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ORIGINAL ARTICLE

Ellic's Exercise Class: promoting physical activities during exergaming with immersive virtual reality

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Abstract
This work presents the design and evaluation of a set of three mini exercise games (exergames), called "Ellic's Exercise Class," which allows people to play in virtual reality (VR) using a head-mounted display (HMD) with the intention to promote physical activities. The exergames require the player to move hands, arms, and body to interact with sporting gameplay events. The game design methodology considers both display advantages and physical limitations in VR technologies. The games are evaluated in a usability study with the goal to understand participants' performance, gaming experience, effectiveness in motivating them to move, and their exercise intensity levels. In the study, we compare play of games in a VR environment simulated through an HMD with the play in front of a standard large flat-screen display (LFD), while ensuring the difficulty level of gameplay to be same in both. The participants' moving distances and their answers in questionnaires show that they become more active and engaged when playing exergames with HMD, but according to heart rate data, there is not significant evidence that playing with HMD would be better than that with LFD in terms of increasing the energy expenditure. We discuss the findings in accordance with the relationship and independence between engagement and exertion in exergaming.

Keywords Exergaming · Virtual reality · Entertainment computing · Human–computer interaction

1 Introduction

An exergame requires a player to move the hands, arms, and body to operate the game. Such physical movements can help improve a player's energy expenditure (Graf et al. 2009; Biddiss and Irwin 2010; Lyons et al. 2011) and increase the player's enjoyment (Lyons et al. 2012; Paw et al. 2008), as compared to stationary games which do not intend the player to move. The design of an exergame is usually based on the rules of real-world exercises. Many existing exergames use flat-screen displays, which do not allow a free-view navigation like people would have in a real-world exercise. Freina and Canessa (2015) mentioned that the ability to exercise is supported by human instincts to understand the spatial relationship between objects and cognitive distance. In virtual reality (VR), the viewpoint provides a stereoscopic vision, and it can copy the player's head movement, so that it mimics a situated and free-view navigation. These features of VR technologies make the gaming experience more instinctive and hands-on, take a more natural use of human's spatial abilities, and therefore have the potential to promote physical activities during exergaming.

In this work, we design, implement, and evaluate three exergames called "Ellic's Exercise Class." Each one is a single-player game. We use a head-mounted display (HMD) device, which simulates an immersive virtual environment and provides the player a plug-and-play solution at a low cost. In comparison with non-HMD VR systems such as head-tracked displays (HTDs), the HMD is easier to set up and maintain (Nunes de Vasconcelos et al. 2019), and it is more suitable for creating personal experiences with immediate surroundings (Mestre 2017). We want to understand whether the HMD-based VR technologies will facilitate a

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positive attitude and a motivated playing behavior, especially when playing an exergame that requires full-body motions. Existing research work has argued that a large flat-screen display (LFD) can enhance gaming experiences (Lin et al. 2006; Finke et al. 2008; Rice et al. 2011). To achieve an immersive experience of exergaming, a LFD may range from at least a 40-inch TV to a wall-sized projection display. In this work, we want to find out whether playing exergames through an HMD will gain a higher exercise intensity level than playing with a wall-sized LFD. Our game design methodology considers the characteristics of display devices and limitations in physical-virtual separation. We set the same difficulty level of gameplay and same play duration for the VR version (with HMD) and non-VR version (with LFD) of the games. The usability study evaluates participants' performance, gaming experiences, effectiveness in motivating them to move, and their exercise intensity levels. We discuss our findings in accordance to the relationship and independence between engagement and exertion in exergaming.

2 Related work

Shaw et al. (2015a) presented some challenges in VR-based exergame design. Related to this work, this section discusses physical movements as gaming input (see Sect. 2.1) and different display systems for exergaming (see Sect. 2.2).

2.1 Physical movement design

Altamimi and Skinner (2012) presented a comprehensive survey about exergames, including the topics of game engagement, input techniques, applied areas, etc. Different from the use of joysticks in stationary games (button-press games), exergames usually use hardware such as accelerometers, cameras, and pads/mats to track players' motions and use them as input in games (Stach et al. 2009); therefore, they enable players' exercises such as gestural motions and energy expenditures.

As regards the design of physical movements in video games, Bianchi-Berthouze et al. (2007) showed the evidence that the use of the players' physical movements as gaming input may increase their feelings of presence. Gao and Mandryk (2011) presented a casual exergame called "GrabApple." They used a Kinect to capture body movements. By jumping, ducking, and moving, the player was able to use a virtual hand in the game to grab falling apples. Reilly et al. (2013) designed an office exergame for people to practice regular body movements in good postures. The game used external sensors to track the player's wrist, neck, and body stretching movements. Mueller and Isbister (2014) presented a set of general and practical guidelines for the design of movement-based games, which are highly applicable to the movement design in exergaming. They expressed that the movements should be associated with appropriate feedback and with certain levels of bodily challenges to the player. Krause and Benavidez (2014) discussed how exergaming could affect physical activities and sports in the future, especially for young people at school ages. The authors expressed that the design of movements and exergames should promote players' self-efficacy beliefs and therefore increase their future participation. Lyons (2015) discussed the energy expenditure with different types of exergames. They concluded two findings: (1) faster physical movements would result in a greater energy expenditure in aerobic games and (2) precise movements would result in better performance than faster movements in balance games. Skjæret-Maroni et al. (2016) analyzed the movement characteristics of older adults and found that the choice of exergame and the difficulty level of play affected older adults' movements during the play. Castañer et al. (2016) proposed a systematic observational method to analyze sequential body movements of children to understand the quality of physical activities. The method was able to aid the exergame design and have the game mechanics elicit the desired quality of physical activities. Hansberger et al. (2017) studied the physical exertion of gesture-based interactions. The user study was performed using a gesture-based video game, yet the evaluation focused on the fatigue and discomfort of mid-air hand and arm gestures, rather than physical exercises. Tece Bayrak et al. (2020) presented a game design strategy that incorporates the rehabilitation requirements, patient condition, and player affordances, and therefore the design strategy established a relationship between the exercise rehabilitation regimen and gameplay.

In this work, the physical movements performed by players are arm, leg, and upper body movements, which are simple and easy-to-learn. We carefully control the difficulty level of play and the play time to provide players a fast-action experience but at a low level of exercise intensity, which will be similar to a casual workout.

2.2 Display systems

The choice on the type of display systems impacts the user presence in immersive environments, and it is an important design factor in exergaming. Cummings and Bailenson (2016) conducted research on the effects of immersive technologies for user presence, and they found that the display systems that use stereoscopic visuals and wider fields of view have a more significant impact on user presence than other technical aspects of immersive technologies. Related to our work, we review some exergaming work that have used VR displays and non-VR alternatives. HTDs and HMDs are two VR display systems supporting head-tracking and stereoscopic visuals (Southard 1995; Kessler et al. 2000). In this section, we looked into three types of display systems, including flat-screen displays (without head-tracking and stereoscopic visuals), HTDs, and HMDs.

2.2.1 Flat-screen displays

Rice et al. (2011) studied the usability and acceptability of gesture-based games for older adults using a large projection-based display device. They used a rear projector projecting the games on a wall-sized screen, which increased the immersiveness of the display and gave the participants a feeling of presence. Kim and Sundar (2013) studied the state of aggressiveness of players in violent video games, with the comparison between the play with a large screen (a 42-inch LCD monitor) and realistic controllers and the play with a small screen (a 27-inch LCD monitor) and a conventional mouse control. They concluded that “controller type and screen size have a significant psychological impact on gamers’ perceived levels of presence and arousal.” Schneider and Graham (2015) developed a video game for cycling exercises. In the game, the player controls an aircraft to race with a computer-controlled bird. The player uses a handheld joystick to control the moving direction and performs cycling motions to power the aircraft up. In the study, the game was displayed on a TV screen. The evaluation results showed that the game was able to improve the participants’ cycling performance, but there was no discussion about potentials with other types of displays.

2.2.2 HTDs

While both HTDs and HMDs can track head movements and support stereoscopic visuals, one difference between HTDs and HMDs is that the HTDs use stationary displays, such as large displays, polarized 3D systems, and Cave Automatic Virtual Environments (CAVEs). López et al. (2012) used the camera of a mobile device for head-tracking and interactions with the stereoscopic visuals on a LCD screen. However, comparing to CAVEs, the immersive experience with the mobile HTD was limited. McMahan et al. (2006) investigated the effects of immersion and interaction techniques in an immersive environment. Their study was based on general 3D manipulation tasks. They used a 4-screen CAVE^{TM} system comprising three sides and one floor. Participants were moving their bodies and arms to accomplish the tasks, but those movements did not contribute to exercises. Finkelstein et al. (2011) designed and implemented the “Astrojumper,” which is an exergame in an HTD system composed of three $8' \times 6'$ projection displays. Later, a new version of the “Astrojumper,” called “Astrojumper-Intervals,” was developed for the studies in Nickel et al. (2012) and Nickel et al. (2012b). This new version was compared to the original Astrojumper exergame with respect to players’ energy expenditures and heart rates. Finkelstein et a. (2013) used the “Astrojumper” to help children with autism, intending to engage them in vigorous exercises and thus leading them to live in a more healthy style. In their experimental study, the game was run on “an immersive surround-screen display system comprising three 2.44 m × 1.83 m *rear-projected stereoscopic screens, each of which used two Barco Gemini projectors to display the images for each eye.”*

2.2.3 HMDs

Tanaka and Hirakawa (2016) developed a VR system with an Oculus Rift HMD and a Kinect V2 sensor for the strength training in fitness. The design methods and gameplays were presented and evaluated in the paper, but they were not evident to the effectiveness of the system in motivating or assisting users in physical exercises. Eckert et al. (2017) designed a VR-based exergame using a Kinect and an Oculus Rift HMD, for the users who are physically impaired. The games were proved to be good for enhancing weak user movements, but the evaluation results did not show evidence of enhancing general and normal exercises. Yoo et al. (2017a) studied the gap between the player’s actual exercise intensity level from physical activities and the perceived exertion during the play of VR-based exergames. They used an HTC Vive HMD in the study. The results showed that the VR-based games were engaging and provided enough exertion for exercising; however, it was not very clear that the reason of providing enough exertion was because of the use of VR or the success of game design. Yoo et al. (2017b) designed a model that represents users’ exertion and performance in VR-based exergames running on an HTC Vive HMD. The model was able to recommend games, personalize games, and allow users to track their exercises, from which a foundation for long-term user modeling could be built. Yoo et al. (2017c) discussed the importance of personalizing a VR-based exergame in order to avoid the risk of under-exercising or over-exercising. They used an HTC Vive HMD. They proposed a strategy to adjust the game difficulty dynamically based on the player’s game performance and level of exertion. They also provided recommendations for designing VR-based games. Barathi et al. (2018) proposed an interactive feedforward method enabling a self competition in VR exergaming to improve players’ performance. They used an HTC Vive HMD. The evaluation results showed that the interactive feedforward method was effective in terms of maintaining players’ intrinsic motivation, but their work explored only a single exergame without the capability to interact with in-game objects.

2.2.4 Comparison with different types of display

Some existing studies have evaluated the effects of different types of display systems for exergaming.

Yoo and Kay (2016) presented a VR-based run-in-place game that motivates the player to perform running in virtual environments. The evaluation results showed a comparison on activity effectiveness with an HMD (using an HTC One mobile device in a Google cardboard), a LFD (a wall-sized projection on a wall-mounted canvas), and a baseline laptop display (a screen size similar to the MacBook display monitor). Their VR game design was similar to a walk-through application. It could be useful for rehabilitation or healthcare, but it is not aligned with the context of fast-actions or intensive body movements presented in common exergames such as Wii Sports and Kinect Sports. Amresh and Salla (2017) designed and set up a home-based VR cycling exergame using a spin machine. They did a usability test to compare the VR version and non-VR version of the game. The VR version used an Oculus Rift HMD, and the non-VR version used a laptop monitor with the screen size similar to an HD LCD display on a modern cycling machine. They concluded that the VR version enhanced the overall workout experience. Buttussi and Chittaro (2018) studied the effects of three different displays on user presence. The displays included a standard desktop display (an ASUS VX279H 27" display with 1920×1080 resolution), an HMD with a narrow field of view (a Sony HMD with 1280×720 resolution for each OLED display and 45° field of view), and an HMD with a wide field of view (an Oculus HMD with 1920×1080 resolution for each OLED display and 100° field of view). The study used a serious game providing the experience of a full emergency evacuation. Although it is not an exergame, the evaluation results on the display's efficacy for user presence are applicable to the design of exergames.

In this work, given the focus on immersiveness, we design, develop, and evaluate the exergames using an Oculus Rift HMD with the goal to promote physical activities, in comparison with the efficacy of physical activities in a wall-sized projection display during the play of the same exergames. Although a few VR-based fast-action exergames are available on the market such as Robo Recall (Wu et al. 2016) and VR Baseball (Rank17 2017), their usability and exercise intensity levels have not been evaluated in comparison with any non-VR display forms. In this work, participants play the same exergames in the VR environment with an HMD and on the wall-sized screen with a LFD. The gaming performance is optimized to the best for the user control and display of their forms.

3 Game design

Many studies in VR systems have been observed as task-specific evaluations (Saposnik et al. 2010; Lange et al. 2012; Shin et al. 2014; Larsen et al. 2009). In accordance to this observation and the literature about game design (e.g., Zyda 2005; Schell 2014) and gamification (e.g., Deterding et al. 2011; Peng et al. 2017; Cao et al. 2019; Molina-Carmona and Llorens-Largo 2020), we designed three mini exergames called "Ellic's Exercise Class." Ellic is a cartoonish elephant character who will guide and assist the player in the games.

Performance in exergames can be largely impacted by the player's motivation [e.g., winning orientation vs. goal orientation (Gill and Deeter 1988)]. Hence, it is important to understand the target group of people and define what motivations they would have when playing the games. For our games, we target for the group of people who need physical movements for general fitness. We want people to have a fun and immersive experience with the games, get motivated to perform extension and flexion movements, and therefore improve their energy expenditures. The games inspire a desire of general physical exercises, rather than for health recovery (e.g., rehabilitation). During the play, the attention of a player will be diverted to how to stand out in the games. The player will unconsciously gain some bursts of energy by consciously performing exercise-inspired gaming actions to achieve high scores.

The games can be played with two different display devices: one is an Oculus Rift HMD, and the other one is a LFD from a wall projector. Both use a pair of Oculus Touch controllers as the game control device. The games are implemented using the Unity 3D game engine and C# scripting language. Environmental assets are obtained from the Unity asset store. The game system starts with a main menu, in which a player can cycle through all three exergames by moving the thumb stick of the Oculus Touch left or right. The player presses the confirm button on the Oculus Touch to start the selected game. The duration of each game is two minutes. The score table will be displayed on the screen after the two-minute play. The player can exit the game at any time if he or she does not want to continue. Each game has a tutorial session before the actual play, instructing the player how to play the game. Figure 1 shows arm, leg, and body movements in correspondence with gameplay activities.

3.1 Design of gameplay

Psychological researchers have raised concerns about attention and distraction in VR (Czub and Piskorz 2014;

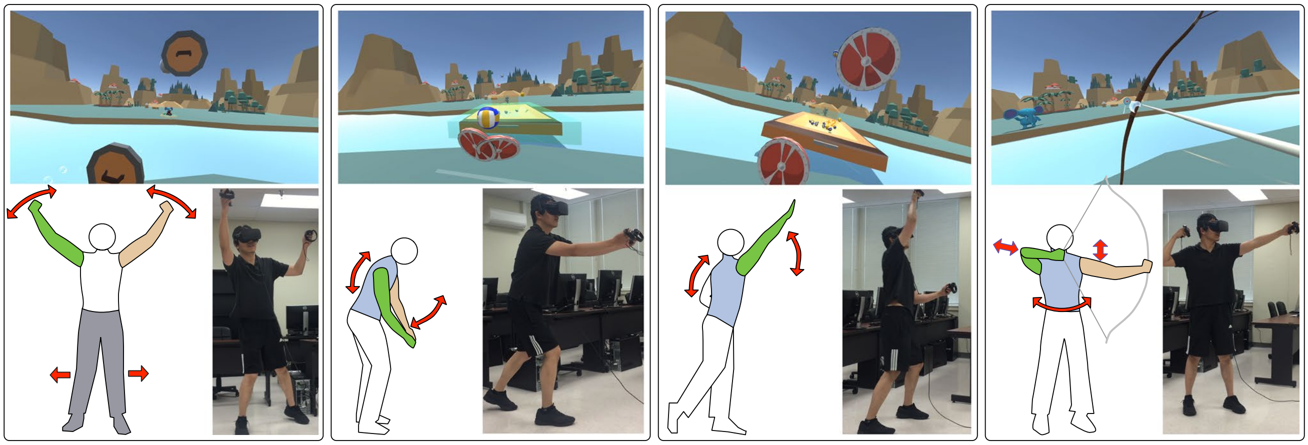

Fig. 1 Diagrams showing arm, leg, and body movements in correspondence with gameplay activities. **a** Movements designed for the blocking game. **b** and **c** Movements designed for the volleyball game. **d** Movements designed for the archery game. The top image inside each diagram is the screenshot at the moment when the player performs the corresponding body and arm movements

Olk et al. 2018). In a VR-based exergame, while the immersive experience draws players' attention, it may distract players from the main task. Shaw et al. (2015b) found that, in the exercycle game, participants had a slight preference for the traditional monitor display. They suggested that it is because the monitor offers a third-person view which improves the control of the virtual exercise bike. In our design, we make target objects in the games obvious to the player. Some objects such as balls are textured with glowing and vivid colors, and some other objects such as the archery target can move at a slow and constant speed, so that objects can be easily identified, and the player can respond quickly to gaming events. If the player does not play actively, for example, lagging on movements or tending to aim but being off the mark constantly, Ellic will post encouraging messages in a pop-up dialog box.

To mitigate possible symptoms of motion sickness in VR, we improve the rendering performance of the games. Game objects are cartoon-looking, low-polygon meshes and simple textures, which reduce the rendering load and create a joyful gaming atmosphere. In all three games, the total number of triangles is less than 300 thousands and the meshes (including UI elements) are textured with about 100 images, so that the games run at very high frame rates. We limit scene oscillations on different axes when the player is controlling the camera. The camera's roll rotation is disabled, since it could make the player feel the scene shakes when moving the body or head frequently during the play. Another way to reduce motion sickness is to reduce sensory disconnect (Shaw et al. 2015a) by making the motions perceived visually same as those in the inertial system. Toward this, our design maps the movements of hands and arms to in-place gameplay actions, such as blocking, hitting, and shooting, rather than conducting an intensive walk-around exploration of the virtual world.

The interface and in-game information (e.g., the timer and scores) are displayed in the same way in the HMD and LFD versions of the games. In both versions, hand motions are mapped onto the virtual hands. The player can see the rendering of virtual hands which help identify its spatial relationship with in-game objects. However, the perceived rendering can be different in the HMD and LFD. The camera in the HMD moves in response to the head movement, while the camera in the LFD is static. The HMD has a wider field of view than that of the LFD, so the player can see more in the HMD. In the LFD, the rendering of virtual hands is displayed on a projector screen, which may make the player feel the virtual hands are at a greater distance than those in the HMD.

3.1.1 Blocking game

A virtual wall composed of 5×10 translucent colorful cubes is created behind the player's avatar. Ellic stands at a distance and shoots balls with a cannon toward the cubes. The avatar holds two shields in hands. In order to protect the cubes from being hit by balls, the player moves the hands, arms, and body to block balls away, as shown in Fig. 1a.

Ellic can shoot regular balls and special balls. Special balls can damage a larger region on the virtual wall or are more challenging to block than regular balls. There are three types of special balls: a giant ball that can hit multiple cubes at once, a triple-shoot ball requiring the player to block three times in a row, and a naughty ball with wobbling motions. The ball's initial force and shooting direction are generated using physics simulations in the Unity game engine. The score of the player's performance is a percentage value, calculated as $\frac{\text{\# of ball blocked}}{\text{total \# of balls}} \times 100$. In this game, fast reactions and wide-field movements are primary motions that the player is expected to perform.

3.1.2 Volleyball game

Ellic throws volleyballs to the avatar. A basket is placed in front of the avatar. The player moves the arms and body as shown in Fig. 1b, c to bounce or spike balls. The player earns 1 point if the ball goes into the basket. After every four balls, Ellic throws a bonus ball. The player earns 2 points if the bonus ball goes into the basket. The player earns 0.5 point if the ball is hit but not bounced into the basket. The score of the player's performance is the sum of all points that the player earns.

In this game, the player is expected to move the body and adjust arm positions in order to bounce or spike balls accurately. To achieve a good score, the player needs a good sense of the controller's sensitivity for bouncing or spiking balls.

3.1.3 Archery game

In this game, the player shoots arrows to a moving target. The player needs to keep turning the body and adjusting arm positions in order to aim the target and then moves the arms as shown in Fig. 1d to shoot an arrow. If the arrow hits the target, the player gains 0.5 to 2.5 points based on how far away the hit is from the center of the target. The score of the player's performance is the sum of all points that the player earns. The flight path of the arrow is determined by physics simulations in the Unity game engine. The head and tail of the arrow are added with different mass and air resistance. The hand positions and the distance between two hands determine the arrow's initial flight angle and the launch force. The player is expected to focus on how to accurately aim the target, by holding the bow stably while slowly turning the body toward the moving target. Assuming the player's dominant hand is the right hand, here are the action steps to shoot an arrow:

1. The player uses the controller in the left hand to hold the bow and aim the target.
2. The player uses the controller in the right hand to pick up the arrow, by holding down the trigger of the controller. Then, he or she moves the controller to put the arrow on the bow.
3. The player pulls the right arm to the chest and then releases the trigger of the right-hand controller to launch the arrow.

3.2 Game mechanics

Figure 2 shows four major components of the game mechanics. The left- and right-hand controllers detect positions, rotations, and velocities of the player's hands. Physical hand movements are mapped onto the avatar's virtual hands.

Ellic is an AI-controlled character as a fitness coach in the games. Ellic takes the following responsibilities:

1. Ellic interacts with the player such as throwing volleyballs. Ellic is controlled by a continuous and circular AI module, which results in random actions. In particular, the AI module determines Ellic's rotating range, randomizes its rotating speed, the angle and power for throwing balls, and controls the throwing frequency. The results of AI are also affected by the progress and performance of the player in the game.

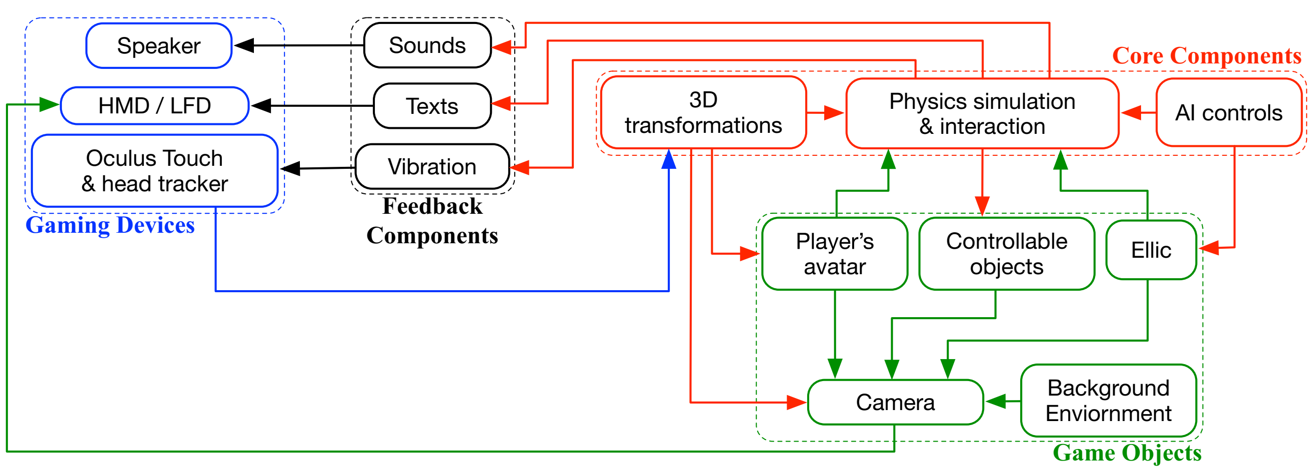

Fig. 2 The four gameplay mechanics components, including gaming devices, core components, game objects, and feedback components

2. During the tutorial session, Ellic demonstrates what movements the player should do. The movement demonstrations are programmed in C# scripts.
3. During the play, Ellic can teach the player how to play, as necessary. A conditional strategy is used to determine if the player needs help or not. For example, in the archery game, if the player does not shoot an arrow in 15 seconds, Ellic explains how to shoot it.

Motions of controllable objects such as balls and arrows are simulated with physics simulations. They correspond to realistic collisions and interactions. For example, in the volleyball game, the player may bounce a ball at its bottom or spike it from the top. The ball reacts according to the gravity, hit points, collisions, and the force added by the player.

Exergames need to promote tension and require a fast reaction of the player. To support this, an immediate feedback system is added in the game. It includes vibration, sounds, and texts. Vibration is added on the controllers and triggered when the player has a contact with an object. The vibration intensity is determined based on the force intensity generated at the contact. Sounds are transmitted to the speaker when an object is hit by the player or a new object is instantiated. Texts are used to show earned points and Ellic's messages. Earned points are displayed next to a hit object, and messages can be displayed in the pop-up dialog box above the Ellic.

4 Experiment

We performed a usability study using the exergames described in Sect. 3. Figure 3 shows the pictures of the usability study. In the study, we used an in-game version of the game experience questionnaire (GEQ) (IJsselsteijn et al. 2013). Law et al. (2018) pointed out the problematic psychometric properties in the GEQ, but it is still one of popular questionnaires to measure game players' experience. Sabet et al. (2019) also evaluated the GEQ and suggested that it should not be used in a long-duration experiment. In our study, the duration is short.

Participants play the games under the same gameplay conditions. For each game, the parameters that control the gameplay difficulty level, such as gaming time, the number of balls launched, the moving path of the archery target, etc., are set to be same in the HMD and LFD versions. Specific values of the control parameters are discussed together with participants' gaming experiences in Sect. 5.1. In this section, we describe details of the experiment.

4.1 Demographic

Participation of the study is voluntary. We recruited a total of 20 participants including 11 males and 9 females. Their ages are between 18 and 37 ($M = 25.35$, SD = 4.79). Six participants have the experience of playing VR video games, and the other 14 participants had never played a VR game. In regard to their exercise background, 3 participants exercise daily, 13 participants exercise weekly, and 4 participants almost do not exercise at all. Six participants expressed that they are good at sports, 8 participants are moderately good at sports, 5 participants are skilled in sports, and 1 participant expressed no sport skill at all.

4.2 Methodology

We set up the usability study in a research laboratory in the university. We obtained the approval for the study from the university's Institutional Review Board of Human Subjects Committee. The study took about one hour for each participant. Upon arrival, the participant filled a consent form and was assigned with a unique participation ID. He or she then answered a demographic questionnaire, which includes the questions related to participant's experience in gaming, virtual reality, and exercise. Then, the participant wore a Fitbit device in order to monitor the heart rate, which was turned on when the participant was ready for the games. The heart rate is related to the amount of calorie burning,

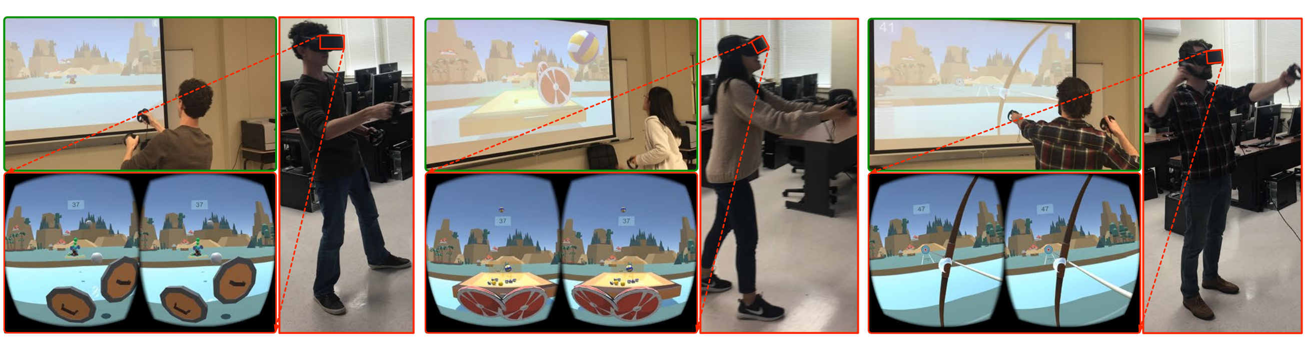

Fig. 3 Pictures of the usability study showing the participants played the exergames with the HMD (right and bottom-left pictures with red frames) and LFD (top-left pictures with green frames)

so it is an important factor for measuring the level of energy expenditure and exercise intensity. Before playing any game, there was a session for each participant to get familiar with the use of Oculus Touch controllers and the display devices.

The study included a total of 6 trials (3 games × 2 display devices). In each trial, the participant played one game with one type of display device, either an HMD or a LFD. After playing the game in the trial, the participant filled an in-game GEQ. There was a 5-min break between trials. If a participant's ID is an odd number, he or she first performs the three trials that use the LFD, and then performs the other three trials that use the HMD. Participants with even IDs first perform the three trials that use the HMD, and then performs the trials that use the LFD. After every three trials, the participant filled a core GEQ, each for one display device across all three games. At the end of the study, the participant was asked to give overall evaluations of the study by answering a few interview questions.

As a result, we received a total of 10 questionnaires from each participant, including 1 demographic questionnaire, 6 in-game GEQs, 2 core GEQs, and 1 interview questionnaire. In total, we collected 200 questionnaires from all participants.

4.3 Data recording

The gaming system is able to record data items for evaluation and analysis, as listed below:

1. Gameplay-related items, including (1) the blocking game: the number of balls shot, the number of balls blocked by the player, and the total score that the player earned; (2) the volleyball game: the number of balls thrown, the number of balls hit by the player, the number of balls bounced into the basket, and the total score that the player earned; and (3) the archery game: the number of arrows shot, the number of arrows hit on the target, and the total score that the player earned.
2. The total distance of hand movements computed by summing up hand position offsets detected by the Oculus Touch controllers between successive frames.
3. The heart rates tracked by the Fitbit device.

4.4 Safety and protection

All participants had understood how to play the games before doing the trials. We set up a restricted zone in the virtual world. The zone was calibrated to match the boundaries of the physical space, so participants did not have a risk of hitting surroundings. Objects can be interacted with or controlled only in the zone. If a participant steps out the zone, a warning message will show on the screen. During the experiment, an investigator stood close to the participant to protect him or her, in the case of the occurrence of any unbalanced body movements.

5 Results and analysis

Both the core GEQ and in-game GEQ were used to evaluate participants' gaming experiences. We conducted a one-way analysis of variance (ANOVA) to analyze the effect of gameplay scores, GEQs, moving distances, and heart rates between two groups, HMD and LFD. All statistical results were based on the significance value of $\alpha = 0.05$.

5.1 Performance and gaming experience

Table 1 shows the comparison results between the participants' HMD experimental data and their LFD data. For the blocking game, the total number of balls launched by Ellic was fixed at 122. The "Blocked" column in the table means the averaged number of balls blocked by participants. The averaged score that the participants earned with HMD ($M = 86.02$, SD = 9.36) was significantly higher than that with LFD ($M = 52.21$, SD = 12.33), $F(1, 38) = 95.38$, $p < 0.001$. On average, wearing the HMD increased participants' performance by 33.82%. For the volleyball game, the total number of balls launched by Ellic was fixed at 66. The "Bounced-In" column in the table means the averaged number of balls bounced or stroke into the basket by participants. On average, wearing the HMD increased participants' bounced-in rate by 42.80%. For those balls not going into the basket, participants either reached or completely missed them. The "Missed" column in the table means the number of balls completely missed. Participants reached 11.96 more balls (or 18.12% more) on average when wearing the HMD. The averaged score that the participants earned with HMD ($M = 62.00$, SD = 9.23) was significantly higher than that with LFD ($M = 36.50$, SD = 8.29), $F(1, 38) = 82.46$, $p < 0.001$. For the archery game, the "Score" column is the averaged total point that the participants earned. The averaged score with HMD ($M = 74.18$, SD = 35.15) was higher than LFD ($M = 40.85$, SD = 19.34), $F(1, 38) = 13.80$, $p < 0.001$. Thus, wearing the HMD to play the exergames made the participants gain a significantly better gameplay performance than playing with LFD. With LFD, the virtual hands are displayed on the projector screen, which may make the player feel the virtual hands appear a bit far away from where the physical hands are. This can be a reason why the gameplay performance in the LFD version was worse than that in the HMD version.

According to the explanation by Poels et al. (2007), questions in a GEQ cover seven evaluation components, which are *Competence*, *Sensory and Imaginative Immersion*, *Flow*, *Tension/Annoyance*, *Challenge*, *Negative Affect*, and *Positive*

Table 1 The experimental results of three exergames recorded for evaluating the gaming experience

	Blocking game				Volleyball game					Archery game			
	Blocked (avg. #)	Total	Blocking rate (%)	Score (avg. #)	Bounced-in (avg. #)	Missed (avg. #)	Total	Bounced-in rate (%)	Score (avg. #)	Hit (avg. #)	Total shots (avg. #)	Hit rate (%)	Score (avg.)
HMD	104.96	122	86.03	86.03	43.60	0.80	66	66.06	62.00	43.36	55.06	78.75	74.18
LFD	63.70	122	52.21	52.21	15.36	12.76	66	23.27	36.50	26.40	42.56	62.03	40.85

Affect. The in-game GEQ includes 14 questions, and the core GEQ includes 33 questions. Participants answered each question by giving a score between 0 and 4 which represents the lowest rate to the highest rate for the question. Table 2 shows the averaged scores and how the questions are mapped into the seven components. For Sensory and Imaginative Immersive, we have $F(1,38)=4.61, p=0.04$, and for Flow, we have $F(1,38)=4.79, p=0.03$. Since the p values are smaller than 0.05, wearing the HMD resulted in a significant enhancement over LFD in those components. For Competence, we have $F(1,38)=2.71, p=0.11$, and for Positive Affect, we have $F(1,38)=3.63, p=0.06$. The p values are slightly larger than 0.05 but still close to it, so wearing the HMD was likely to have a significant enhancement in those components. For Challenge, we have $F(1,38)=0.12, p=0.73$, for Tension, we have $F(1,38)=0.54, p=0.47$, and for Negative Affect, we have $F(1,38)=0.51, p=0.48$. The p values are greatly larger than 0.05. Thus, there was not a significant enhancement in those components.

From the above analysis, we reach the conclusion that for exergames where players' motions are more or less in-place actions in the real and game world, and where the game control device and interface design are the same (e.g., using the same handheld controller and no additional visual aids in non-VR display), HMDs will result in a better game experience. A main drawback of using LFD is that a player has to spend extra cognitive efforts to understand the relations between the physical movements and transmitted controlling behaviors in the virtual environment, which is a 3D world but projected to the 2D viewport on the LFD. This process with LFD increases the player's cognitive load and consequently increases the player's reaction time to operate objects. In contrast, the HMD provides an immersive 3D environment that can intuitively engage players. The HMD's stereoscopic rendering capability provides a better depth awareness for the player to justify and estimate events at a natural level of visual perception as they do in the real world. This reduces the chance of having cognitive loading latency. Also, the head tracker on the HMD provides the naturalness for the first-person camera control. The camera moves and rotates together with the player's head, so that it removes unnatural viewing experience occurring in a fixed or auto camera, which, however, exists in LFD-based games.

5.2 Effectiveness in motivating players to move

We measured the motivational effectiveness of the games by using the hand moving distance accumulated from the position changes of the hand controllers. One goal of the exergames is to motivate players to move and make them actively participate in the activities simulated by the gameplay mechanics. We used Oculus Unity SDK in our

Table 2 The GEQ data collected from the participants

Components	(Core #, in-game #)	Questions	In-game GEQ						Core GEQ	
			HMD			LFD			HMD	LFD
			Blocking game	Volleyball game	Archery game	Blocking game	Volleyball game	Archery game		
Competence	(2, 9)	I felt skillful	2.55	2.45	2.80	2.05	1.85	2.20	2.65	2.20
	(10, –)	I felt competent	–	–	–	–	–	–	2.60	1.95
	(15, –)	I was good at it	–	–	–	–	–	–	2.65	2.50
	(17, 2)	I felt successful	2.65	2.70	2.80	2.40	2.05	2.30	2.70	2.30
	(21, –)	I was fast at reaching the game's targets	–	–	–	–	–	–	2.55	1.80
	Average		2.60	2.58	2.80	2.23	1.95	2.25	2.63	2.15
Sensory and imaginative immersion	(3, 1)	I was interested in the game's story	3.10	3.10	3.20	2.70	2.70	2.90	2.75	2.75
	(12, –)	It was aesthetically pleasing	–	–	–	–	–	–	2.70	2.20
	(18, –)	I felt imaginative	–	–	–	–	–	–	2.70	2.20
	(19, –)	I felt that I could explore things	–	–	–	–	–	–	2.75	2.00
	(27, 4)	I found it impressive	3.20	3.10	3.05	2.60	2.45	2.50	3.15	2.75
	Average		3.15	3.10	3.13	2.65	2.58	2.70	2.93	2.40
Flow	(5, –)	I was fully occupied with the game	–	–	–	–	–	–	2.95	2.65
	(13, 5)	I forgot everything around me	3.00	3.00	2.95	2.70	2.30	2.40	2.85	1.90
	(25, –)	I lost track of time	–	–	–	–	–	–	2.40	1.90
	(28, –)	I was deeply concentrated in the game	–	–	–	–	–	–	3.45	2.80
	(31, –)	I lost connection with the outside world	–	–	–	–	–	–	2.70	1.70
	(–, 10)	I felt completely absorbed	3.05	2.85	3.00	2.40	2.40	2.05	–	–
	Average		3.03	2.93	2.98	2.55	2.35	2.23	2.87	2.19
Tension/annoyance	(22, –)	I felt annoyed	–	–	–	–	–	–	0.35	0.20
	(24, 8)	I felt irritable	0.60	0.65	0.75	0.70	0.80	0.70	0.50	0.50
	(29, 6)	I felt frustrated	0.80	0.40	0.45	0.75	1.15	1.25	0.55	1.15
	Average		0.70	0.53	0.60	0.73	0.98	0.98	0.47	0.62
Challenge	(11, –)	I thought it was hard	–	–	–	–	–	–	1.50	1.85
	(23, –)	I felt pressured	–	–	–	–	–	–	0.85	0.60
	(26, 12)	I felt challenged	2.70	2.05	2.75	2.30	2.70	2.55	2.40	2.10
	(32, –)	I felt time pressure	–	–	–	–	–	–	1.25	1.15
	(33, 13)	I had to put a lot of effort into it	2.55	2.15	2.55	2.40	2.45	2.50	2.2	2.05
	Average		2.63	2.10	2.65	2.35	2.58	2.53	1.64	1.55

Table 2 (continued)

Components	(Core #, in-game #)	Questions	In-game GEQ						Core GEQ	
			HMD			LFD			HMD	LFD
			Blocking game	Volleyball game	Archery game	Blocking game	Volleyball game	Archery game		
Negative affect	(7, –)	It gave me a bad mood	–	–	–	–	–	–	0.25	0.30
	(8, –)	I thought about other things	–	–	–	–	–	–	0.60	1.20
	(9, 7)	I found it tiresome	1.45	0.95	1.30	0.75	0.90	1.05	0.85	0.85
	(16, 3)	I felt bored	0.75	0.60	0.55	0.65	0.70	0.70	0.50	0.50
	Average		1.10	0.78	0.93	0.70	0.80	0.88	0.55	0.71
Positive affect	(1, 11)	I felt content	2.95	2.90	2.90	2.20	2.45	2.40	3.10	2.50
	(4, –)	I thought it was fun	–	–	–	–	–	–	3.15	3.00
	(6, –)	I felt happy	–	–	–	–	–	–	3.30	2.85
	(14, 14)	I felt good	3.35	3.40	3.65	2.80	2.85	3.05	3.50	2.85
	(20, –)	I enjoyed it	–	–	–	–	–	–	3.40	2.90
	(30, –)	It felt like a rich experience	–	–	–	–	–	–	3.50	2.50
	Average		3.15	3.15	3.28	2.50	2.65	2.73	3.29	2.82

The "core #" and "in-game #" are the question IDs in the core GEQ and in-game GEQ, respectively

implementation. It allows to track the locations of hand-held controllers, with which we computed the moving distance of each hand. Table 3 shows the moving distances and the heart rates recorded from the participants.

Overall, wearing the HMD ($M = 323.47$, SD = 54.18) resulted in greater hand moving distances than using the LFD ($M = 259.57$, SD = 62.17), where $F(1, 38) = 12.01$, $p = 0.001$. The distance increase in the blocking game was 37.85%, where the increment of HMD ($M = 159.99$, SD = 42.08) over LFD ($M = 116.07$, SD = 38.70) was significant, since $F(1, 38) = 11.80$, $p = 0.001$. The distance increase in the volleyball game was 17%, where the increment in the distance with HMD ($M = 114.88$, SD = 21.99) was significant in comparison with the distance with LFD ($M = 97.80$, SD = 26.34), since $F(1, 38) = 4.95$, $p = 0.03$. The smallest distance increase occurred in the archery game, which was by 6.32%. In the archery game, the increment of HMD ($M = 48.60$, SD = 14.95) over LFD ($M = 45.70$, SD = 14.50) was not significant, since $F(1, 38) = 0.39$, $p = 0.54 > 0.05$. This is because the blocking and volleyball games require a player to react to balls quickly. We observed that participants performed more body movements to enhance such active reactions. The quicker and more frequent reactions a player performed, the higher increase was on the total moving distance, which happened more natural and intuitive in the immersive environment provided by the HMD. In the archery game, on average, the right hand moved more than the left hand. This is because all participants used the right hand to perform the motions of pulling arrows, while the left hand was used to maintain a still pose in order to aim the target. We also observed that the moving distance could be affected due to cognitive loads when the player was perceiving the mapping of real hand movements onto the virtual hands. The LFD version of the games likely causes a higher cognitive load for the player to make sense of the mapping, while the mapping through the HMD version was more intuitive and therefore makes players react to gaming events faster than doing in the LFD version of the games.

5.3 Exercise intensity level

The exercise intensity refers to the energy expended when exercising. We measured the exercise intensity using the heart rate data from the Fitbit device. The heart rate is the human's built-in system for measuring an individual's exercise intensity level. The heart rate data from our participants are shown in Table 3. From the data, we found that 4 participants retained a high exercising-level heart rate before starting a play trial. This was because the resting time between the trials was probably not enough for them to cool themselves down, or because they were in an excising activity before coming in our study but did not inform us about it. Thus, we excluded their data from the analysis of the exercise intensity. Figure 4 shows the heart rate data over the time of each game. The horizontal axis is divided into two parts in consistence with the setting of the play trials. The first part is the 30-second tutorial time for participants to get ready for the play, and the second part is the actual game playing time.

We also recorded participants' resting heart rate, which was 74.27 beats per minute on average. The resting heart rate was recorded with participants standing. It was at a slightly high end of the standard range of resting heart rate. The VR device was new to some participants, and the games were new to all participants. The resting heart rate was a bit high possibly due to participants' raising curiosity about the VR device and excitement to the games. During the play of games, participants' heart rates with HMD and LFD were both increased significantly over the resting heart rate (M = 74.27, SD = 8.47). For HMD, we have $F(1, 30) = 51.24$, $p < 0.001$. For LFD, we have $F(1, 30) = 50.13$, $p < 0.001$. Our exergames raised the participants' heart rate by an average of 31.25%. According to the explanation in Better Health Channel (2015)—an digital entity of the Department of Health and Human Services in Australia, a moderate-intensity physical activity for people at the age of 25 corresponds to a heart rate in the beat range of [98, 137] per minute. Regardless of using an HMD or LFD, the blocking and volleyball games have met this expectation, while the archery game did not but it was close to the low end of the range, since it was designed to be a relatively stationary game.

As shown in Fig. 4, during the tutorial time, the heart rates with HMD and LFD were stable with a slow rate of increase over time. During the game playing time, regardless of using an HMD or LFD, the heart rate jumped up quickly and became relatively stabilized after reaching the beat range of moderate-intensity. The figure shows that the heart rate with HMD was slightly higher than that with LFD. It was an average of 3.34% increment over the heart rate with LFD for all three games. According to the statistical analysis, we found that the increment of the heart rate with HMD (M = 98.01, SD = 10.21) was not significant in comparison with the heart rate with LFD (M = 94.84, SD = 7.96), since $F(1, 30) = 0.96$, $p = 0.34 > 0.05$. Thus, there was no evidence to show that the VR version of the games could advance the non-VR version in terms of increasing the exercise intensity level.

6 Overall feedback

At the end of the experiment, participants were asked to give scores for additional interview questions about their overall impression of the games, in which "1" is very negative and "10" is very positive. We asked the questions of "What is your overall impression of the games with HMD?" and "What is your overall impression of the games with LFD?" Participants gave an overall score of 9.25/10 for the games with HMD, and gave 4.90/10 for the games with LFD. We asked the question of "How tired do you feel after playing these exergames?" On average, the participants gave a score of 5.55/10, which indicates a moderate intensity level of exercising. For the question of "Would you like to play VR exergames for exercising in the future?", the participants gave a score of 9.60/10, and all participants expressed that they would like to try more exergames with HMD in the future.

As VR-based exergames are becoming an extra supplement for exercises, the games we developed would engage people to exercise in daily life and motivate people who do not do exercise very often. After our study, 11 participants expressed that they will buy an HMD device to play exergames in the future.

We received delightful feedback from participants about our games. For example, one participant said he was fully engaged, so he did not realize he was getting tired and forgot paying attention to the time. Another participant commented that he liked our exergames and enjoyed the gaming experience, but he was not in favor of wearing the HMD because he wore glasses. He expressed that the HMD was a little hard to put on or take off.

For the question of "Do you feel motion sickness during the usability study?", the participants gave an averaged score of 1.60/10. Some participants commented that they

Table 3 The heart rate and hand moving distance recorded during the experiment

	Blocking game				Volleyball game				Archery game			
	Moving distance (m)			Heart Rate	Moving distance (m)			Heart Rate	Moving distance (m)			Heart Rate
	Left hand	Right hand	Total		Left hand	Right hand	Total		Left hand	Right hand	Total	
HMD	146.19	173.80	319.99	100.38	91.35	138.40	229.75	101.59	28.48	68.72	97.20	92.04
LFD	107.90	124.24	232.14	97.37	81.90	113.70	195.60	98.71	32.92	58.48	91.40	88.44

All values are averaged over all participants

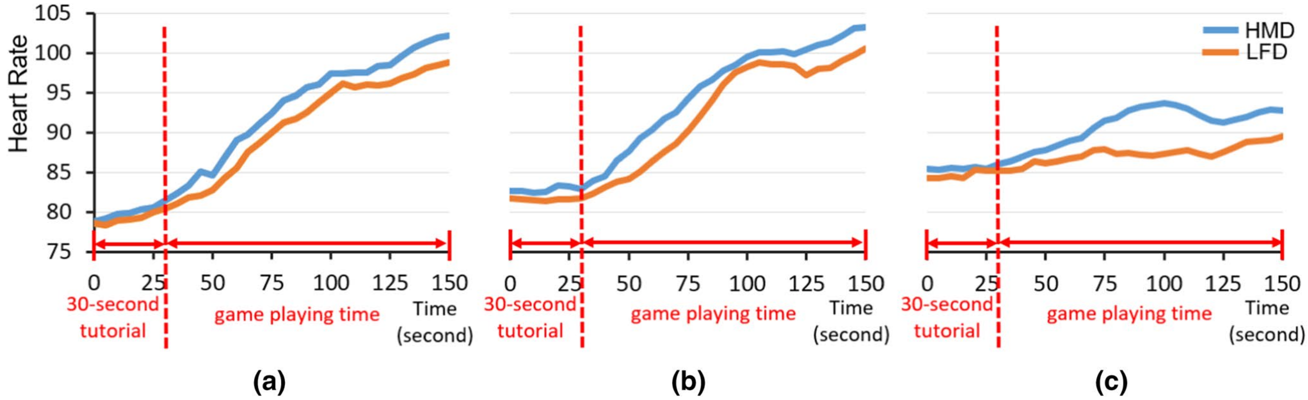

Fig. 4 Participants' average heart rate over time during the play. **a**–**c** Are the results from the experiment with the blocking game, volleyball game, and archery game, respectively

had motion sickness in other VR games, but they did not feel motion sickness in our games. Some participants also expressed that they would like to play more exergames such as baseball and tennis games with a multi-player option.

All participants finished the usability study without any risks. For the question of "Do you feel afraid of hitting surroundings during the usability study?", participants gave an averaged score of 3.40/10, which indicate they felt fairly safe to play the exergames with HMD and LFD.

7 Discussion and future work

Our work was to study whether or not applying VR technologies for exergaming would be generally effective in promoting people's physical activities and exertion. In particular, we were interested in knowing, in comparison with widely used flat-screen display devices, whether or not the newer immersive display provided by an HMD would constantly advance in exergaming, or it could be constrained under certain circumstances. We considered this is an important and fundamental question since VR technologies continue to be introduced into many exergames and used for fitness, training, rehabilitation, and education. Toward our goal, we designed and studied exergames in immersive virtual environments supported by the HMD and handheld controllers.

The three exergames required players to move in different ways: moving the body and hands sideways in the blocking game, bouncing and spiking in the volleyball game, and holding and pulling on arms in the archery game. Those exergames put core scenarios of aerobic exercises into practice, including reaction drills (blocking), movement control drills (volleyball), and stretching drills (archery). For each game we developed, we intentionally created an identical difficulty level of gameplay for both HMD and LFD versions of the games, so that the engagement and exertion comparisons were not affected by any variation in gameplay. We were aware of discussions in the literature about the symptoms of motion sickness caused by VR (Moss and Muth 2011; Treleaven et al. 2015). When designing and implementing the games, we added restrictions on certain mechanics features which could make players disoriented. For example, a roll rotation of the camera was disabled to make players stay balanced during the play. We textured the gaming scenes with intermediate and cool colors without any glare or reflectivity to reduce eye strains. In our experiment, we did not observe any participant being motion-sick during or after playing the games with HMD.

Our experimental results show that the immersive environment provided by the HMD resulted in more engaging experience than the environment with the standard large flat-screen; however, there was no evidence to show that wearing the HMD would be more effective than using the LFD in increasing the exercise intensity level. This suggests that players will feel more enjoyable when playing with HMD, so there can be a higher chance that players choose to play more trials of a VR-based exergame and subsequently improve their physical activities in the long term. If the goal is to use an exergame for exercising within limited time or a limited number of trials, the gameplay mechanics itself should be the factor that affects the energy expenditure, rather than the playing environment.

Possibly, it was an interesting observation that, when the difficulty level of gameplay and the play duration were set to be the same for playing with HMD and LFD, the moving distance with HMD was significantly greater than with LFD, but the increase in heart rates with HMD was not significant. In other words, playing the games with HMD better motivated participants to move physically, but they achieved a nearly same level of energy expenditure, regardless of using an HMD or LFD. This observation suggests that the VR version of an exergame can be used to better motivate people who do not usually engage in exercises than using a non-VR setting of the exergame. For example, a VR-based exergame can be more beneficial for non-motivated individuals in a warm-up trial or some low-level activities that are not much fun to perform, where VR technologies can make them be willing to repeat the movements for a longer period of time and possibly improve their motivations in those activities. This is supported by similar findings by Molina et al. (2014), where VR-based games were created to rehabilitate physical functioning of old adults with basic movements.

According to the analysis of the heart rate data and the feedback received from the participants, our exergames reached a moderate level of exercise intensity. The difficulty level of gameplay is determined by the control parameters of the game, which can be turned, so that the exercise intensity level can change accordingly from moderate to light, or to vigorous. In the future, we plan to add an AI component to automatically adjust the difficulty level of gameplay and the play duration based on a player's exercise capability. This can be achieved by taking the method presented by Xie et al. (2018). It will be possible for the AI component to analyze the gaming behaviors of the player and adjust the games dynamically to maximize the exercise effectiveness.

We found that, during the play, participants tended to move or lean in a particular direction. For example, some participants tended to move forward, while some others tended to move backward. If the movements required in a game are intense, the Guardian System provided by the Oculus VR SDK may not be sufficient to keep players in the safety zone. In the future, in the case of developing a vigorous-intensity version of the games, we will add additional run-time feedback features, such as warning sounds and controller vibrations, to enhance a player's safety awareness.

Motion sensing devices, like the Oculus Touch adopted in our exergames, have been widely used as game control devices to interact with game objects in the virtual world. It is possible that, after players become familiar with gameplay rules, they may seek a "lazy" way of using the device, so they do not spend enough physical efforts as they are supposed to (Sun and Lee 2013; Alex et al. 2017; Lee and Lim 2017). Evidences of seeking lazy ways to play exergames can be seen in commercial games like Wii Sports or Kinect Sports. In the future, we would like to investigate possible cheating plays in VR-based exergames.

The study had a total of 20 participants, which could be a limitation on the sample size. In the future, we want to collaborate with fitness experts to study the influence of VR-based exergames in aerobic fitness, especially on the trainee's long-term benefits. In future studies, we will invite more participants and give them longer time to play. We also plan to develop an HTD version of the exergames and evaluate it by comparing to the LFD and HMD versions, and find out whether the HTD version will have a similar benefit as that of the HMD version. Also, we will try to add a multi-player mode in the games, so that people at different places can play and exercise together. It will be interesting to see whether or not players become more excited with the support of a multi-user competitive spirit in VR.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

References

Alex M, Chen C, Wünsche BC (2017) A review of sensor devices in stroke rehabilitation. In: 2017 international conference on image and vision computing New Zealand (IVCNZ), pp 1–6

Altamimi R, Skinner G (2012) A survey of active video game literature. J Comput Inf Technol 1(1):20–35. https://doi.org/10.1371/journal.pone.0065351

Amresh A, Salla R (2017) Towards a home-based virtual reality game system to promote exercise. In: Proceedings of the 50th Hawaii international conference on system sciences. http://hdl.handle.net/10125/41240

Barathi SC, Finnegan DJ, Farrow M, Whaley A, Heath P, Buckley J, Dowrick PW, Wuensche BC, Bilzon JLJ, O'Neill E, Lutteroth C (2018) Interactive feedforward for improving performance and maintaining intrinsic motivation in VR exergaming. In: Proceedings of the 2018 CHI conference on human factors in computing systems, ACM, New York, NY, USA, CHI'18, pp 408:1–408:14. https://doi.org/10.1145/3173574.3173982

Better Health Channel (2015) Exercise intensity. https://www.betterhealth.vic.gov.au/health/healthyliving/exercise-intensity. Accessed 16 Mar 2020

Bianchi-Berthouze N, Kim WW, Patel D (2007) Does body movement engage you more in digital game play? and why? In: Paiva ACR, Prada R, Picard RW (eds) Affective computing and intelligent interaction. Springer, Berlin, pp 102–113. https://doi.org/10.1007/978-3-540-74889-2_10

Biddiss E, Irwin J (2010) Active video games to promote physical activity in children and youth: a systematic review. Arch Pediatr Adolesc Med 164(7):664–672. https://doi.org/10.1001/archpediatrics.2010.104

Buttussi F, Chittaro L (2018) Effects of different types of virtual reality display on presence and learning in a safety training scenario. IEEE Trans Vis Comput Graph 24(2):1063–1076. https://doi.org/10.1109/TVCG.2017.2653117

Cao L, Peng C, Hansberger JT (2019) Usability and engagement study for a serious virtual reality game of lunar exploration missions. In: Informatics, multidisciplinary digital publishing institute, vol 6, p 44

Castañer M, Camerino O, Landry P, Pares N (2016) Quality of physical activity of children in exergames: sequential body movement analysis and its implications for interaction design. Int J Hum Comput Stud 96:67–78. https://doi.org/10.1016/j.ijhcs.2016.07.007

Cummings JJ, Bailenson JN (2016) How immersive is enough? A meta-analysis of the effect of immersive technology on user presence. Media Psychol 19(2):272–309. https://doi.org/10.1080/15213269.2015.1015740

Czub M, Piskorz J (2014) Distraction of attention with the use of virtual reality. Influence of the level of game complexity on the level of experienced pain. Pol Psychol Bull 45:480–487. https://doi.org/10.2478/ppb-2014-0058

Deterding S, Dixon D, Khaled R, Nacke L (2011) From game design elements to gamefulness: defining gamification. In: Proceedings of the 15th international academic MindTrek conference: envisioning future media environments, vol 7. ACM, pp 9–15. https://doi.org/10.1145/2181037.2181040

Eckert M, Zarco J, Meneses J, Martínez JF (2017) Usage of VR headsets for rehabilitation exergames. In: Bioinformatics and biomedical engineering. Springer International Publishing, pp 434–442. https://doi.org/10.1007/978-3-319-56154-7_39

Finke M, Tang A, Leung R, Blackstock M (2008) Lessons learned: Game design for large public displays. In: Proceedings of the 3rd international conference on digital interactive media in entertainment and arts. ACM, New York, NY, USA, DIMEA'08, pp 26–33. https://doi.org/10.1145/1413634.1413644

Finkelstein S, Nickel A, Lipps Z, Barnes T, Wartell Z, Suma EA (2011) Astrojumper: motivating exercise with an immersive virtual reality exergame. Presence Teleoper Virtual Environ 20(1):78–92. https://doi.org/10.1162/pres_a_00036

Finkelstein S, Barnes T, Wartell Z, Suma EA (2013) Evaluation of the exertion and motivation factors of a virtual reality exercise game for children with autism. In: 2013 1st workshop on virtual and augmented assistive technology (VAAT), pp 11–16. https://doi.org/10.1109/VAAT.2013.6786186

Freina L, Canessa A (2015) Immersive vs desktop virtual reality in game based learning. In: European conference on games based learning, academic conferences international limited, p 195. https://search.proquest.com/docview/1728409770?pq-origsite=gscholar

Gao Y, Mandryk RL (2011) Grabapple: The design of a casual exergame. In: Anacleto JC, Fels S, Graham N, Kapralos B, Saif El-Nasr M, Stanley K (eds) Entertainment computing—ICEC 2011. Springer, Berlin, pp 35–46. https://doi.org/10.1007/978-3-642-24500-8_5

Gill DL, Deeter TE (1988) Development of the sport orientation questionnaire. Res Q Exerc Sport 59(3):191–202. https://doi.org/10.1080/02701367.1988.10605504

Graf DL, Pratt LV, Hester CN, Short KR (2009) Playing active video games increases energy expenditure in children. Pediatrics 124(2):534–540. https://doi.org/10.1542/peds.2008-2851

Hansberger JT, Peng C, Mathis SL, Areyur Shanthakumar V, Meacham SC, Cao L, Blakely VR (2017) Dispelling the gorilla arm syndrome: the viability of prolonged gesture interactions. In: Lackey S, Chen J (eds) Virtual, augmented and mixed reality. Springer International Publishing, Cham, pp 505–520

IJsselsteijn W, de Kort Y, Poels K (2013) The game experience questionnaire. Technische Universiteit Eindhoven. https://research.tue.nl/en/publications/the-game-experience-questionnaire

Kessler GD, Bowman DA, Hodges LF (2000) The simple virtual environment library: an extensible framework for building VE applications. Presence Teleoper Virtual Environ 9(2):187–208. https://doi.org/10.1162/105474600566718

Kim KJ, Sundar SS (2013) Can interface features affect aggression resulting from violent video game play? An examination of realistic controller and large screen size. Cyberpsychol Behav Soc Netw 16(5):329–334. https://doi.org/10.1089/cyber.2012.0500

Krause JM, Benavidez EA (2014) Potential influences of exergaming on self-efficacy for physical activity and sport. J Phys Educ Recreat Dance 85(4):15–20. https://doi.org/10.1080/07303084.2014.884428

Lange B, Koenig S, Chang CY, McConnell E, Suma E, Bolas M, Rizzo A (2012) Designing informed game-based rehabilitation tasks leveraging advances in virtual reality. Disab Rehabil 34(22):1863–1870. https://doi.org/10.3109/09638288.2012.670029

Larsen CR, Soerensen JL, Grantcharov TP, Dalsgaard T, Schouenborg L, Ottosen C, Schroeder TV, Ottesen BS (2009) Effect of virtual reality training on laparoscopic surgery: randomised controlled trial. Br Med J 338:b1802. https://doi.org/10.1136/bmj.b1802

Law ELC, Brühlmann F, Mekler ED (2018) Systematic review and validation of the game experience questionnaire (GEQ)—implications for citation and reporting practice. In: Proceedings of the 2018 annual symposium on computer–human interaction in play. ACM, New York, NY, USA, CHI PLAY'18, pp 257–270. https://doi.org/10.1145/3242671.3242683

Lee Y, Lim Yk (2017) How and why I cheated on my app: user experience of cheating physical activity exergame applications. In: Proceedings of the 2017 ACM conference companion publication on designing interactive systems. ACM, New York, NY, USA, DIS'17 companion, pp 138–143. https://doi.org/10.1145/3064857.3079134

Lin T, Hu W, Imamiya A, Omata M (2006) Large display size enhances user experience in 3D games. In: International symposium on smart graphics. Springer, Berlin, pp 257–262. https://doi.org/10.1007/11795018_27

López MB, Hannuksela J, Silvén O, Fan L (2012) Head-tracking virtual 3-d display for mobile devices. In: 2012 IEEE computer society conference on computer vision and pattern recognition workshops. IEEE, pp 27–34

Lyons EJ (2015) Cultivating engagement and enjoyment in exergames using feedback, challenge, and rewards. Games Health J 4(1):12–18. https://doi.org/10.1089/g4h.2014.0072

Lyons EJ, Tate DF, Ward DS, Bowling JM, Ribisl KM, Kalyararaman S (2011) Energy expenditure and enjoyment during video game play: differences by game type. Med Sci Sports Exerc 43(10):1987–1993. https://doi.org/10.1249/MSS.0b013e318216ebf3

Lyons EJ, Tate DF, Komoski SE, Carr PM, Ward DS (2012) Novel approaches to obesity prevention: effects of game enjoyment and game type on energy expenditure in active video games. J Diabetes Sci Technol 6(4):839–848. https://doi.org/10.1177/193229681200600415

McMahan RP, Gorton D, Gresock J, McConnell W, Bowman DA (2006) Separating the effects of level of immersion and 3D interaction techniques. In: Proceedings of the ACM symposium on virtual reality software and technology. ACM, New York, NY, USA, VRST'06, pp 108–111. https://doi.org/10.1145/1180495.1180518

Mestre DR (2017) CAVE vesus head-mounted displays: ongoing thoughts. Electron Imaging 2017(3):31–35. https://doi.org/10.2352/ISSN.2470-1173.2017.3.ERVR-094

Molina KI, Ricci NA, de Moraes SA, Perracini MR (2014) Virtual reality using games for improving physical functioning in older adults: a systematic review. J NeuroEng Rehabil 11(1):156. https://doi.org/10.1186/1743-0003-11-156

Molina-Carmona R, Llorens-Largo F (2020) Gamification and advanced technology to enhance motivation in education. In: Informatics, multidisciplinary digital publishing institute, vol 7, p 20

Moss JD, Muth ER (2011) Characteristics of head-mounted displays and their effects on simulator sickness. Hum Factors 53(3):308–319. https://doi.org/10.1177/0018720811405196

Mueller F, Isbister K (2014) Movement-based game guidelines. In: Proceedings of the SIGCHI conference on human factors in computing systems. ACM, New York, NY, USA, CHI'14, pp 2191–2200. https://doi.org/10.1145/2556288.2557163

Nickel A, Kinsey H, Barnes T, Wartell Z, (2012a) Supporting an interval training program with the astrojumper video. In: Meaningful play, 2012, East Lansing. MI, USA

Nickel A, Kinsey H, Haack H, Pendergrass M, Barnes T (2012b) Interval training with astrojumper. In: 2012 IEEE virtual reality workshops (VRW), pp 161–162. https://doi.org/10.1109/VR.2012.6180931

Nunes de Vasconcelos G, Malard ML, van Stralen M, Campomori M, Canavezzi de Abreu S, Lobosco T, Flach Gomes I, Duarte Costa Lima L (2019) Do we still need CAVEs? Simulation - VIRTUAL AND AUGMENTED REALITY 3. https://www.researchgate.net/profile/Mateus_Van_Stralen/publication/335598963_Do_we_still_need_CAVEs/links/5d9342fd92851c33e94b8b54/Do-we-still-need-CAVEs.pdf. Accessed 8 Jan 2020

Olk B, Dinu A, Zielinski DJ, Kopper R (2018) Measuring visual search and distraction in immersive virtual reality. R Soc Open Sci 5(5):172331–172331

Paw MJCA, Jacobs WM, Vaessen EP, Titze S, van Mechelen W (2008) The motivation of children to play an active video game. J Sci Med Sport 11(2):163–166. https://doi.org/10.1016/j.jsams.2007.06.001

Peng C, Cao L, Timalsena S (2017) Gamification of Apollo lunar exploration missions for learning engagement. Entertain Comput 19:53–64. https://doi.org/10.1016/j.entcom.2016.12.001

Poels K, De Kort Y, IJsselsteijn W (2007) The Game Experience Questionnaire: development of a self-report measure to assess player experiences of digital games. Technische Universiteit Eindhoven. https://research.tue.nl/en/publications/d33-game-experience-questionnaire-development-of-a-self-report-me. Accesesd 5 May 2020

Rank17 (2017) VR baseball. https://www.oculus.com/experiences/rift/1637237046293678/. Accessed 10 Dec 2019

Reilly D, Westecott E, Parker D, Perreault S, Neil D, Lapierre N, Hartman K, Bal H (2013) Design-driven research for workplace exergames: the limber case study. In: Proceedings of the first international conference on gameful design, research, and applications. ACM, New York, NY, USA, Gamification'13, pp 123–126. https://doi.org/10.1145/2583008.2583030

Rice M, Wan M, Foo MH, Ng J, Wai Z, Kwok J, Lee S, Teo L (2011) Evaluating gesture-based games with older adults on a large screen display. In: ACM SIGGRAPH 2011 game papers, ACM, New York, NY, USA, SIGGRAPH'11, pp 3:1–3:8. https://doi.org/10.1145/2037692.2037696

Sabet SS, Griwodz C, Möller S (2019) Influence of primacy, recency and peak effects on the game experience questionnaire. In: Proceedings of the 11th ACM workshop on immersive mixed and virtual environment systems. ACM, New York, NY, USA, MMVE'19, pp 22–27. https://doi.org/10.1145/3304113.3326113

Saposnik G, Teasell R, Mamdani M, Hall J, McIlroy W, Cheung D, Thorpe KE, Cohen LG, Bayley M (2010) Effectiveness of virtual reality using wii gaming technology in stroke rehabilitation: a pilot randomized clinical trial and proof of principle. Stroke 41(7):1477–1484. https://doi.org/10.1161/STROKEAHA.110.584979

Schell J (2014) The art of game design: a book of lenses. AK Peters/CRC Press, Boca Raton. https://doi.org/10.1201/b22101

Schneider ALJ, Graham TCN (2015) Pushing without breaking: nudging exergame players while maintaining immersion. In: 2015 IEEE games entertainment media conference (GEM), pp 1–8. https://doi.org/10.1109/GEM.2015.7377222

Shaw L, Wünsche B, Lutteroth C, Marks S, Callies R (2015a) Challenges in virtual reality exergame design. In: Marks S, Blagojevic R (eds) Proceedings of the 16th Australasian user interface conference (AUIC), 2015, Australian Computer Society, pp 61–68. https://pdfs.semanticscholar.org/7dc2/8e0ca4a75cf6fa6aebf39d3afda73fcbf752.pdf

Shaw LA, Wünsche BC, Lutteroth C, Marks S, Buckley J, Corballis P (2015b) Development and evaluation of an exercycle game using immersive technologies. In: Proceedings of the 8th Australasian workshop on health informatics and knowledge management (HIKM 2015), Australian Computer Society, Inc. (ACS)

Shin JH, Ryu H, Jang SH (2014) A task-specific interactive game-based virtual reality rehabilitation system for patients with stroke: a usability test and two clinical experiments. J Neuroeng Rehabil 11(1):32. https://doi.org/10.1186/1743-0003-11-32

Skjæret-Maroni N, Vonstad EK, Ihlen EAF, Tan XC, Helbostad JL, Vereijken B (2016) Exergaming in older adults: movement characteristics while playing stepping games. Front Psychol 7:964

Southard DA (1995) Viewing model for virtual environment displays. J Electron Imaging 4(4):413–420. https://doi.org/10.1117/12.217267

Stach T, Graham TCN, Brehmer M, Hollatz A (2009) Classifying input for active games. In: Proceedings of the international conference on advances in computer entertainment technology. ACM, New York, NY, USA, ACE'09, pp 379–382. https://doi.org/10.1145/1690388.1690465

Sun TL, Lee CH (2013) An impact study of the design of exergaming parameters on body intensity from objective and gameplay-based player experience perspectives, based on balance training exergame. PLoS ONE 8(7):e69471. https://doi.org/10.1371/journal.pone.0069471

Tanaka Y, Hirakawa M (2016) Efficient strength training in a virtual world. In: 2016 IEEE international conference on consumer electronics-Taiwan (ICCE-TW), IEEE, pp 1–2. https://doi.org/10.1109/ICCE-TW.2016.7521030

Tece Bayrak A, Wuensche B, Reading SA, Lutteroth C (2020) Games as systems for rehabilitation: a design strategy for game-based exercise rehabilitation for Parkinson's disease. In: Proceedings of the 53rd Hawaii international conference on system sciences. http://hdl.handle.net/10125/64167

Treleaven J, Battershill J, Cole D, Fadelli C, Freestone S, Lang K, Sarig-Bahat H (2015) Simulator sickness incidence and susceptibility during neck motion-controlled virtual reality tasks. Virtual Real 19(3):267–275. https://doi.org/10.1007/s10055-015-0266-4

Wu H, Xie T, hu N (2016) Robo recall. In: SIGGRAPH ASIA 2016 VR showcase. ACM, New York, NY, USA, SA'16, pp 12:1–12:2. https://doi.org/10.1145/2996376.2996386

Xie B, Zhang Y, Huang H, Ogawa E, You T, Yu L (2018) Exercise intensity-driven level design. IEEE Trans Vis Comput Graph 24(4):1661–1670. https://doi.org/10.1109/TVCG.2018.2793618

Yoo S, Kay J (2016) VRun: running-in-place virtual reality exergame. In: Proceedings of the 28th Australian conference on computer–human interaction. ACM, New York, NY, USA, OzCHI'16, pp 562–566. https://doi.org/10.1145/3010915.3010987

Yoo S, Ackad C, Heywood T, Kay J (2017a) Evaluating the actual and perceived exertion provided by virtual reality games. In: Proceedings of the 2017 CHI conference extended abstracts on human factors in computing systems. ACM, New York, NY, USA, CHI EA'17, pp 3050–3057. https://doi.org/10.1145/3027063.3053203

Yoo S, Heywood T, Tang LM, Kummerfeld B, Kay J (2017b) Towards a long term model of virtual reality exergame exertion. In: Proceedings of the 25th conference on user modeling, adaptation and personalization. ACM, New York, NY, USA, UMAP'17, pp 247–255. https://doi.org/10.1145/3079628.3079679

Yoo S, Parker C, Kay J (2017c) Designing a personalized VR exergame. In: Adjunct publication of the 25th conference on user modeling, adaptation and personalization. ACM, New York, NY, USA, UMAP'17, pp 431–435. https://doi.org/10.1145/3099023.3099115

Zyda M (2005) From visual simulation to virtual reality to games. Computer 38(9):25–32. https://doi.org/10.1109/MC.2005.297