studies, the acceptance value for motion sickness of each locomotion technique should be evaluated in order to design a suitable interaction technique for VR applications.

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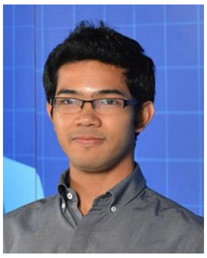

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