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Research Article

A Study of Physical Fitness and Enjoyment on Virtual Running for Exergames

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Virtual Reality (VR) technology has advanced forward in everyday life where virtual fitness is possible through physically moving around in the real world. Exergame is a video game for exercise aimed at making exercise more fun. VR exergame applies these trends together for virtual fitness with immersive game play. The VR locomotion is traveling in VR, which is commonly used in adventure role-playing games (RPG). Virtual running can be applied as a locomotion technique for VR exergames. The design of virtual running in VR exergames should be considered as an exercise for fitness and also for enjoyment. This paper proposed two motion-based locomotion techniques: ArmSwing and Squat for virtual running, which are considered as aerobic and strength exercise. These two postures were used to study how physical exertion affected players while interacting in the test scene. Usability, motion sickness, and enjoyment were assessed to analyze the differences of each posture. The results showed that motion sickness and enjoyment of ArmSwing and Squat were not different, while usability was different where ArmSwing was rated higher than Squat. The results from the interviews suggest that most players preferred aerobic exercise (ArmSwing) more than strength exercise (Squat) for a long period of exercise. However, for a short period of exercise, players preferred strength exercise more than aerobic exercise. The adventure-based RPG for exercise needs a solution design appropriate for virtual running in VR, and our results can be a guideline for developers in order to handle motion-based locomotion for VR exergames.

1. Introduction

Virtual Reality (VR) technology has stepped up to have more roles in our daily lives, including exercise and playing games. Fitness game or exergame is a term referring to using video games for exercise, which relies on technology that can track body movement [1]. VR immersion is a new trend for exergames because body movements can be detected by VR sensors and also immerse a user's feelings [2]. Therefore, the movement in the virtual environment corresponds to the physical movement, which makes the VR application suitable for exergames.

Especially, the use of exergames encourages users to interact with the content, which makes VR fitness a perfect integration of technology and exercise (Yoo, Carter, and Kay [3]). Recently, the VR industry is growing at a fast pace, and the market size of consumer VR hardware and software is projected to increase from 6.2 billion U.S. dollars in 2019 to more than 16 billion U.S. dollars by 2022 [4]. There is a high possibility that VR exergames will become popular in the future. VR systems have many possible advantages for sports training that can precisely control the environment and standardize the situation. Additional information can be integrated to provide operational guidelines, and the environment can be changed dynamically to create different competitive situations [5]. Although this technology is new, it shows promising results in high participation rates, more enjoyment, more motivation [6–8], and more fun than other forms of exercise. The fact is that most people are bored and do not have the discipline to traditional exercise, which is one of the main reasons for a high level of inactivity [9]. Therefore, immersive VR exergaming is a new opportunity for engaging more players than standard exercise and may distract participants from exertion required and the feeling of fatigue. We can play exergames from a variety of consoles. The following examples can display about the tools to play exergames.

There are many game consoles such as Xbox, PlayStation, and Nintendo. However, for exergaming, additional accessories may be needed to physically interact with the console instead of using just buttons on the gamepad. Although there are other consoles available, we focused on these three consoles because they offer the most common exergames on the market. The Xbox is a gaming console from Microsoft. In order to play exergames with the Xbox, it requires the Kinect system, which is a motion capture system that recognizes player body movements and integrates them into the game play. The Xbox system with Kinect does not require any accessories, making it the first gaming system where free body movement is possible. Exergames using the Xbox Kinect have the potential to enhance balance training and broader rehabilitation compared to standard exercise [10]. The PlayStation (PS) is a console from Sony. It includes the PlayStation Camera, a motion sensor akin to the Xbox's Kinect peripheral. Moreover, there is the move controller, which is conceptually similar to Nintendo's Wii Remote. These combinations allow for more free body movement than the Nintendo but less than the Xbox. However, exergames on the PS are more preferable to players than the Xbox [11]. The Nintendo Wii gaming console is popular for sport games, aiming to develop new game franchises that target fitness gaming. In particular, the Wii Remote controller can be used as a handheld pointing device and can detect movement in three dimensions. Since its release, the Wii has delivered many peripheral devices for exergames such as the Wii Balance Board and Motion Plus. The Wii Fit is a popular exergame for Wii with several activities using the Balance Board. It has been used for physiotherapy rehabilitation [12] and adopted for fitness applications focused on the elderly [13]. A new version called the Nintendo Switch (NX) is a hybrid console, which can be used as a home console or a portable device. Its wireless Joy-Con controllers come with standard buttons and directional analog sticks, a motion sensor, tactile feedback, and a heart rate sensor, all of which are useful for exergames. The Ring Fit Adventure is a popular exergame for the NX, which is a turn-based RPG, where player movements and battle actions are based on performing certain physical activities.

These consoles are non-VR platforms and successfully stimulate exercise for players. However, exergames can be further integrated with VR immersion to go beyond in terms of VR exergames. We found that exergames in the VR market can be classified under several types as follows: fitness, dancing, boxing, arm workout, leg workout, sport simulation, and competition. We can see that most of them are for casual fitness, and virtual running is still lacking due to low user interest, and the VR device may not appropriate for running in place. However, virtual running can be applied for adventure-based role-playing games (RPG), which can motivate players to play exergames for a longer time. There is also a gap in posture design for virtual running corresponding to the hardware. It is related to the locomotion technique in VR, where motion sickness is concerned. There are comments from VR exergame reviews [14] that should be considered. Many players state that the quality of the graphics had a particularly strong impact on perceived enjoyment, which may invoke motion sickness if the frame rate is not high enough. Furthermore, players disliked the games when the controls were too complex.

In this research, we proposed exergames to the next level with VR immersion with the design and development of virtual running for VR exergames to entertain players and stimulate exercise. The next section about VR headset trend was introduced to demonstrate the future and trend of VR devices. Then, Section 3 described the virtual running and related works. Section 4 presented the design and development of virtual running for the experiment. The study was related to the criteria of usability, enjoyment, and motion sickness. The virtual running techniques used in the experiment were designed differently according to low exertion and high exertion. Section 5 showed our experiment with the results and discussion in Section 6. The experimental results can support VR exergame developers in understanding the usage and the effects of virtual running for players, facilitating RPG exergame design. Finally, Section 7 described the conclusion and contribution of this work.

2. VR Headsets Comparison and Trend

The design of the VR exergame is mainly dependent on the characteristics of the head mounted display (HMD) device and controllers. Considering the various commercial VR headsets with controllers that have been developed since 2017 (Tables 1 and 2), we found that Oculus, HTC, and Windows Mixed Reality (WMR) are the advanced products created by technology vendors this market. The Steam Hardware Survey results for November 2020 [15] showed the following as the most popular active devices for VR: Oculus 53.34%, HTC 21.89%, WMR 5.82%, and others 18.95%.

The Oculus Go is the first standalone VR headset of the Oculus dedicated display and mobile computing hardware including a handheld controller using relative motion tracking. However, it is a nonpositional 3DoF tracking. The Oculus Rift S and Oculus Quest were released in May, 2019. The Oculus Quest is proposed to be a standalone device, while the Rift S is still PC-tethered with more performance. The Oculus Insight technology is used for motion tracking bundled with an iteration of the controllers, and the inside-out technology is the new standard for positional tracking of VR headsets [16, 17]. Hand tracking is the new feature of the Oculus Quest, using the on-board cameras to identify the movements of the fingers and hands without handheld controllers [18].

The HTC Vive has been launched since 2016, and it is the achieved product of HTC with a large working area, high performance display, and tracking accuracy [19]. The controllers provide a new approach for interacting in VR [20]. The HTC Vive Pro is a PC-tethered with full feature set for hardcore gamers upgraded their resolution display and Lighthouse 2.0 base stations, allowing more space to 10 m 10 m.

Table 1: Hardware and technology comparison of Oculus and HTC VR headsets.

Device	Oculus Rift CV1	Oculus Go	Oculus Rift S	Oculus Quest	HTC Vive	HTC Vive pro	HTC Vive Focus+	HTC Vive Cosmos
Release date	2016-03-28	2018-05-01	2019-05-21	2019-05-21	2016-04-05	2018-04-05	2018-11	2019-02-19
Type	PC-tethered	Standalone	PC-tethered	Standalone	PC-tethered	PC-tethered	Standalone	Standalone
Price	599$	199$	399$	399$	599$	1299$	599$	699$
Display and resolution	OLED 1080 × 1200, 94° FOV	Dual fast-switch LCD 1280 × 1440, 100° FOV	Dual fast-switch LCD 1280 × 1440, 90° FOV	OLED 1440 × 1600, 100° FOV	OLED 1080 × 1200, 110° FOV	AMOLED 1440 × 1600, 110° FOV	AMOLED 1440 × 1600, 110° FOV	LCD 1440 × 1700, 110° FOV
Refresh rate	90 Hz	60-72 Hz	80 Hz	72 Hz	90 Hz	90 Hz	75 Hz	90 Hz
Tracking technology	Accelerometer, gyroscope, magnetometer, camera-based	3DoF, gyroscope, accelerometer, magnetometer, proximity sensors for detecting	5x cameras-based, insight tracking, accelerometer, gyroscope, magnetometer	4x cameras-based, insight tracking, accelerometer, gyroscope, magnetometer	Accelerometer, gyroscope, 2 lighthouse base stations with IR laser emitters	Accelerometer, G-sensor, gyroscope, proximity, IPD sensor, 2 base stations 2.0 with SteamVR tracking	2x cameras-based, G-sensor, gyroscope, VIVE wave, hand tracking SDK	6x cameras-based, G-sensor, gyroscope, IPD sensor, eye tracking
Positional tracking	Constellation outside-in through USB-connected IR LED sensor	Non-positional 3DOF tracking	Inside-out (Oculus Insight)	Inside-out (Oculus Insight)	Outside-in through USB-connected IR LED sensor	Outside-in through SteamVR tracking	Inside-out tracking	Inside-out tracking
Controller	Oculus touch motion tracked controllers	Orientation-tracked remote 3DOF controller with pointer capabilities, touchpad with 3 buttons	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	SteamVR wireless motion tracked controllers with a track pad, grip buttons, and a dual-stage trigger	SteamVR wireless motion tracked controllers with a track pad, grip buttons, and a dual-stage trigger	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

Note that only headset products with the controllers included.

Table 2: Comparison of HMDs compatible with Windows Mixed Reality (WMR) and SteamVR platform.

Device	Lenovo Explorer	Dell Visor	Acer AH101	Asus HC102	Samsung Odyssey+	Valve index	HP Reverb	Pimax 8 K PLUS bundle
Release date	2017-10-4	2017-10-17	2017-10-17	2018-02-20	2018-10-22	2019-05-01	2019-05-6	2019-12-16
Type	PC-tethered	PC-tethered	PC-tethered	PC-tethered	PC-tethered	PC-tethered	PC-tethered	PC-tethered
Price	449$	450$	399$	399$	500$	999$	599$/649$	1399$
Display and resolution	LCD 1440 × 1440, 110° FOV	LCD (RGB subpixel) 1440 × 1440, 110° FOV	LCD 1440 × 1440, 95° FOV	LCD 1440 × 1440, 95° FOV	AMOLED 1440 × 1600, 110° FOV	LCD 1440 × 1600, 130° FOV	LCD 2160 × 2160, 114° FOV	LCD 3840 × 2160, 200° FOV
Refresh rate	90 Hz	90 Hz	90 Hz	90 Hz	60 Hz/90 Hz	90 Hz, 120 Hz, 144 Hz	90 Hz	60-110 Hz
Tracking technology	2x cameras-based, accelerometer, gyro sensor, magnetometer, proximity	2x cameras-based, accelerometer, gyro sensor, magnetometer, proximity	2x cameras-based, accelerometer, gyro sensor, magnetometer, proximity	2x cameras-based, accelerometer, gyro sensor, magnetometer, proximity	Gyroscope, 3-axis compass, proximity sensor, IPD sensor	SteamVR tracking, 2.0 lighthouse based stations	2x cameras-based, gyroscope, accelerometer, magnetometer	SteamVR tracking, 2.0 lighthouse based stations
Positional tracking	Inside-out tracking	Inside-out tracking	Inside-out tracking	Inside-out tracking	Inside-out tracking	Outside-in tracking	Inside-out tracking	Outside-in tracking
Controller	6DOF controller with haptic feedback, thumb stick, touchpad, analog trigger, grap button, Windows, and menu button, compatible with Xbox One Controller	6DOF controller with haptic feedback, thumb stick, touchpad, analog trigger, grap button, Windows, and menu button, compatible with Xbox One Controller	6DOF controller with haptic feedback, thumb stick, touchpad, analog trigger, grap button, Windows, and menu button, compatible with Xbox One 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	Knuckle controllers with all fingers detection through capacitive sensors, each controller features a system button, thumbstick, touchpad, analog index trigger, grip button	6DoF dual controllers tracked by HMD with multifunction touchpad, menu button, Windows start button, grab button, thumbstick, trigger, and also compatible with Xbox One Controller	Knuckle controllers with all fingers detection through capacitive sensors, each controller features a system button, thumbstick, touchpad, analog index trigger, grip button

The Vive Trackers are integrated to support more tracking and interactions. The HTC Vive Focus+ is the first standalone VR headset of HTC with inside-out tracking technology. The controller is redesigned to use 6DoF ultrasonic tracking. The VIVE wave and hand tracking SDK offer an open interface enabling interoperability between numerous mobile VR headsets and accessories, supporting mainstream game engines with a cross platform tool to track hand position and gesture recognition. The HTC Vive Cosmos refined inside-out tracking with six camera sensors. The controller is upgraded from the HTC Vive Focus with precision joysticks. Although all HTC Vive headsets are PC-tethered, the wireless adapter with the WiGig technology can transform HTC Vive to a standalone headset [21, 22].

WMR is a mixed reality platform based on the Windows 10 operating system, providing mixed reality experiences with compatible HMDs from Acer, Dell, HP, Lenovo, and Asus [23, 24]. Most WMR devices have the same specification with PC-tethered and inside-out motion tracking features integrated. The handheld motion controllers are included. In addition, all WMR headsets are compatible with the Xbox controller. The Samsung Odyssey+ come up with the Anti-SDE (Screen-Door Effect) filter applied to the display and also has a slightly different controller design which makes it different from the other WMR headsets [25] but also compatible with the SteamVR platform. The Valve Index is a high-end HMD, which is also compatible with the SteamVR platform. The headset uses an improved version of the Lighthouse tracking system. It has a 120 Hz display, with an option up to 144 Hz, producing realistic VE even moving head. The knuckle controllers come with all fingers trackable, which is one of the most effective VR controllers [26]. The Pimax is a HMD device with outside-in technology that focuses on high resolution and a wide range of display up to 8K. The new Pimax 8K PLUS comes with a bundle set, including the Valve Index Controllers and SteamVR Base Stations. The inside-out technology for tracking will come with expansion modules in the next generation [27].

From the survey of the VR headsets available in the market and the development of new devices, we found that there is a trend for more standalone wireless devices that come with inside-out tracking technology. The controller is more effective in finger detection, which supports the development of applications and more user interaction. However, applying this technology to virtual running may not be suitable for stationary running because the headsets are still heavy. We have to wait for new technology on HMD glasses to become compact in size. Therefore, the virtual running design for VR exergames should be physically consistent with movement, which is a motion-based locomotion technique designed by focusing on exertion by various parts of the body.

3. Virtual Running and Related Works

Virtual running is directly related to VR locomotion, which comes in many forms. The motion-based locomotion is the most suitable form that can be applied to exercise because it must be activated by user movement. Related research includes the application of transforming user movement into locomotion in VR. However, motion-based locomotion was previously developed with a focus on UI and UX [28] rather than for exercise.

3.1. Motion-Based Locomotion. Motion-based locomotion is a continuous locomotion through physical interaction of the user's movement in the VR space [28] and relies on the guardian-based or room-scale-based locomotion. The guardian-based locomotion focuses on stationary interaction instead of moving around as with the room-scale-based locomotion.

Cherni et al. [29] explored locomotion techniques in VR between 2012 and 2019. Several studies applied body motion for locomotion to enhance spatial perception and user experience, which increases the sensation of one's own self-motion. The techniques related to exercise are classified as the following user-body centered techniques: leaning based and walk simulation. Leaning-based simulation is separated as arm-based, head-based, and trunk-based simulation. All techniques rely on a part of the body, which is referred to in its name. Head-based and truck-based simulations use physical leaning or tilting in a standing or seating position, focusing on control through posture.

The arm-based simulation uses the human arm to control movement, which is called the arm-swinging method. Arm-Swinging is one of the techniques that lets the user move forward when they move their arms. This technique has many different approaches. Some research use the Myo Armband, a forearm tracking device with various features [30–32]. The direction of the armband is tracked to check whether the user moves their arm or not, which is used for movement tracking. The results [30, 32] showed that this method outperformed the simple joystick in spatial orientation and that it is comparable to physically walking on foot.

Walking-in-place (WIP) is a technique to simulate as similar as possible the manner of walking through the real world, where feet movement is tracked and then translated to movement in the virtual environment with the room-scale-based locomotion. However, the WIP locomotion technique requires using additional hardware, and the interaction area is limited by the room size [32, 33]. There were research results showing that physical locomotion outperformed both walking-in-place and arm-swinging in terms of spatial awareness.

Gesture-based technique is one of motion-based techniques that uses hand gestures to control movements in VR. Some VR headsets do not have a hand tracking system and require additional accessories. The Leap Motion device has been modified allowing users to use hand gestures, which are already defined [34, 35]. However, nowadays, HMD devices have built-in cameras with inside-out technology to enable hand tracking allowing users to interact with their hands.

3.2. Applications of Motion-Based Locomotion. From the literature review, there are many studies that have applied virtual running or VR gaming for exercise. In general, these studies focused on common issues, including usability, motion sickness, and enjoyment of playing game. Following research are related to see their studies including the results and can be used to be a basis for our work.

Yoo and Kay [36] presented VRun, a virtual running exergame allowing players to jog in place through a virtual world. The experiment has been tested on three systems: a laptop, a large display, and a HMD using Google Cardboard. The HMD received the best usability score from the SUS (System Usability Scale), while the most immersive system was the large display. The result showed that HMD is useful for virtual running. However, the large display may be more acceptable for longer exercise periods.

Next, VRmove [3] was proposed as a design framework for VR games. This framework analyzed data on the basis of exertion and enjoyment. They demonstrated the use of the VRmove framework to inform the design of a new game. The results showed that enjoyment was linked to light exertion and multiple movements. The Goldilocks effect was the highlight with the design of VR exergames. The balance of exergames should take into account the level of exertion while being engaging enough to distract players from actually feeling fatigued.

The evaluation of the actual and perceived exertion from VR games [37] was presented to compare gaming with exercise. The contribution was in the insights about the exertion in gaming, which highlighted the potential value for improving exercise levels. The Borg score was used to compare VR games to be considered as exercise. Fruit Ninja was comparable to walking, while Hot Squat to running, and Holopoint to dancing. The results from this study pointed towards VR as being able to deliver enough exertion to be considered as exercise in terms of both the cardiovascular level and particular muscle groups.

There was research that applied the WIP method using position and orientation tracking called jog-in-place [38]. This research proposed a recognition method to distinguish a motion and transform it to virtual velocity. Their method did not recognize the squatting motion but included WIP steps. This locomotion provided users with a natural navigation experience, which can be used to walk in an infinite virtual environment in VR applications. The results showed that virtual velocity worked with an accuracy of 99.32%. There were some participants that complained about dizziness, but none experienced motion sickness.

RabbitRun [39] is a serious game with an immersive experience to engage low back pain (LBP) patients in a virtual environment and distract them from the pain while performing LBP exercises. The usability evaluation results showed that the RabbitRun game was enjoyable and acceptable. Moreover, it was easy to learn and play, and most of the participants were willing to play the game at home. This game enhanced the rehabilitation outcome of patients and can be used to motivate patients to move and train for longer periods.

There was a research presenting Rift-a-bike [40], an immersive VR game that enhances the exercise bike experience with challenges, levels, points, badges, and prizes to support physical exercise. Their results showed that gamification increased the user's enjoyment during the physical activity. They also provided guidelines for applying gamification features for fitmersive games. According to relevant research, we found that VR exergames have many positive effects on exercise [41, 42], such as motivating players to exercise, attracting players to exercise for longer periods, and enhancing player enjoyment. The results showed that playing VR exergames can be compared to real exercise [43]. From previous research, the HMD device is useful for virtual running and increases immersion, while the large display is better for longer periods of exercise. Virtual running is an interesting point for VR exergames using HMD. The solution to make users comfortable and acceptable is a concern in our study. Therefore, it is interesting to study how exertion should be for short and long exercise periods. The design of different postures for virtual running is proposed with light and heavy workouts to investigate usability, motion sickness, and enjoyment of users.

4. Design and Development

The exercise posture consists of four exercise types: aerobics, strength, flexibility, and balance [44]. The aerobic exercise such as walking, running, swimming, biking, and dancing is the key to build and maintain cardio endurance. The strength conditioning such as squat is the exercise to strengthen the bones, muscles, and connective tissues. The balance training such as yoga poses can improve stability to keep body upright, including legs and core. The body balance makes moving easier and prevent injury. The flexibility is the activities that lengthen and stretch muscles or functional abilities, such as reaching, bending, or stooping. Initially, this research focused on physical exercise postures to study the effects of exercise postures on virtual running. The aerobic and strength are the exercise using more exertion than balance and flexibility. Therefore, we can use these two postures to investigate appropriate duration time and relationship between physical fitness and user preference.

As for the VR headset trend review, we can see that the inside-out tracking technology used with tracking controllers is the trend of VR devices, and the Oculus Rift S also supports this technology. Therefore, the design of the interaction technique was based on the Oculus Rift S with Touch controllers. We separated virtual running techniques into two cases: low exertion and high exertion. The ArmSwing virtual running was a representation of less exertion using arm swinging for locomotion, while the Squat virtual running was a representation of high exertion using squat posture for locomotion. The implementation using OVRinput on Unity3D (Figure 1) of our virtual running locomotion techniques is defined with the following details:

4.1. ArmSwing Virtual Running. In the design of virtual running with arm swinging, the biomechanics of real walking [45, 46] was considered using gait cycle to describe the human walking pattern, which can be applied to the design. However, gait cycle [47] consists of two main phases: (1) stance and (2) swing, which is the posture of the legs and arms, respectively. Recently, VR headset devices as reviewed can detect only the position of the head and hands from the

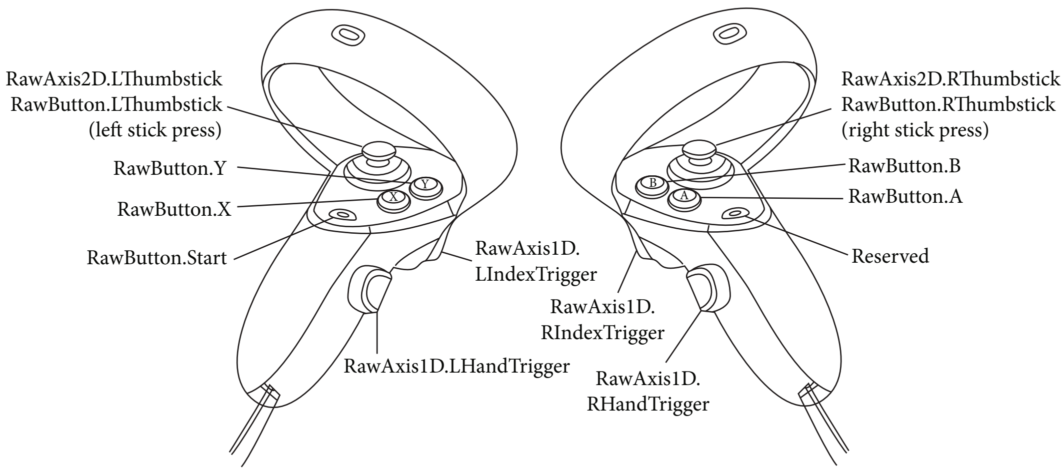

Figure 1: OVRInput API for unity uses to query controller state.

Data: *LHandT rigger, RHandT rigger,* $\vec{L}$, $\vec{R}$, and $\vec{H}$ as trigger controllers and position of left hand, right hand, and head, respectively.

Result: Locomotion by arm swinging applied on $\vec{H}$.

begin

$swing_{threshold}$, $acc_{threshold}$, $iner_{threshold}$ ← swing range, acceleration, inertia

for *frame i =1* **to** *N* **do**

if *LHandTrigger is True* **and** *RHandTrigger is True* **then**

$l_L \leftarrow \|\vec{L}_i - \vec{L}_{i-1}\|$

$l_R \leftarrow \|\vec{R}_i - \vec{R}_{i-1}\|$

$lswing \leftarrow l_L + l_R/2$

if $f_{swing} > swing_{threshold}$ **then**

$\vec{H} \leftarrow \vec{H} + (l_{swing}\ acc_{threshold})(\vec{L} + \vec{R}/\|\vec{L}_i + \overline{\vec{R}_i}\|)$

else

$\vec{H} \leftarrow inert_{hreshold}\,\vec{H}$

else

$\vec{H} \leftarrow \vec{0}$

Algorithm 1: ArmSwing virtual running.

HMD and controllers, but the leg position cannot be detected without the use of accessories. In this research, we were restricted to the VR headset without using other accessories. We designed the use of arm swinging to move the arm only with the HMD and controllers. Therefore, we designed the locomotion movement by swinging the arms, which was calculated by the speed from the distance of the controllers being swung, while the locomotion direction was calculated from the position and direction of the controllers. Biomechanics indicate that walking speed (v) is related to step frequency (f) and step length (l) [47] in the following equation:

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

The continuous walking or running movement has arms and legs alternating with the similar frequency and pattern of swinging at a particular speed value [48]. Then, we claimed that the ratio of arm swinging and leg striding distance has the constant value and transformed the (1) equation to use with ArmSwing virtual running. The step frequency (f) can be changed to step frame-by-frame, and step length (l) can be changed to the distance of arm swinging for each frame. The walking speed (v) was transformed to the virtual running speed by calculation of the arm swinging distance for each frame.

The arm swinging distance is calculated from the distance of the controller positions frame-by-frame, and both distances are averaged together. If the value is greater than the specified swing threshold, the user avatar will be moved from the original position of $\vec{H}$ of the previous frame. The direction of movement is calculated from the unit vector of $\vec{L}$ (left controller direction) and $\vec{R}$ (right controller direction) as in Figure 2.

Movement speed is calculated from the average controller distance multiplied by the acceleration threshold. Since

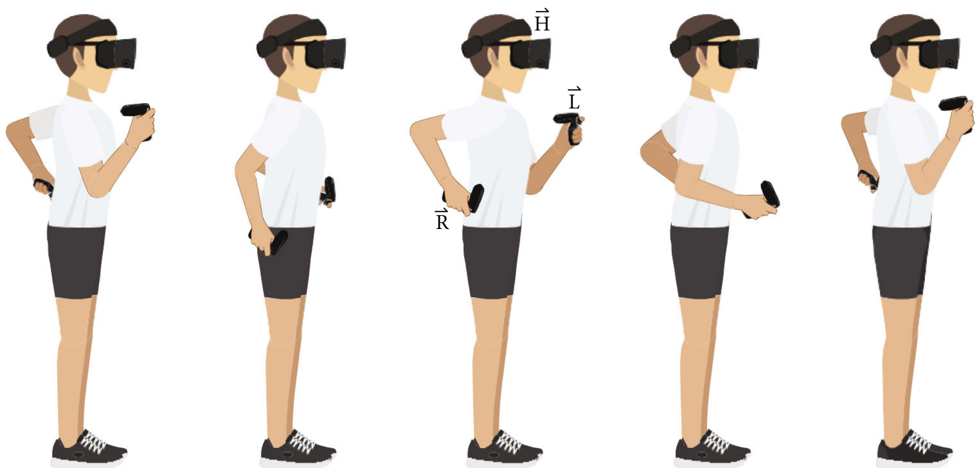

FIGURE 2: Virtual running with the ArmSwing posture.

Data: *LHandT rigger, RHandT rigger,* $\vec{H}$, and γ as trigger controllers, head position and angle between $\vec{H}$ and Z-axis, respectively.
Result: Locomotion by squat applied on $\vec{H}$.
begin
  $squat_{threshold}, gaze_{threshold}, acc_{threshold}, iner_{threshold}$ ← squat range, gaze, angle, acceleration, inertia
  for *frame i=1* **to** *N* **do**
    if *LHandTrigger is True* **and** *RHandTrigger is True* **and**
      $0 < \gamma < gaze_{threshold}$ **then**
        $l_{squat} \leftarrow Hy_i - Hy_{i-1}$
        if $f_{squat} > squat_{threshold}$ **then**
          $\vec{H} \leftarrow \vec{H} + (l_{squat}\ acc_{threshold})(\vec{H}/\|\vec{H}\|)$
        else
          $\vec{H} \leftarrow iner_{threshold}\vec{H}$
        else
        $\vec{H} \leftarrow \vec{0}$

ALGORITHM 2: Squat virtual running.

the motion is a frame-by-frame calculation, the speed result respects to the continuous movement. However, if the user stops swinging their arms but still presses the LHandTrigger and RHandTrigger buttons, the movement result will gradually slow down according to the inertia threshold until the motion is stopped. If the user release the LHandTrigger and RHandTrigger buttons, the movement will stop immediately.

4.2. Squat Virtual Running. The squat is an excellent lower body workout, and it is a popular exercise that can be done without using any equipment. Since the purpose of this research needed a design with a high exertion posture greater than swinging arms, the squat posture was applied to virtual running. People have different physiology, including differences in the length of the thigh bone, body, and flexibility [49]. Each person has a different squat posture depending on their physiology. The design, therefore, emphasized the continuous squat up and down without having to rush, but the weight must always be put on both feet [50].

From equation (1), we can also apply this equation to use with Squat virtual running. Step frequency (f) can be changed to step frame-by-frame, and step length (l) can be changed to the distance of squatting up and down. Then, the walking speed (v) can be transformed to the virtual running speed by calculation of the squatting distance for each frame.

The squat distance is calculated from the distance of moving the HMD position up and down following the squat posture. Therefore, only the Y-axis distance ($H_y\vec{j}$) of the HMD is calculated as detailed in Figure 3. If the value is greater than the specified squat threshold, the user avatar will be moved from the original position of $\vec{H}$ of the previous frame. We added the gaze angle threshold to avoid a wrong movement when the user bent or lifted his face more than the specified degree. Since the motion is a frame-by-frame calculation, the result is a continuous movement with the same direction of the HMD. Similar to ArmSwing virtual running, if the user stops swinging their arms but still presses

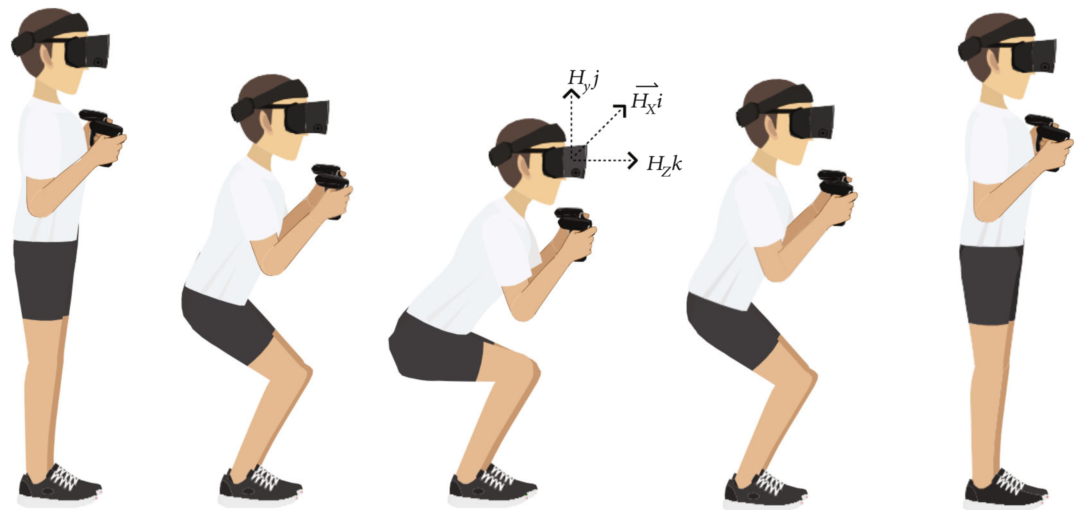

Figure 3: Virtual running with the Squat posture.

the LHandTrigger and RHandTrigger buttons, the movement result will gradually slow down according to the inertia threshold until the motion is stopped. If the user releases the LHandTrigger and RHandTrigger buttons, the movement will stop immediately.

5. Experiment

The objective of this research was to evaluate the performance of virtual running for exercise. Our experiments were held on the university campus, announcing 30 volunteers via social media. The method started with the introduction, warm-up, and testing VR headset. Then, each participant was required to test both virtual runnings. We designed different postures of virtual running to represent different exertions, which included the ArmSwing and Squat. The ArmSwing posture was a representation of aerobic exercise for virtual running, while the Squat posture was a representation of strength exercise. Usability and motion sickness of both the ArmSwing and Squat postures were evaluated to see the different in terms of usage. Then, the performance of each posture in terms of time and heart rate was assessed. In addition, the enjoyment during usage was assessed to see the differences of each posture. Both results were used to analyze the advantages and disadvantages of each posture. The final step was an interview to confirm the results of the experiment. This experiment was focused on VR exercises that caused tiredness or fatigue, where participants could stop or continue whenever they desired.

5.1. Virtual Environments. In our experiment, the scene was designed to assess the virtual running techniques, which included ArmSwing and Squat. The scene was a racetrack decorated with the surrounding atmosphere. The virtual environments used in the experiment can be downloaded for free from the asset store in the Unity Game Engine. The assets and virtual environments were adapted and resized for our virtual running test. Participants were required to exercise by virtual running, which took around 1-2 minutes from the start to finish point. All participants used the same route in the designated area so that everyone ran the same distance.

5.2. Evaluation. After testing, participants were measured for their heart rates. Then, they were allowed to take some rest and answered three questionnaires. The heart rate was measured to check the user's fatigue of each posture in order to confirm the exertion of the virtual running design. The ArmSwing posture was designed as low exertion virtual running. It should result in a lower heart rate than the Squat posture, which was designed as high exertion virtual running. While the participants were taking their rest, they were given three questionnaires about motion sickness, system usability, and user enjoyment of the physical activity. After completing the experiment, there was an interview about their preferences for comparison of the two different virtual running postures.

5.3. Questionnaires and Interview. There were three questionnaires in our experiment. The first questionnaire was about motion sickness, and simulator sickness was used to assess symptoms of users while using the HMD (Oculus Rift S). The second questionnaire was about system usability, which was used to assess the design of the virtual running postures. The last questionnaire was about physical activity enjoyment to assess user enjoyment while using the virtual running postures. Finally, at the end of experiment, there was an interview to compare user preferences for both virtual running postures.

The Simulator Sickness Questionnaire (SSQ) is related to a type of motion sickness that is experienced in training. The awareness of the differences between simulated motions in a virtual environment and user movements can occur and lead to simulator sickness [51, 52]. SSQ symptoms indicate three constructs of simulator sickness, which are nausea, oculomotor, and disorientation. These symptoms can reduce the efficiency of virtual running and result in systematic effects such as decreased simulator use and safety, which can affect user preference. The users gave a score between 1 and 5 points to tell how much they felt with each symptom. "1 point" is strongly severe, "2 points" is severe, "3 points" is moderate, "4 points" is slight, and "5 points" is no symptom. The SSQ questionnaire was divided into different subscales as follows:

(i) *Comfortable*. The overall sensations of the user during usage

(ii) *Nausea*. Symptoms such as increased salivation, sweating, stomach awareness, and burping

(iii) *Oculomotor*. Symptoms such as fatigue, headache, eyestrain, and difficulty focusing

(iv) *Disorientation*. Symptoms such as vertigo, dizziness, and blurred vision

The System Usability Scale (SUS) was developed as a tool to be used in usability engineering [53, 54] to provide a rough estimate of a system's ease of use. This questionnaire is a Likert scale questionnaire, and the results obtained from this test were quantitative. This SUS questionnaire contained 10 items for users to rate. The users gave a score between 1 and 5 points to tell how much they agreed with each item. "1 point" is strongly disagreed, and "5 points" is strongly agree. The questionnaire of SUS is described as follows:

(i) I think that I would like to use this system frequently

(ii) I found the system unnecessarily complex

(iii) I thought the system was easy to use

(iv) I think that I would need the support of a technical person to be able to use this system

(v) I found the various functions in this system were well integrated

(vi) I thought there was too much inconsistency in this system

(vii) I would imagine that most people would learn to use this system very quickly

(viii) I found the system very cumbersome to use

(ix) I felt very confident using the system

(x) I needed to learn a lot of things before I could get going with this system

The SUS score of both virtual running postures were evaluated to see the performance in terms of efficiency, effectiveness, and overall ease of use. Each participant rating had a scale of 0-100 by calculating the answers with the formula as follows:

(i) X = Sum of the points for all odd-numbered questions – 5

(ii) Y = 25 – Sum of the points for all even-numbered questions

(iii) SUS Score $= (X + Y) \times 2.5$

The average SUS score was 68, which meant that system was an okay system above 50th percentile. The SUS scores can be divided into the following levels: >80.3 excellent, 68-80.3 good, 68 okay, 51-68 poor, and <51 awful.

The Physical Activity Enjoyment Scale (PACES) is a Likert Scale questionnaire as a tool to evaluate user enjoyment when doing physical activity such as rehabilitation or exercise. The 8-items PACES version [55] was used instead of the original 18 items, and the revised scale is invariant and a valid measurement to assess enjoyment of physical activity. We adapted the questions to fit our experiment. Participants were asked to rate the question, "How do you feel at the moment about the virtual running you have been doing?" using a 5-point rating scale similar to the SUS questionnaire. Higher PACES scores reflected greater levels of enjoyment. The 8-item PACES questionnaire is described as follows:

(i) I find it pleasurable

(ii) It is a lot of fun

(iii) It is very pleasant

(iv) It is very invigorating

(v) It is very gratifying

(vi) It is very exhilarating

(vii) It is very stimulating

(viii) It is very refreshing

The interview at the end of experiment consisted of several questions about user preference on low exertion and high exertion of virtual running. We wanted to know user's feelings about the use of the virtual running exercises and to compare their preferences in terms of design, exertion, and playing time. The answer may be one of the postures they preferred or may include both of them equally the same.

(i) Which virtual running posture do you prefer to use

(ii) Which virtual running posture do you prefer if playing for a long period

(iii) If playing for a short period, which virtual running posture do you prefer to use

5.4. Research Protocol. In our experiment, 30 participants who volunteered were given step-by-step explanations as shown in Figure 4. The introduction and importance of this research are explained. The operation of virtual running was described, which included the Arm-Swing and Squat posture. Before testing, the participants were encouraged to warm up because the experiment involved the use of muscles. The participants were notified that after completing each virtual running they had to answer the questionnaires and interview at the end. Furthermore, the participants were notified that using the Oculus Rift S with the controllers could cause symptoms during the test, and they could stop the experiment at any time. When the participants understood everything clearly, then the experiment began.

Since each participant was required to assess two virtual running postures, the sequence in the experiment affected

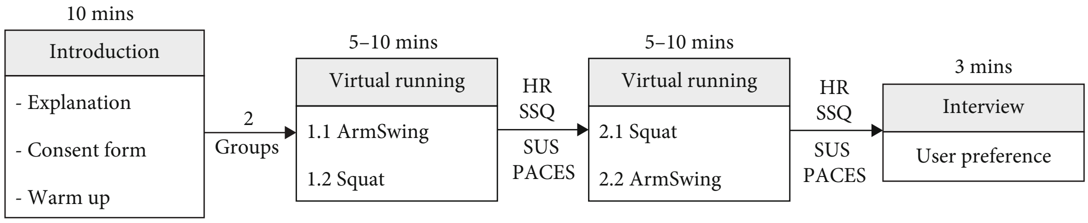

Figure 4: Research protocol with two groups of participants in the experiment.

their fatigue and evaluation. Therefore, all participants were separated into two groups with fifteen participants in each group to switch starting postures and avoid bias from exertion. All groups were tested two times with the ArmSwing and the Squat posture. Figure 5 shows the selection menu before starting and participants during the experiment as shown in Figure 6. After each experiment, the participants must remove the HMD device and complete the posttest evaluations by answering the SSQ, SUS, and PACES questionnaires before moving on to test the next virtual running posture. Finally, participants had to complete the experiment with an interview to compare their preferences on the two different postures.

6. Results and Discussion

The results of the study were collected from 30 participants, consisting of 18 men and 12 women. The average age of all participants was 27.40 years from 19 to 45 years old. The average weight was 70.23 kilograms from 42 to 120 kilograms. The average height was 165.40 centimeters from 152 to 187 centimeters. The Shapiro-Wilk test was used to check the normal distribution of the observations and the results of all questionnaires. The SSQ, SUS, and PACES results were not normal distributed, which were considered as nonparametric data. Then, a nonparametric Wilcoxon test was used to evaluate the differences between ArmSwing and Squat, where the samples of the participants were the same and considered as dependent samples. The results of the experiment were divided into the following areas.

6.1. Heart Rate and Running Time. The results of the virtual running testing showed that after using the ArmSwing posture, the participants had an average heart rate of 88.53 BPM, with an average time of 94.77 seconds. For virtual running with the Squat posture, the participants had an average heart rate of 114.97 BPM with an average time of 112.83 seconds. We can see that our testing in a short period of time, the aerobic exercise of the virtual running design with ArmSwing had a lower heart rate than strength exercise with Squat. In addition, participants used less time to run with ArmSwing than Squat because the strength exercise required more exertion, which made them more tired.

6.2. Motion Sickness Result. The results from the SSQ questionnaire (Table 3) showed that virtual running with ArmSwing and Squat had no differences in motion sickness (p value $=0.34722>0.05$). In addition, 79.17% of the participants had no abnormal symptoms between running with both postures. That meant both virtual running designs can be adapted for locomotion in VR. The participants had very little motion sickness during the virtual running experience. Moreover, both designs can be applied to exergames, where this movement is necessary in RPG game styles with VR and locomotion.

6.3. Usability Results. The SUS results from the questionnaire were converted to 0-100 points to evaluate the usability performance of virtual running. The results showed that the converted SUS scores from participants for the virtual running experience with ArmSwing and Squat were 86.5 and 82.67, respectively. The results implied that both virtual running postures' usability performance was excellent, and the score of the ArmSwing was slightly more than the Squat.

In the aspects of effectiveness and efficiency by learnability and usability, the learnability dimension can be evaluated from the subscales at items 4 and 10. The average scores of items 4 of ArmSwing and Squat were 2.07 and 2, respectively. That meant a few of both virtual running participants thought they needed a technical person to support using this system. Similarly, the average score of items 10 of ArmSwing and Squat equaled 1.5 and 1.7, respectively. That meant a few of both virtual running participants thought they needed to learn a lot to use this system. The usability dimension can be evaluated from the other eight items, and the results were in the same direction as the SUS score. It suggested that both virtual running postures were effective and efficient to use.

However, when testing the differences with the Wilcoxon signed-rank test (Table 3), it was found that the SUS scores of both postures were significantly different (p value $=0.03318<0.05$). Therefore, the design of virtual running with the ArmSwing posture was better than the Squat posture in terms of usability.

6.4. User Enjoyment Results. The user enjoyment of virtual running was measured using the PACES questionnaire. The results (Table 3) showed that the enjoyment of virtual running with ArmSwing and Squat had no differences (p value $=0.29372>0.05$). The enjoyment scores from the PACES questionnaire with a total score of 40 for the virtual running experience with ArmSwing and Squat were 34 and 34.47, respectively. The highest average scores from the PACES questionnaire for the ArmSwing and Squat postures were "It's very invig- orating" with scores of 4.4 and 4.67, respectively. It suggested that the participants felt that using both postures in the virtual running experience stimulated exercise, feeling strong, feeling healthy, and feeling full of energy.

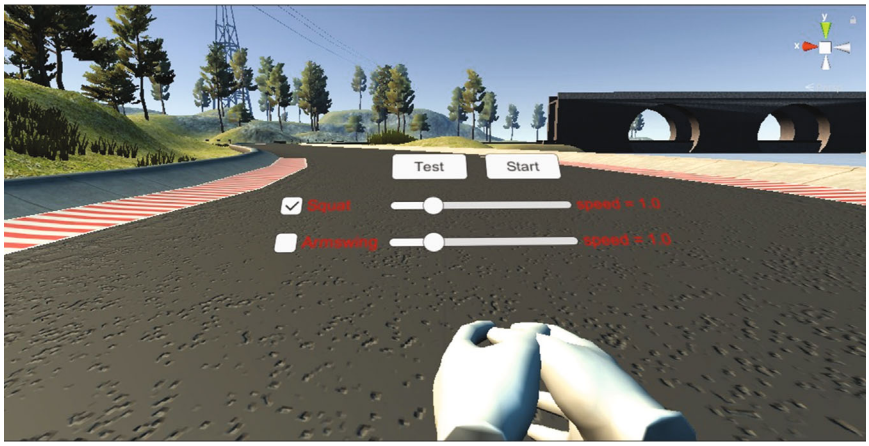

Figure 5: User interface of virtual running selection.

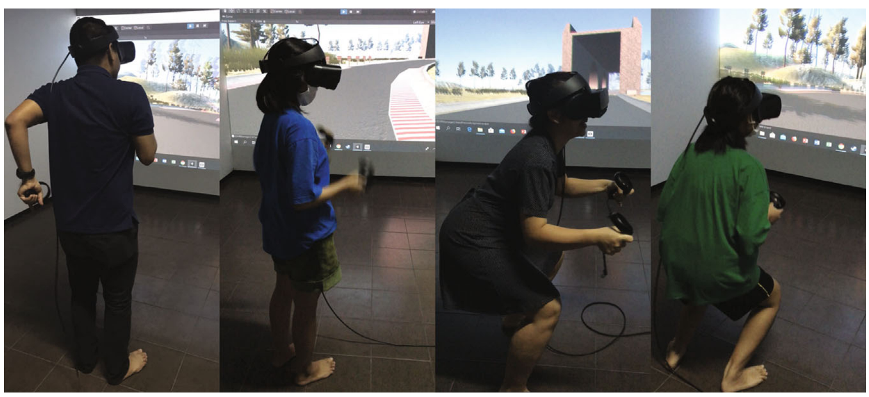

Figure 6: Participants during the experiment testing.

Table 3: The results of the Wilcoxon signed-rank test for motion sickness, usability, and enjoyment (*significant $p < 0.05$, **highly significant $p < 0.01$).

	Motion sickness	Usability	Enjoyment
ArmSwing	19	86.5	34
Squat	18.87	82.67	34.47
W	27	61	103.5
z	-0.9414	-2.1265	-1.0493
p value	0.34722	0.03318	0.29372
Significant		*	

6.5. Interview Results. Our first question was about which virtual running posture the participant preferred in general from overall usage. The results of the interview (Figure 7) showed that 17 participants preferred the ArmSwing posture, 9 participants preferred the Squat posture, and 4 participants liked both postures equally. Considering the overview of results from usability, motion sickness symptoms, and enjoyment, it can be seen that the participants preferred virtual running with ArmSwing more than Squat.

In the second question, we asked about the duration of the virtual running exercise. If the participant had to exercise with these two postures for a long period of time, which posture would they prefer? The results of the interview showed that 27 participants preferred the ArmSwing posture, with only 2 participants who preferred the Squat posture more and only 1 participant who voted both postures the same. It can be seen that 90% of the participants preferred the aerobic exercise (low exertion) more than the strength exercise (high exertion) of virtual running when having to play for a long period.

In the third question, we asked the same as the second question but modified it to ask which posture they would prefer for a short period of time? The results showed that 12 participants preferred the ArmSwing posture, whereas 17 participants preferred the Squat posture more and only 1 participant voted both postures the same. It can be seen that 56.7% of the participants preferred strength exercise (high exertion) when playing only for a short time. However, even if just exercising for a short period of time, 40% of the participants still chose the aerobic exercise (low exertion).

6.6. Association Results. The Pearson correlation coefficient [56, 57] was used to measures linear correlation between two variables. The value is between +1 and -1, where 1 is total positive linear correlation, 0 is none correlation, and -1 is total negative linear correlation. We used Pearson correlation

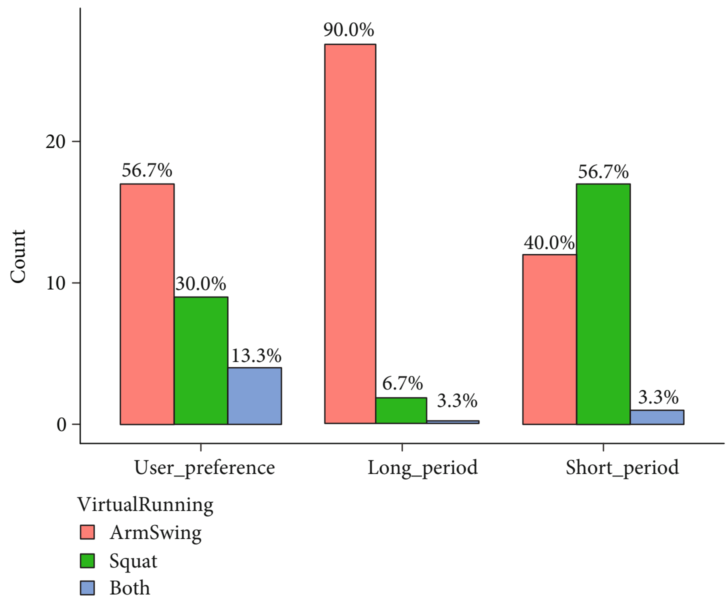

Figure 7: Results from the interview with questions about preference and playing time.

Table 4: The association by the Pearson correlation coefficient between ArmSwing and Squat in terms of motion sickness, usability, and enjoyment (*significant $p < 0.05$, **highly significant $p < 0.01$).

	Motion sickness	Usability	Enjoyment
R	0.8595	0.8286	0.8434
T statistic	8.8973	7.8315	8.3075
p value	1.1882E-09	1.5699E-08	4.8671E-09
Significant	**	**	**

Table 5: The association by the Pearson correlation coefficient between SUS and PACES scores of the ArmSwing and the Squat (*significant $p < 0.05$, **highly significant $p < 0.01$).

	SUS-PACES (ArmSwing)	SUS-PACES (Squat)
R	0.5249	0.3794
T statistic	3.2634	2.1698
p value	0.0029	0.0387
Significant	**	*

coefficient to measure linear correlation between gender, age, and BMI with the SSQ, SUS, and PACES scores of both postures. It was found that these values were not correlated to each other.

However, when we studied the relationship between the ArmSwing posture and the Squat posture, we found that the scores from questionnaires of both postures were correlated with highly significant (Table 4). In addition, when the players had less motion sickness in the ArmSwing posture, they also have less motion sickness in the Squat posture. When the players felt that usability of the ArmSwing posture was good, the Squat posture was also good usability. And when the players enjoyed with the ArmSwing posture, they also enjoyed with the Squat posture. When we studied the relationships between SSQ, SUS, and PACES scores on each posture, we found that the scores between SUS and PACES were correlated (Table 5); the ArmSwing posture was highly significant (p value =0.0029<0.01), and the Squat was significant (p value =0.0386<0.05).

It implied that gender, age, and BMI have no effect on virtual running of both aerobic exercise and strength exercise. However, it was found that both ArmSwing and Squat postures were correlated to motion sickness, usability, and user enjoyment on the same way. And in any posture, when the players felt that the posture was good usability, the players were also enjoyed to that posture (the usability is direct variation to the user enjoyment).

6.7. Discussion. The inside-out tracking technology is the trend of VR headsets with useful controllers and hand tracking. Exergames by this VR tracking will be the future with immersive gameplay while doing exercise. Motion-based locomotion in VR is related to physical interaction, which walking or running simulation can apply for the exercise. This is interesting for designing VR exergames that should be physically consistent with movement focusing on exertion by various parts of the body.

This research studied the criteria of usability, enjoyment, and motion sickness. Our experiment and interview results showed that virtual running with ArmSwing is preferred for an extended period than Squat but preferred Squat in a short period. Most research [30–32] have better results of WIP than ArmSwing in terms of usability and motion sickness. However, the trend of VR headsets is going to use inside-out tracking. ArmSwing and Squat are interesting to promote as a virtual running posture. Our heart rate result of ArmSwing was 88.53 BPM (99.77 seconds), which was not much different from [31] with 95 BPM (mission completed). In comparison, the heart rate result of Squat was 114.97 BPM

(112.83 seconds) related to WIP [31] with 120 BPM (mission completed).

In the interview, participants voted Squat because they want more exertion if they were in the short period of gameplay. However, they relaxed when using ArmSwing by a little exertion. They felt the mission have no challenge, which can make the exergame boring. This suggestion implied that we should design VR exergames with appropriate exertion and challenge. Moreover, intensive exertion during gameplay can make players discouraged and do not want to continue playing even though the enjoyment for exergames did not mention too much in VR previously. Our PACES result suggested that their experience in ArmSwing and Squat stimulated exercise with enjoyment feeling. Design and development of RPG exergame in VR should adjust effort for varying exertion difficulty to avoid boring and encourage challenge.

7. Conclusion

This work presented exercise through virtual running. The two postures were proposed with ArmSwing and Squat as the representation of aerobic and strength exercise, respectively. Virtual running with ArmSwing required low exertion, whereas the Squat required high exertion based on the posture and heart rate. The results showed that motion sickness and user enjoyment of both postures were not different, showing that both virtual running designs worked the same way in terms of comfort and fun. In contrast, the usability of the ArmSwing posture was better than the Squat posture. However, both postures had SUS scores more than 80.3, which were excellent usability. The interview results showed that users preferred aerobic exercise (ArmSwing) when playing for an extended period of time. The results suggested that if playing for a short period, 56.7% of users chose strength exercise (Squat) because they felt high exertion. However, there were still 40% of users preferred aerobic exercise (ArmSwing) as it required less exertion and was more comfortable. Moreover, if users preferred aerobic exercise, they preferred strength exercise also.

The virtual running design can further develop in RPG exergames. The results suggested that alternating postures should be implemented in the design to avoid feeling bored while also reducing injuries from the same pose for a long time and supporting the challenge to exercise. The design and development of VR exergames should entertain players with acceptable exertion and timing to encourage exercise by considering posture while playing. Future work should focus on redesign virtual running extended to whole postures (including aerobic, strength, flexibility, and balance) to design virtual running postures for RPG exergames with the appropriate time and fit for the physiology of each user.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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