THESIS

ASSESSING USABILITY OF FULL-BODY IMMERSION IN AN INTERACTIVE VIRTUAL

REALITY ENVIRONMENT

Submitted by

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ABSTRACT

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Improving immersion and playability has a direct impact on the effectiveness of certain Virtual Reality applications. This project looks at understanding how to develop an immersive soccer application with the intention to measure skills, particularly for the use of assessment and health promotion. This project will show the requirements to create a top-down immersive experience with commodity devices. The particular system serves the simulation of a soccer training environment to evade opponents, pass to teammates, and score goals with the objective to systematically increase the difficulty of the game by moving from easier to more complex tasks. It is hypothesized that the performance will go down as the level of difficulty increases. If our hypothesis is confirmed, this system could aid in return to play readiness (with an OK by a physician) or to promote health to non-athletes. This thesis describes the necessary steps for developing highly immersive applications and provides future directions for human-subject experiments.

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I must express extreme gratitude to my parents and to my sister for providing me with the support and continuous encouragement, which got me through some tough times throughout my years of study and research. This would not have been possible without them.

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Chapter 1

Introduction

The advent of Virtual Reality (VR) Head-Mounted Displays (HMDs) as commodity devices have driven the introduction of more and more games that can be played and appreciated by the general public. In addition to games, there are other types of VR applications, including training [1, 2], rehabilitation [3, 4], and simulation [4–6], among others. This effort answers the question about what is the necessary components to create a fully top-down immersive VR soccer training simulator using minimal equipment that can be used for return-to-play concussion assessment or promoting health. The system presented here, **SoccerSim VR**, integrates all the features required for a true immersive experience with the exception of haptic sensing.

SoccerSim VR takes advantage of immersion. The users are put on a virtual soccer field and ask to perform various game related situations (evading opponent, pass to a teammate, score a goal). Users have complete control of their body (avatar's body). One of the significant features of the system is to provide metrics to aid the ready-to-play decision. This thesis sets the foundations by providing a complete system and a design of experiments for future researchers.

With Virtual Reality becoming more and more popular and increasingly reaching typical households, a large number of research labs around the world have started using Virtual Reality (VR) in their research. Immersion is critical when you want people to believe they are someplace other than their home or office. When a VR application does not allow full-body movement, it may reduce the immersion. Just a small addition of hands visible in the 3D space increases immersion, imagine having a complete body (human or not). This requires full-body tracking to map real-world movements to the virtual world. Full-body tracking leads to a more immersive feeling and actions more in line with the real world [7]. During the past years, many different motion capture technologies have been developed in order to fully track the human body. Few of the solutions include attaching markers to key body parts, video-based systems use IR or depth data capture via cameras (e.g., Vicon, ART, OptiTrack, Kinect, RealSense), inertial systems use trackers with accelerometers (e.g.,

Xsens, and several others), electromagnetic systems utilize emitters and detectors of electromagnetic field (e.g., Ascension, Polhemus). Since, current marker-less devices tend to show jittering, tracking instability and false pose detection, and, for full-body, low resolution and precision.

This thesis's primary contribution is to provide an immersive system for a specific domain (e.g., return-to-play or health promotion) using commodity devices. The system includes everything needed to conduct a user experiment, and it sets the way forward (Chapter 5) on how to conduct a user study.

Chapter 2

Literature Survey

The key points targeted in this thesis are immersion, presence, and virtual body ownership. Berkman et al. defined immersion as "user's engagement with a VR (virtual reality) system that results in being in a flow state" [8]. The human mind does two types of processing based on the information provided. Bottom-up processing refers to understanding and processing all the sensory data as it comes in. On the other hand, Top-down processing is driven by cognition. The brain fills in the missing gaps of information based on what it knows and what it expects [9]. Another way of looking at it is by providing all the sensory information that five senses of the human body can understand leads to a bottom-up approach to immersion and presence. On the other hand, just providing a bare minimum, in case of VR - visual information, and letting the brain fill in the rest of the information is top-down processing. Arousing body ownership when a user controls a virtual body that moves the same ways as the real body will enhance the sensation of presence for the user and support the idea of virtual body ownership [10].

Capturing the real body movements and producing the same movements by a virtual body is a problem without a perfect solution today. There have been a lot of different approaches. Some researchers built custom trackers, while in the past few years vendors have introduced their own (e.g., HTC Vive trackers). For example Caserman et al. introduced an accurate, low-latency body tracking approach for VR-based applications using Vive Trackers [11]. Drobnjakovic et al. proposed a full-body motion tracking architecture for Virtual Personal Trainer system. They used 9-axis Inertial Measuring Unit(IMU) sensors, which provided accurate full-body tracking with the freedom of wireless communication to a host device. A 3D camera was used as a stabilizing agent by providing a point of reference. It also helped to counteract the inherent gyroscopic IMU drift and interference from surrounding electromagnetic fields [12]. The Motion Capture suits that use light-based markers or sensors to track each joint are difficult to use. They are weighty, intrusive, and above all, expensive.

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The introduction of low-cost, high-speed depth sensors, such as Microsoft Kinect for Xbox [13], has increased the popularity of marker-less human pose estimation techniques using depth images. The use of depth data has allowed the realization of many reliable human pose estimation systems that can output the position of some joints in order to reconstruct the human skeleton. Okada et al. presented a method for marker-less human motion capture using a single camera. They used a shape-from-silhouette approach to assess 3D surfaces, followed by tree-based filtering to estimate poses in real-time [14]. Similar to Okada et al.'s work, Grest et al. proposed an example-based approach [15]. Pre-captured motion exemplars were used to estimate the body configuration. Many exemplars should be tested to obtain the best-matched one leading to single predicted pose match.

Leoncini et al. presented an approach to simulate a collaborative virtual environment [16]. They introduced a fusion technique for data incoming from multiple Kinect sensors. Furthermore, they also included fusion strategies for multi-body tracking based on Kinect along with head-tracking and head-mounted Leap Motion Controllers data in order to get body-tracking with the full hand detail, which enables direct hand manipulation in applications such as first-person virtual maintenance training. The fusion part of leap motion and the Kinect sensor determines which sensor tracks the hand, depending on the position of the hand.

Although Facebook has released its hand tracking feature in Oculus Quest headsets, it is still researching on full-body tracking. They have taken it a step further where they track body movements on muscle activation levels. They did state that this is a research project, not a product, and the launch may be years away [17].

Chapter 3

Details about hardware and software

The system was developed using Unreal Engine 4 on Alienware Aurora R8 with intel i9-9900K Processor, 32 GB memory, and Nvidia RTX 2080 Ti Graphics card. Although the development system had high specifications, the software runs perfectly well on any VR ready computer. Finally, 3DS Max and Blender were used for character rigging and other alterations. The program was developed on Oculus Rift S. An HMD was used for tracking in-game camera position.

3.1   Minimum hardware requirements

1. **Microsoft Kinect 2:** The system uses the Microsoft Kinect to track the body movements. It provides 25 tracking points that signify different joints.

2. **VR Head Mounted Display:** Any commercial HMD should support the system. Although the system is not HMD dependent and it doesn't need specific VR controllers, but IR interference was observed between the HTC Vive and the Microsoft Kinect. Due to IR interference, the Oculus Rift S or other camera-based tracking HMDs are preferred.

3. **At least one hand controller:** Although controllers are not needed for their conventional use, the left controller is used to track the position of the body to define the center of gravity. This ensures that the body doesn't move forward when looking down or crouching. The current prototype has fixed relative positions of HMD and controller in xy-plane. This means there might be some positioning problems depending on the waist size but can be changed in code.

4. **Windows computer:** At least an NVIDIA GeForce 1060 graphics card and i7 processor is required. Any VR ready computer with Windows OS supports the system.

3.2 Software

1. **Unreal Engine 4:** It provides necessary graphics details that are required for an immersive experience. Since there is no haptic feedback, the way to make people believe what they experience is real is through sight. Unreal Engine 4 also has a third-party plugin called Kinect4Unreal, which gives the joint coordinates to Unreal. This allows subjects to have a virtual body that they can use to interact with the virtual world.

2. **Kinect4Unreal:** Kinect4Unreal (sometimes abbreviated to K4U) is a middle-ware plugin between Unreal Engine 4 and Microsoft Kinect 2. It provides functions for utilizing all the features provided by Microsoft Kinect 2 in the form of Blueprint visual scripting system. The idea behind this plugin is to allow developers to focus more on application design rather than understanding and utilizing the data provided by Microsoft Kinect 2. It provides over 30 original nodes, all with extensive documentation and prebuilt Avateering systems.
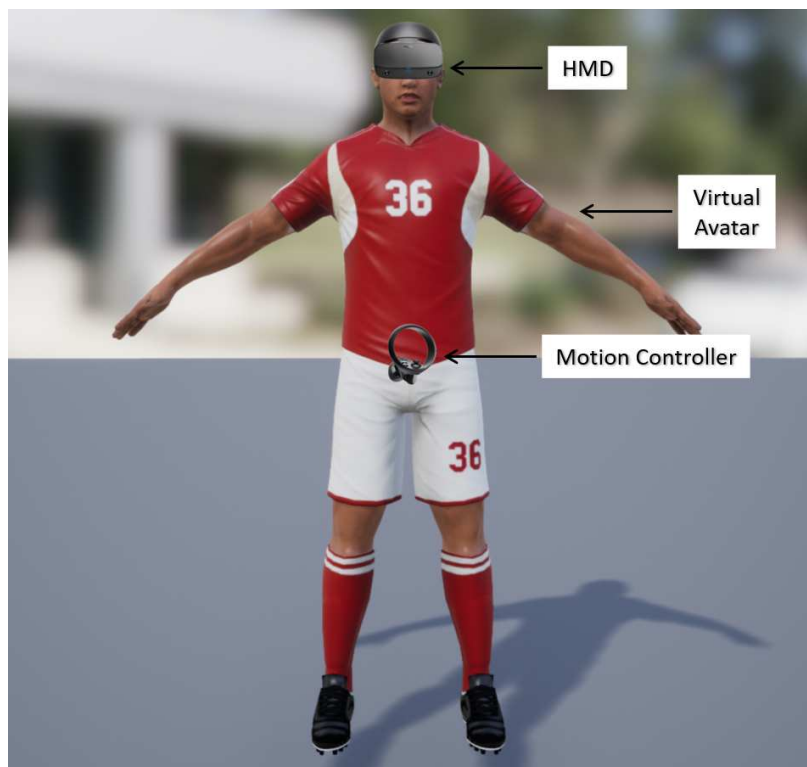
Figure 3.1: Virtual Avatar with VR HMD hardware

Chapter 4

Unreal Engine 4 Design Details

4.1   Male and Female Avatars

SoccerSim VR provides two options for avatar selection. Generic Male and Generic Female. The meshes of both the avatars were bought and downloaded from TurboSquid [18]. TurboSquid provides 3D models for a variety of industries. Think of it as Amazon for 3D models. Depending on the asset, it can provide animations, materials, and posses and free services for conversion to multiple platforms like Unreal Engine 4, Unity, 3DS Max. The avatars were rigged on 3DS Max. The rig used was the one provided by the Unreal Engine 4 team. The rig can be seen from the skeleton menu of SK_Mannequin.

Figure 4.1: SK_Mannequin provided by Unreal Engine 4

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SK_Mannequin is a Skeletal Mesh provided by the Unreal Engine 4 team as a start-up content for Third Person games (Figure 4.1). It has multiple properties. The main ones are material selection and container for classes required for movement. The classes are:

1. **Physics Asset:** It is called "SK_Mannequin_PhysicsAsset." When "Physics" is enabled, it provides the necessary structure and features for physics to work on the body properly. This means interacting with the environment is not limited to the default capsule collision. It also helps with body movements. For example, if the character is injured and some limbs are paralyzed or when a character dies, the ragdoll movement can be shown using Physics Asset. It also helps put limits on the range of movement of the limbs to simulate real-world joint constraints.

2. **Animations:** The Unreal Engine 4 team also provides few animations like "Walking." "Running," and "Jumping." These animations are used to display movements. Without these animations, there won't be any limb movements. The only thing users see is a still character floating around in space.

3. **Animation Blueprint:** Joining animations and putting conditions on animation triggers is handled by Animation Blueprint. A simple example is when you want to transition from 'standing still' to 'walking' to 'running' depending on how much pressure you apply on the joystick can be programmed in Animation Blueprint.

4. **Skeleton:** The last class provided by the team (probably the most important of these all) is a Skeleton or rig called "UE4_Mannequin_Skeleton". This is the rig that specifies the bones, their location, and rotation. Different parts of the mesh are coupled with appropriate bones. This specifies the amount of influence a particular bone has on the specified mesh region. You don't want the leg region of mesh to move when the bones in arms are moving. The animations are applied to rigs and not mesh. Developers can change the mesh and have the same animation as long as the rig is the same. This comes handy when you have multiple characters whose movements are the same but look different.

The Skeleton/Rig and running animation from this asset were used in most of the characters. There are two reasons for using this Rig - a) The Kinect4Unreal plugin only recognizes the bone structure of this rig. And b) it is much easier to transfer a mesh on to an already constructed rig than create a new rig for every mesh.

The four characters used throughout this system are shown in Figure 4.2. Figures 4.2a and 4.2c shows player avatars, and Figures 4.2b and 4.2d show their respective opponents. The teammates have the same jersey like the players, so the player characters are used for that too.

For more immersive experience and virtual body ownership, the avatars have to look as close to their real bodies as possible. Waltemate et al. conducted a study where they had six different conditions for the subjects [19]. The conditions were - generic avatar made with character creator program with regular clothes, non-individualized scanned avatars with regular cloths, personalized avatars with respective clothes, and all three avatar styles in motion capture suits instead of regular cloths. They found that personalized avatars significantly increase virtual body ownership, virtual presence, and dominance compared to generic counterparts. Having personalized avatars is almost impossible when you are trying to make a system that requires minimal equipment. The alternative is to have a customizable option similar to games like Witcher, WWE.

(a) User Male Avatar

(b) Opponent Male Avatar

(c) User Female Avatar

(d) Opponent Female Avatar

Figure 4.2: Avatars

Figure 4.3: Participant Level 3D widget

4.2 Participant Level

The level displays a blank scene with a 3D object. This object contains a widget that is used to display menus and information. The widget is simple, where it displays the participant ID, which is assigned to the player, as shown in Figure 4.3.

The 3D object is attached to the camera. This allows the widget to follow the player's viewport at all times. Unreal Engine 4 provides a widget class which can be attached to the viewport of the player, but that is for screen playing. There are two reasons for not providing this feature in VR playstyle. 1. VR has a larger field of view, which makes it difficult to design and visualize the widget. 2. Having a menu stuck to the player's face with objects in the background tends to increase the chances of simulator sickness. In an effort to reduce the simulator sickness, the whole level is kept blank hence there is no visible point of reference relative to the menu.

4.3 Start Level

(a) Start Level Male Avatar

(b) Start Level Female Avatar

Figure 4.4: Start Level

This is the first time the players see the soccer field and their body in the virtual world. In this level, players have the chance to move around and get familiar with their virtual body. The players find themselves in front of a mirror, as shown in Figure 4.4. Adding mirror in the configuration stage is inspired by Gonzalez et al.'s work. They presented their finding on how Real-Time Mirror Reflections of Motor Actions impacts Virtual Body Ownership in an Immersive Virtual Environment [20]. Disconnecting from the real world and immersing yourself in a virtual one takes time,

especially when it is an unfamiliar environment. It is essential that players feel the virtual body is their own.

This level serves four purposes:

1. Introduction to their virtual body and familiarizing the feeling of real-life movement mapped to this virtual body. The mirror helps solidify the idea of virtual body ownership.

2. Opportunity to move around in the virtual environment to build up confidence and understand the area that the players can move around without bumping into something or someone.

3. Setting height of the player so that avatar has the same height and the movements are as close to real-world as possible.

4. Selecting gender for the avatar. The choice is provided if in case the adapting system needs this feature. Ideally, players select their gender to increase the feelings of virtual body ownership.

4.4   Practice Task Levels

These levels are for the player to get used to the system and its workings. In these levels, the players perform one task at a time, and the task remains the same for all trials until level changes. The trials on each level start with the keypress 'T.'

4.4.1   Practice Evade Level

The level can be started with the keypress "1."

In this level, the players are spawned in the middle of the field. They face forward (facing Kinect). Opponents spawn in three different lanes, randomly, one at a time with an interval of two seconds. The level continues till the players collide five times with the opponents. A snapshot of the task is shown in Figure 4.5. The opponents can be identified easily by the color of their jersey. Male opponents have Yellow and Black jersey as opposed to Red and White. Female opponents have Blue and White as opposed to White and Black. The opponents spawned are of two types,

Figure 4.5: Evade Level

with a ball, and without a ball. The selection of the type of opponent depends on whether there is a soccer ball on the field. This means that once an opponent with a soccer ball spawns successive opponents won't have a ball with them until the opponent with the soccer ball reaches the end of its path and is destroyed. This ensures that there is only one soccer ball on the field. Increasing the number of players spawned at a time or decreasing the time gap between each successive opponent spawn can add additional difficulty.

There are 2 objectives to complete.

1. Evade the on-coming opponents without the ball

2. Tackle the opponents with the ball (stand in the way)

The collision on the opponents is a simple capsule collision, while on players, all significant parts have their own collision box. The significant parts are Palms, Forearms, Arms, Chest, Head, Thighs, Lower Legs, and Feet. It is considered unsuccessful evade if any of these collision boxes overlap the capsule collision on opponent players. On the other hand, not overlapping with the capsule collision of the player with the soccer ball is considered as failure.

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4.4.2 Practice Goal Level
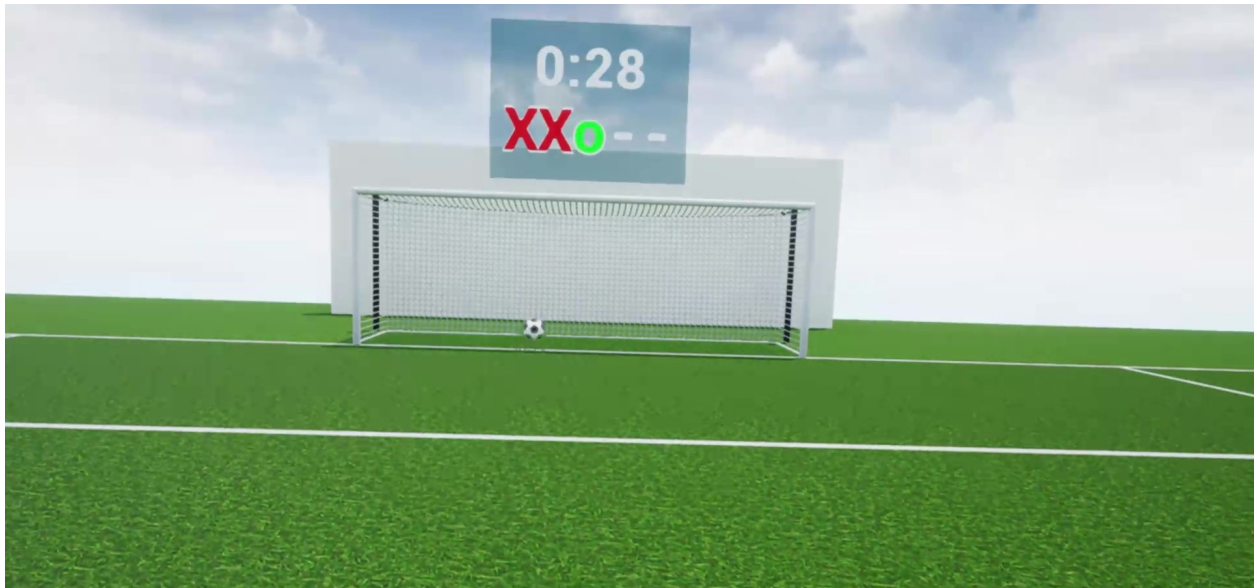
(a) Goal Level
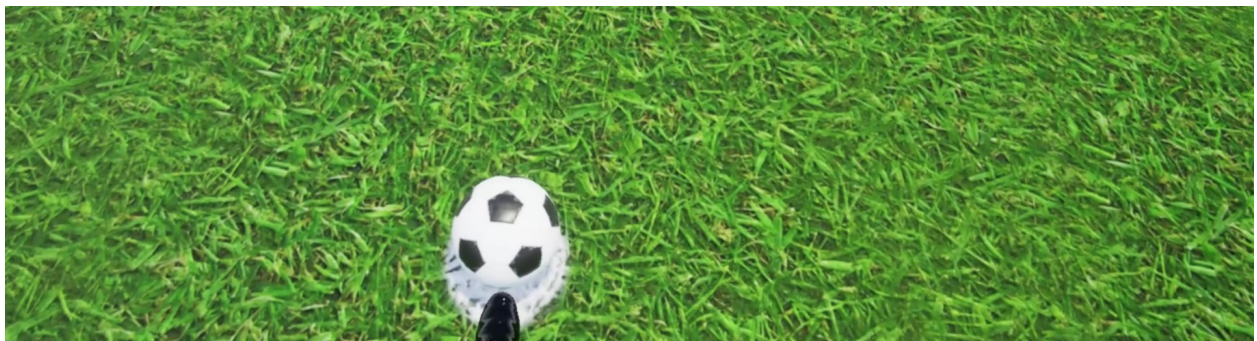
(b) Goal Level Kick

Figure 4.6: Goal Level

The level can be started with the keypress "2."

This is a penalty kick simulation. A penalty kick is when the soccer ball is placed on the white dot, as shown in Figure 4.6b, and the task is to kick the ball in the goal. There is a goalkeeper who tries to block the ball (in this simulation, there is no goalkeeper). In this task, the soccer ball spawns every seven seconds. The player has 4.5 seconds to hit the ball. The reason for 4.5 seconds is to facilitate faster reaction speed and athletic movements. The players get five attempts. A snapshot of the task is shown in Figure 4.6.
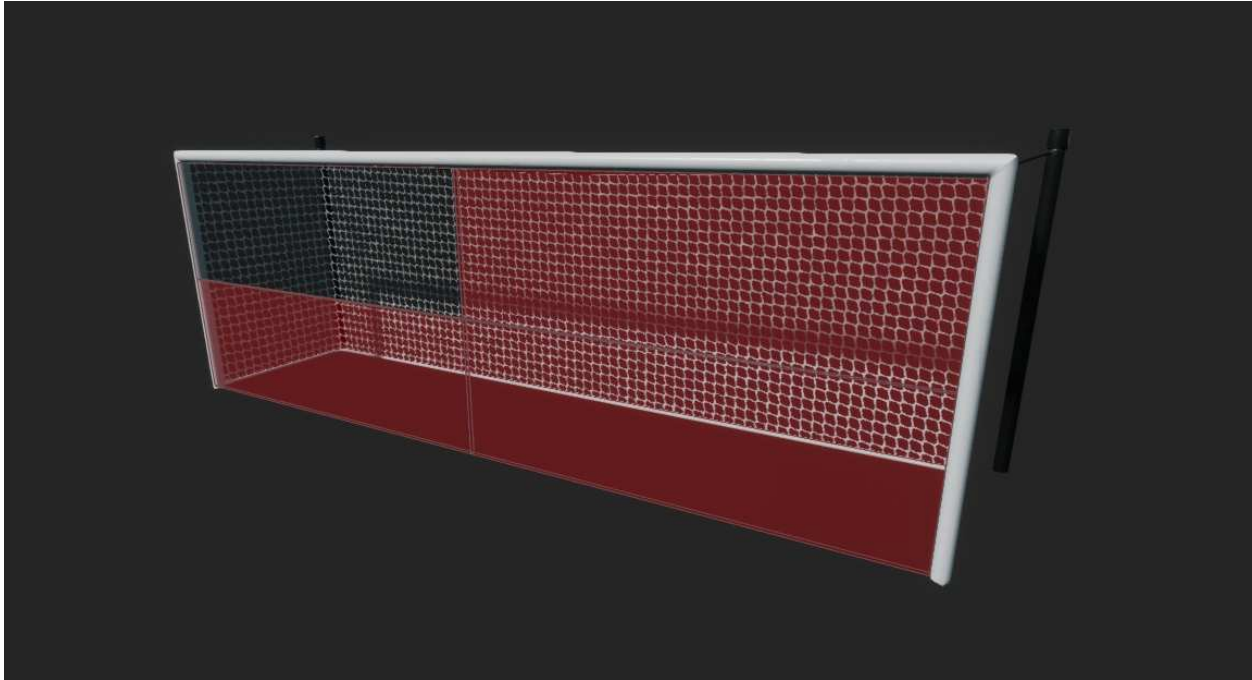
Figure 4.7: Four quadrant Goalpost

There are two types of goalposts available:

1. **Simple:** This type has a simple goal, and the players can aim at any part of the goal.

2. **Segmented:** The goal is split into four parts, as shown in Figure 4.7. One of the segments is transparent, while the other three red. The task is to aim at the transparent section. After each attempt, the target section changes randomly. This variation adds an additional level of difficulty.

The collision boxes are set up in multiple places. One to cover the whole goal. This is required to check if and when the ball goes in the goal. In the case of the Segmented type goal post, there are 4 collision boxes to check for each section.

4.4.3 Practice Pass Level

The level can be started with the keypress "3."

The task is simple, kick the ball to your teammate. The teammates can be identified by their jersey color. Male Red and White and female White and Black. Unlike the goal task, there is

(a) Pass Level

(b) Pass Level Kick

Figure 4.8: Pass Level

no white spot where the ball appears, but it always is the same spot in the virtual world and the same place in the real-world as the white spot in goal task. Players have to kick the ball to their teammates who spawn randomly in three different positions. This means the players have to readjust their aim every attempt. In a regular soccer game, you do not pass precisely to your teammates. The aim is adjusted depending on opponents, and your teammates can adjust their

position to receive the ball. To incorporate this idea, teammates have a blue ring around them, which is the target region where the player is supposed to kick. Decreasing the size of the circle increases the difficulty. Similar to Goal task, the ball is spawned every seven seconds, and the player has 4.5 seconds to hit the ball. Similar to Goal Task, the players get five attempts. A snapshot of the task is shown in Figure 4.8. Figure 4.9 shows a player performing kick action.

The size collision bounds recorded for teammates depend on the size of the ring. The height of the collision box is also important and is slightly higher than the actual height of teammates. Having too high collision bounds is inaccurate as the players can't jump that high to receive the ball.

Figure 4.9: Participant kicking in real world

4.5   Single Task Levels

In these levels, the players perform one task at a time, and the task remains the same for all trials till level changes. The trials on each level start with the keypress 'T.'

4.5.1   Evade Level

The level can be started with the keypress "4."

This level has the same requirements as the corresponding practice level. However, in contrast to the practice level where the number of trials was five, here, the number of trials is 20.

4.5.2   Goal Level

The level can be started with the keypress "5."

This level has the same requirements as the corresponding practice level. However, in contrast to the practice level where the number of trials was five, here, the number of trials is 20.

4.5.3   Pass Level

The level can be started with the keypress "6."

This level has the same requirements as the corresponding practice level. However, in contrast to the practice level where the number of trials was five, here, the number of trials is 20.

4.6   Double Task Levels

In these levels, the players perform two tasks one after the other. This means that for each trial, players are tasked to do two different tasks without a break. The trials on each level start with the keypress 'T.' The number of trials for each Double task levels is 20. While comparing the performance with Single Task Levels, it is important to maintain the same distances and time intervals for all levels.

4.6.1 Evade + Goal Level

The level can be started with the keypress "7."

Imagine a scenario where the opponents have the soccer ball, the player has to navigate through a soccer field, tackle the player with the ball to get the ball and score. The idea of this level is to simulate this scenario. The task starts with opponents coming at the player the same as the Evade Task. There is a delayed response to when the ball is spawned with the opponent. This is to ensure that the first few opponents don't have the ball, and the player has to perform the evade task. Once the opponent with the soccer ball spawns, the player has to tackle (again, just stand in front) and get the ball from the opponent. Once the player has the ball, he/she has to kick it in the goal completing one trial. To maintain consistency with the previous tasks the number of trials is set to 20. The distance that opponents travel and the distance that the player has to kick the ball is kept the same as Single Tasks to ensure that proper comparison can be done.

4.6.2 Evade + Pass Level

The level can be started with the keypress "8."

Imagine a scenario where the opponents have the soccer ball, the player has to navigate through a soccer field, tackle the player with the ball to get the ball and pass to their teammate. The idea of this level is to simulate this scenario. The task starts with opponents coming at the player the same as the Evade Task. There is a delayed response to when the ball is spawned with the opponent the same as Evade + Goal Level. Once the opponent with the soccer ball spawns, the player has to tackle (again, just stand in front) and get the ball from the opponent. Once the player has the ball, he/she has to kick it to their teammate completing one trial. To maintain consistency with the previous tasks the number of trials is set to 20. The distance that opponents travel and the distance that the player has to kick the ball is kept the same as Single Tasks to ensure proper comparison can be done. Also, the size of the bounding circle, which signifies a successful pass is kept the same as Single Tasks.

4.6.3 Pass + Goal Level

The level can be started with the keypress "9."

Imagine a scenario where the player has the soccer ball; they pass to their teammate, and the teammate returns the ball to the player because the player is in a good position to score. So, after receiving the ball, the player kicks and scores. The idea of this level is to simulate this scenario. The task starts with a soccer ball spawning in front of their feet. The player has to kick to their teammate. It is assumed that the player receives the ball properly. Once the player has the ball again, he/she has to kick it in the goal completing one trial. The number of trials is set to 20. The distance that the player has to kick the ball is kept the same as Single Tasks to ensure proper comparison can be made. Also, the size of the bounding circle, which signifies a successful pass is kept the same as Single Tasks.

4.7   Triple Task Level

In this level, the players perform three tasks one after the other performing each task 20 times. This means that for each trial, players are tasked to do three different tasks without a break. The trials on each level start with the keypress 'T.' While comparing the performance with Single Task Levels and Double Task Levels, it is important to maintain the same distances and time intervals for all levels.

The level can be started with the keypress "0."

Imagine a scenario where the player has the soccer ball, they pass to their teammate, but the ball is stolen by opponents. Now the player has to navigate through a soccer field, tackle the player with the ball to get the ball back. After reacquiring the ball, the player kicks and scores. The idea of this level is to simulate this scenario. The task starts with a soccer ball spawning in front of their feet. The player has to kick to their teammate. At this time, opponents start coming at the player the same as the Evade task. There is a delayed response to when the ball is spawned with the opponent the same as Evade + Goal and Evade + Pass Levels. Once the opponent with the soccer ball spawns, the player has to tackle (again, just stand in front) and get the ball from the

opponent. Once the player has the ball, he/she has to kick it to their teammate completing one trial. To maintain consistency with previous tasks the number of trials is set to 20. The distance that opponents travel and the distance that the player has to kick the ball is kept the same as Single and Double Tasks to ensure proper comparison can be made. Also, the size of the bounding circle, which signifies a successful pass, is kept the same as Single and Double Tasks.

4.8   Scoreboard

Although not a level, the scoreboard is an integral part of the system. During the development phase of this system, it was pointed out that displaying scores may be helpful and encouraging. People tend to change the way they are doing a task, depending on the outcome. If they think the outcome is favorable, they continue to do the task in the same way, but if they feel there can be improvements, then they try different things. This, in the context of simulating the real world, people try to change how they swing their legs, which part of their leg they use to hit the ball or how far away from opponents they have to be to evade them successfully. Understanding that they are not moving fast enough or far enough away from the opponents increases their use of number of muscles and energy, in other words making them more active. This is helpful when you are trying to promote health.

The way scoreboards are designed, there are specific data structures in the Game State object to store the events of each level. Game State and Game Instances are objects that can be accessed across levels. Think of them as global variables/objects. These are especially useful for storing information like player health or points scored and communicating between levels. The data structures are in the form of maps, where the key and value depend on the task. Since the data is stored in the Game State object, they can be accessed from Scoreboard objects. The Scoreboard object takes the data and extracts the necessary information from it.

(a) Practice Evade Scoreboard before trial starts (b) Practice Goal Scoreboard with one success and three failures

(c) Goal Scoreboard before trial starts

(d) Pass Scoreboard with two unsuccessful passes
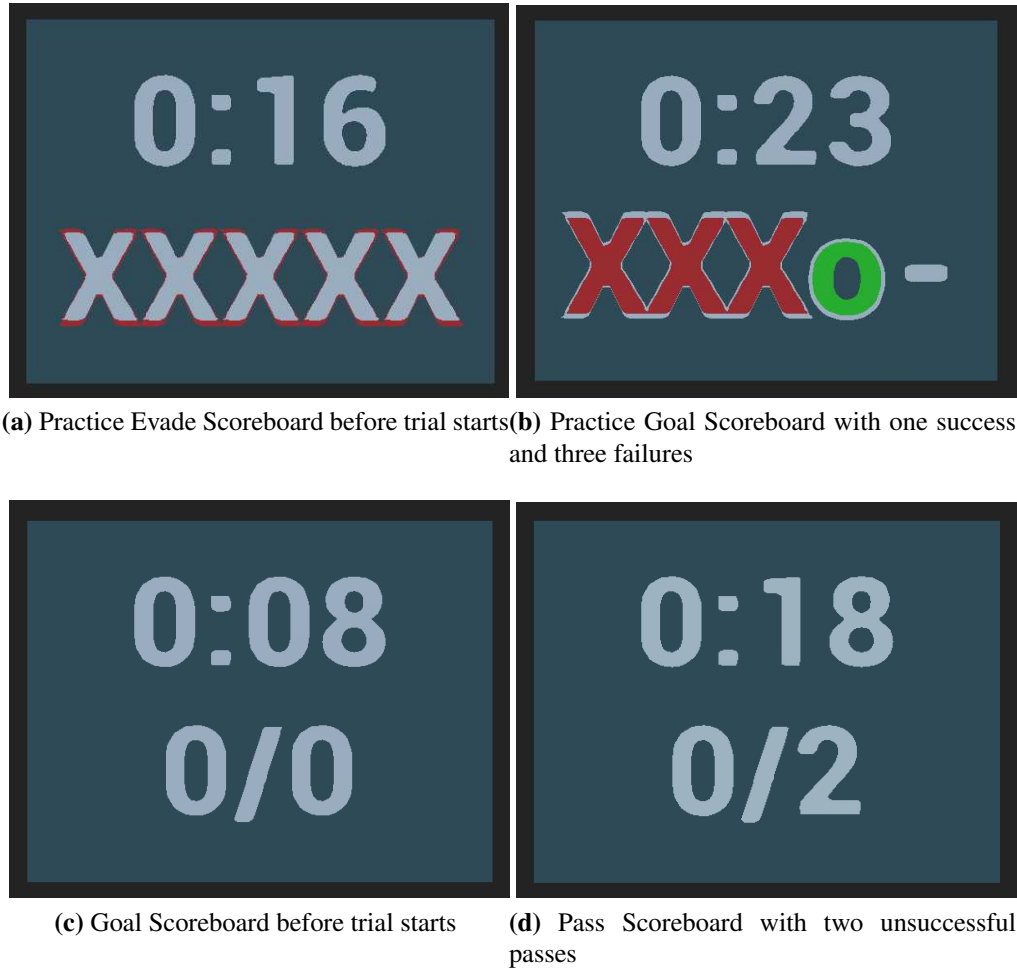
Figure 4.10: Scoreboards

The Scoreboard displays two readings.

1. **Time:** The time displayed is in the form of mm:ss(minutes:seconds) where count starts when the level loads. This means every time a new level is loaded, the clock resets. The time recorded in log files is the same as this.

2. **Score:** This depends on the number of trials. Since the practice levels have a small number of trials, the score is tracked by displaying "-" (hyphen). As trials progress, the hyphen is converted to "O" (circle) or "X" (cross) depending on the successful or unsuccessful outcome. When trail numbers are high like in case of Single Task Levels (20 each), the score is tracked by "successful/total" format. The count on total increases with each trail, and with each successful outcome, successful count increases.

4.9 Data Collection

Most of the data collection is done inside the system itself. Although Unreal Engine 4 Blueprints don't provide any function to read from or write to a file. There are C++ functions to handle file interaction. Two UFUNCTIONS were written in C++. These UFUNCTIONS are user-defined C++ functions that can be accessed from inside Unreal Engine 4. It creates a blueprint node for each function. The way to implement is to create a C++ file. Define the functions and compile from either Unreal Engine 4 editor or your code editor where you are writing your C++ code. Once it is compiled, as Unreal Engine 4 uses dynamic compiling, you can access the functions right away. If in case the functions are not found, and there are no compilation errors, you may have to restart the Unreal Engine 4 editor.

The two functions are:

1. **LoadTxt:** It takes one parameter - FString file_name. The function reads from the file name provided and returns an FString and success/failure Boolean.

2. **SaveTxt:** It takes two parameters - FString text, FString file_name. The function overwrites the text into the file_name.
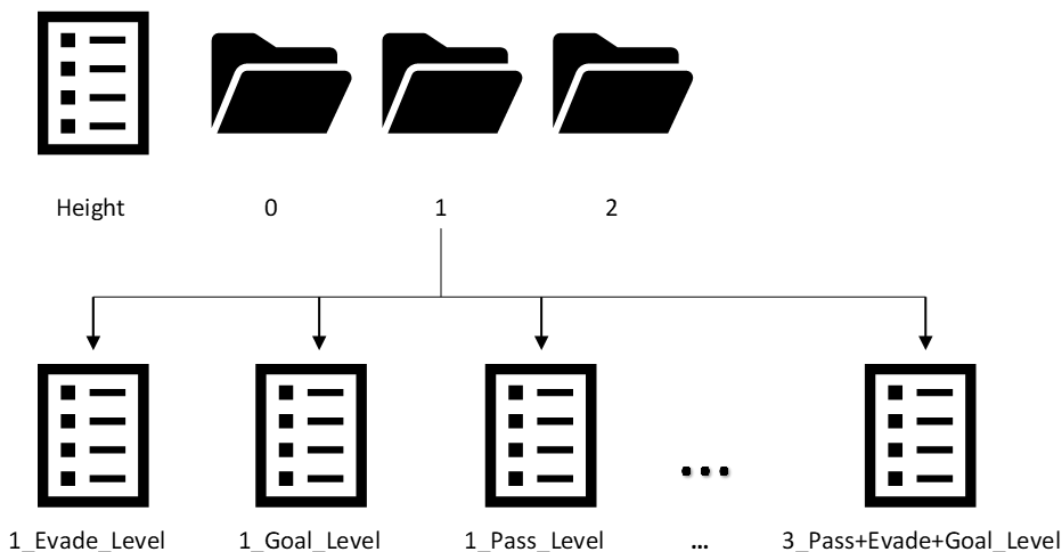
Figure 4.11: Directory Structure

Both functions can handle file_name with the path. The path starts with the root directory of the project. If there is no directory or file that you are trying to access to write a file, it creates the necessary files and directories. On the other hand, when trying to load a file that doesn't exist, it returns failure Boolean.

The directory structure of the data collection is shown in Figure 4.11. The root directory of the project holds a directory called Records. This holds one file called Height, which stores the participant number and their respective height. The other directories are created as new participants use the system. A new directory is created for each participant and is labeled by participant number. Each participant directory has log files for each level. The naming of each log file depends on the level name since level name is enough to determine what task it holds. A sample log file for the Evade level is shown in Figure 4.12.

Timestamp	Event	Miscellaneous
10.433346	StartTrial	
11.949989	OpponentSpawn	Charging_FemaleTargets
13.466633	OpponentReached_N	Charging_FemaleTargets1
13.466633	OpponentSpawn	Charging_FemaleTargets1
14.73328	OpponentReached_N	Charging_FemaleTargets1
14.916611	OpponentReached_B	Charging_FemaleTargets
14.983276	OpponentReached_N	Charging_FemaleTargets2
14.983276	OpponentSpawn	Charging_FemaleTargets2
15.366604	OpponentEvaded_T	Charging_FemaleTargets
15.6166	OpponentReached_B	Charging_FemaleTargets
16.26659	OpponentReached_N	Charging_FemaleTargets2
16.283257	OpponentReached_N	Charging_FemaleTargets2
16.49992	EndTrial	

Figure 4.12: Sample Log File

Each level is assigned an FString log to store all the significant events that happen. Like a log file, new data is stored at the end of the String. This String is saved to a file just before the next level is loaded. Since SaveTxt function only overwrites the files, all the logs have to be in a single string and can be written on file only once. In the case of the Height file, the append operation is done by first loading the file to a string, appending new height at the end of this String, and then saving the file again with new data.

4.9.1 Data collection key

Evade Events

Each entry in the log file has three columns. First is the time stamp, which stores data in seconds up to six decimal places. Second is the event. And the last column is Miscellaneous: Actor Display Name is added as additional column entry for opponent names.

StartTrial log is added when the Start Task button ("T") is pressed. Every time a new opponent spawns, the OpponentSpawn log is added. The opponent spawned can be in two states, with or without a soccer ball. This can be identified by log entry OpponentReached_X, where X is variable with possible values B (Has Ball) and N (No Ball). There is a large collision box attached to the player, as seen in Figure 4.13. OpponentReached_X entry is added when the opponent reaches this collision box, and depending on if the opponent has a soccer ball appropriate value of "X" is added.
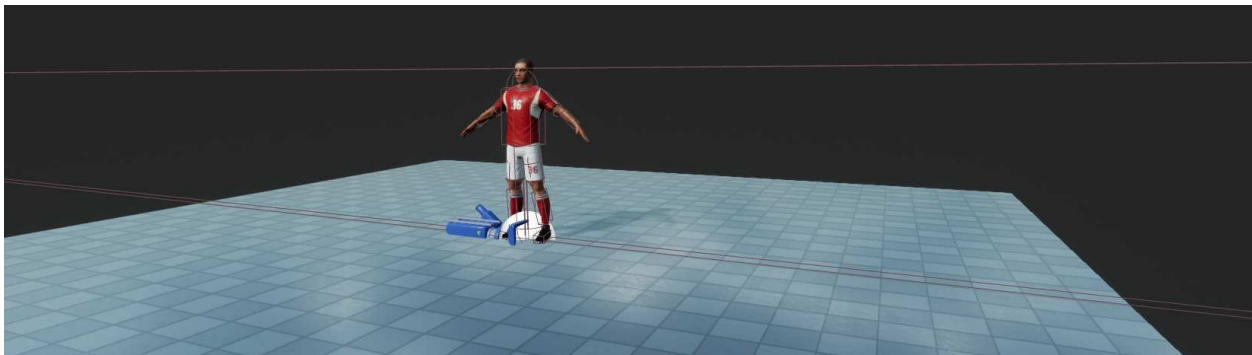
Figure 4.13: Collision box to detect opponent reaching player position

Once the opponent reaches the player position, there are four conditions for evade:

1. **Evade successful, opponent with ball:** No entry added but can be determined by not finding corresponding entry of OpponentEvade_X for OpponentReached_X for opponent name stored in Miscellaneous column who has a ball.

2. **Evade successful, opponent without ball:** No entry added but can be determined by not finding corresponding entry of OpponentEvade_X for OpponentReached_X for opponent name stored in Miscellaneous column who does not have a ball.

3. **Evade unsuccessful, opponent with ball:** OpponentEvade_T entry is added when the player collides with the opponent who has a ball.

4. **Evade unsuccessful, opponent without ball:** OpponentEvade_F entry is added when the player collides with the opponent who does not have a ball.

Finally, when all attempts are done, EndTrial is added.

Here is a summary:
1. StartTrial
2. OpponentSpawn
3. OpponentReached_X   B = Has ball   N = No ball
4. OpponentEvade_X   T = Tackled opponent w/ ball   F = Didn't evade opponent w/o ball
5. EndTrial

Goal Events

Each entry in the log file has three columns. First is the time stamp, which stores data in seconds up to six decimal places. Second is the event. And the last column is Miscellaneous: Soccer Ball Number.

StartTrial log is added when the Start Task button ("T") is pressed. Every time the soccer ball spawns, BallSpawn log is added. KickAttempt log is added by the external controller's Trigger

27
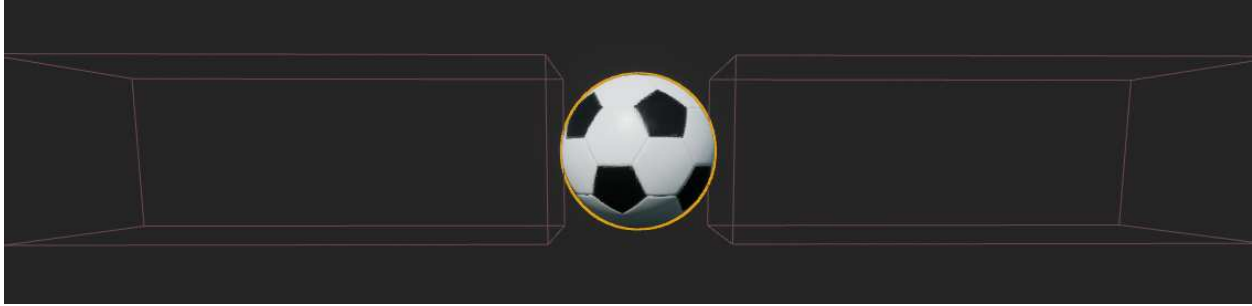
Figure 4.14: Soccer ball with collision boxes on the sides

press operated by the experiment supervisor. This entry is purposefully not added internally. The entry is for kick attempt and not a successful kick attempt. This means every time player tries to hit the ball, this entry has to be added even if they miss. The initial idea was to have two collision boxes on either side of the ball, as shown in Figure 4.14. Collision boxes are imaginary boxes that are around objects that are being checked for collision, like pedestrians on or close to the road, other vehicles and signs or in this case the space beside the soccer ball. These imaginary boxes detect if a foreign object has entered this space. But the way experienced players hit the ball is they step on the side of the ball and hit with the other leg. This records false positives for the KickAttempt log. To avoid that, external button press is used to add the log. The KickSuccess_X can have two results Success or Failure, which are represented by T and F, respectively. There is a large collision box on the goal post. ReachSuccess_T entry is added when the ball enters the goal. If the ball doesn't enter the goal and time span of the ball is up (4.5 seconds), ReachSuccess_F is added, signifying goal failure. Finally, when all attempts are done, EndTrial is added.

Here is a summary:

1. StartTrial

2. BallSpawn

3. KickAttempt

4. KickSuccess_X   T = Kick Success   F = Kick Failure

5. ReachSuccess_X   T = Goal Success   F = Goal Failure

6. EndTrial

Pass Events

Each entry in the log file has three columns. First is the time stamp, which stores data in seconds up to six decimal places. Second is the event. And the last column is Miscellaneous: Soccer Ball Number_Actor Display Name.

StartTrial log is added when the Start Task button ("T") is pressed. Every time the soccer ball spawns, BallSpawn log is added. Similarly, TeammateSpawn is added when a teammate is spawned. Although there are two different entries, they occur at the same time and hence have the same timestamp. Similar to Goal task KickAttempt log is added by the external controller's Trigger press operated by the experiment supervisor. The KickSuccess_X can have two results Success or Failure, which are represented by T and F, respectively. There is a large capsule collision around teammates. ReachSuccess_T entry is added when the ball enters this capsule collision. If the ball doesn't enter this and the time span of the ball is up (4.5 seconds), ReachSuccess_F is added signifying, pass failure. Finally, when all attempts are done, EndTrial is added.

Here is a summary:

1. StartTrial
2. BallSpawn
3. TeammateSpawn
4. KickAttempt
5. KickSuccess_X   T = Kick Success   F = Kick Failure
6. ReachSuccess_X   T = Pass Success   F = Pass Failure
7. EndTrial

Features for Double and Triple Tasks

The entries for Double and Triple tasks are the same as previous depending on the task. To better differentiate the tasks, an additional column is added, which signifies the tasks: **Evade, Goal, Pass.**
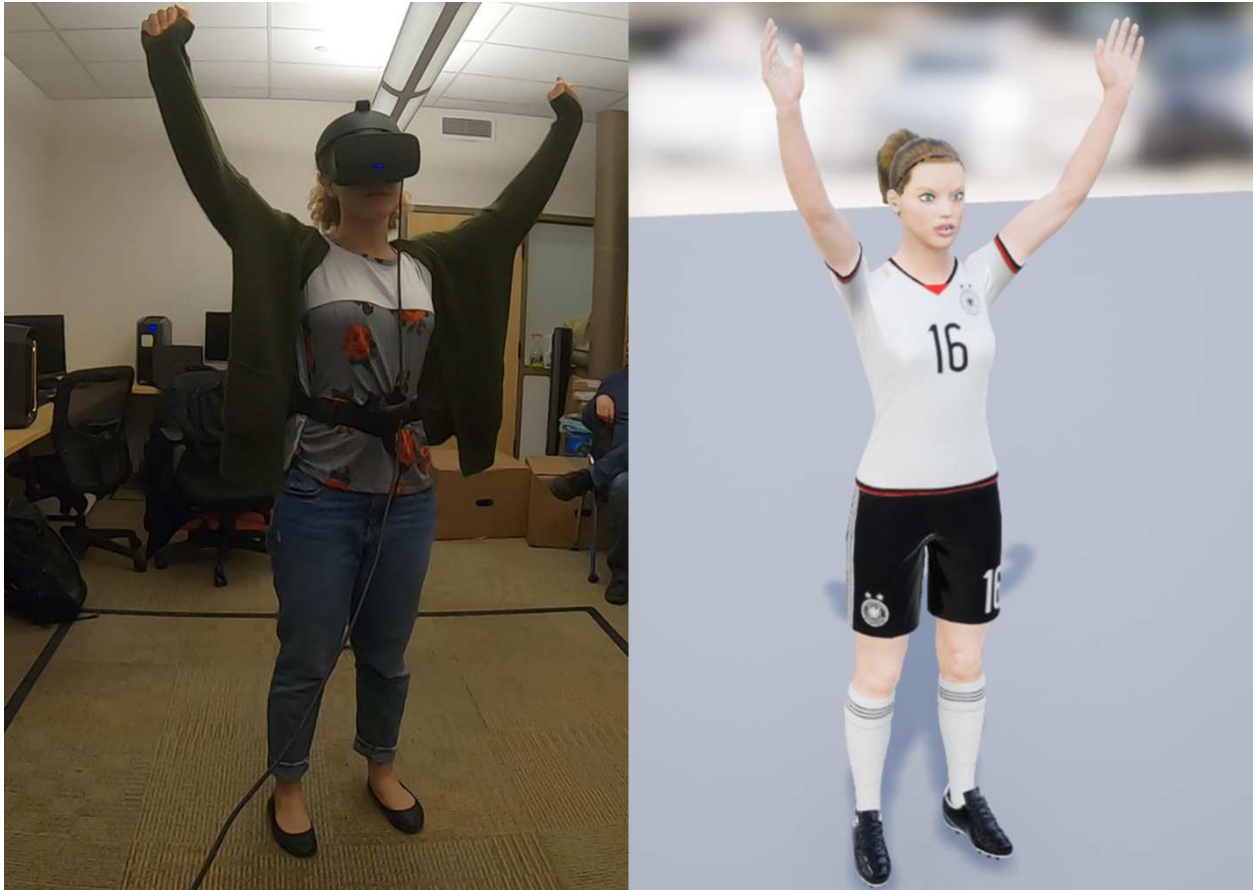

Figure 4.15: Player celebrating successful pilot

Chapter 5

Methodology

Commercial Virtual Reality (VR) products come with handheld controllers, which restricts the freedom of movement. This limits the applications and day-to-day interaction with VR. The purpose of this system is to understand how to develop an immersive soccer application that can be Incorporated into more specific use applications that can be used for assessment and health promotion.

SoccerSim VR uses a VR headset for display and camera tracking. The left controller is used to track the position of the body to define the center of gravity. Microsoft Kinect is used for tracking body movements. This set-up is used because of its affordability and ease of use. Using Microsoft Kinect means that users don't have to wear special suits or trackers. These can be used by the general population.

The participants complete a series of tasks. These are in a Virtual Reality (VR) environment. The participants find themselves in a virtual soccer field. A mirror is spawned in front of them. They can see their virtual body. At this stage, they can select their gender (avatar's gender) for the trial. After that, their height is set. Next, they do practice tasks to get used to the system.

We hypothesize that as task complexity increases, the performance for each individual declines slightly as well. Figure 5.1 shows the hypothesized decrease in performance. The following list has the available drills:

- **Dodge a charging player:** In this task, opponents spawn and start running at the subject. The subject has to move out of the way to not crash into the opponent players. There is a player with a soccer ball, and the subject has to tackle that player. This is important for Level 2 and 3, where there may be a follow-up task.

- **Shoot at goal:** In this task, a soccer ball spawns near the subject's leg. The task is to shoot at the goal.

- **Pass to a player:** In this task, players spawn periodically, and the subject's task is to pass the ball (which spawns close to his/her leg) to the player. The position of the player can be changed.
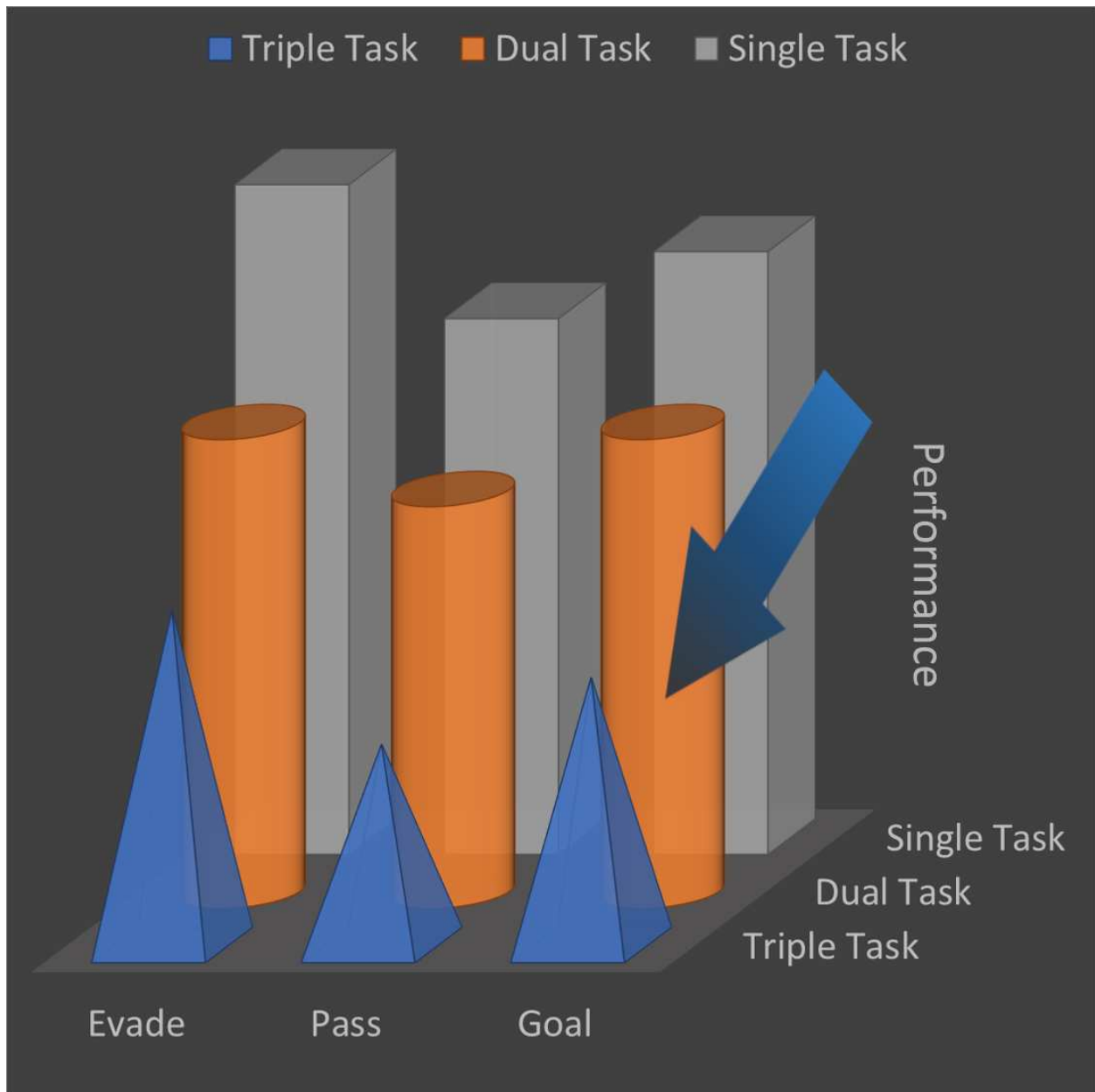

Figure 5.1: Different Levels of Experiment

5.1 Research Experiment

For the experiment, healthy participants are asked to fill out the pre-experiment questionnaire, which asks about their athletic history and any experience with mixed reality headsets. After getting preliminary instructions and information, they perform the following tasks:

1. **Practice levels**: In this level, subjects perform all three tasks. For the Evade task, they have five strikes. For the Goal and Pass tasks, they have five tries. This is for them to get used to the system.

2. **Single task levels**:The three tasks are randomly presented to the subjects. In the Evade tasks, subjects get 20 strikes, and for the Goal and Pass tasks, they have 20 tries. The increased number of tries is because the movements are not 100% the same as the real-world due to hardware limitations.

3. **Double task levels**: The two combinations of the tasks are randomly selected. Depending on the task, the players can either stand close to the goal(in case the task was to evade, get the ball and then kick to the goal) or far away in the case of pass. Both tasks are performed consecutively and repeated. The important thing is that the goal task never precedes the Evade task or the Pass task because once a goal is scored, the field resets, and the subject can't have the ball in their possession again or have opponents charging at them.

4. **Triple task level**: The three tasks are in the order: pass to a player, the player is tackled by an opponent and loses the ball; the subject has to tackle the opponent with the ball and then kick to the goal. This is to mimic a scenario found in actual soccer games. Again following the same pattern as double task, all three tasks are performed before repeating.

Completion of tasks is followed by the system usability survey and post-experiment questionnaire, mainly asking about differences between real and virtual experience and simulator sickness questionnaire.

This is a proof of concept for an immersive interactive environment. The Microsoft Kinect has its limitations where it doesn't track the movement 100% accurately. Also, the area that VR

headsets can track is small, which leads to constraints on freedom of movement like running. While it is easier to overcome Microsoft Kinect's limitation by using Motion Capture suit and cameras, it is expensive. One of the goals of this project this project is to find affordable options for the general population.

Figure 5.2: Shoot at goal task in Virtual environment

5.2   Lethargy and pre-experiment workout

During the pilot tests, what was noticed (observational measure) was that players were not moving around too much and were using minimum effort and movements. Although, as humans, we tend to find a more comfortable alternative, it defeats the purpose of using full-body tracking. What was observed is that as the players progressed further in the levels, and they noticed the movements that they were doing weren't enough to get good results, they started putting in more effort.

There are practice levels in the beginning to get the players familiar with the system. For the main experiment introduction of pre-workout/warm-up exercises might be beneficial. Hoff et al. experimented with studying the reduction of legacy bias in gesture elicitation using Kinesthetic Priming [21]. Half of the participants were subjected to kinesthetic priming. These participants were asked to move a few cardboard boxes under the pretense that space had to be made to perform the experiment. The subjects performed this exercise under the assumption that this wasn't part of the study. Kinesthetic priming was performed on subjects for the study. Although Kinesthetic

Priming is not required for this system, it may be helpful to have them do a warm-up session before using the system.

5.3 Surveys

Currently, participants are asked to fill out a total of five surveys. All the actual surveys are included in Appendix A.

5.3.1 Demographic questionnaire

The survey is done before the experiment. This survey is a pre-experiment survey to get basic information about the participant and their prior experience with different games, consoles, and VR equipment.

5.3.2 Simulator Sickness Questionnaire [22]

The survey is done during or after the experiment. The original survey was published by Kennedy, Lane, Berbaum, & Lilienthal in 1993. It measures - as the name suggests - simulation sickness usually induced by elements of visual display and visuo-vestibular interaction. VR technologies experience these effects of cybersickness. The symptoms are similar to motion sickness but less severe, although prolonged usage of the system can cause higher levels of discomfort. The scale consists of 16 symptoms that the subject has to self asses on four levels: None, Slight, Moderate, and Severe. Figure 5.3 shows a snapshot of SSQ [22].

5.3.3 Physical Activity Enjoyment Scale [23]

The survey is done after the experiment. This survey was developed by Kendziersji and De-Carlo in 1991. They developed this scale as a single factor, multi-item scale to assess the enjoyment of the physical activity that subjects perform in a particular experiment. It is a 7-point Likert scale with 18 questions or opinions. Each question itself is a range of subjective response. Figure 5.4 shows a few of these questions [23]. This scale is especially useful for understanding if the system can be used for health promotion.

Instructions : Circle how much each symptom below is affecting you <u>right now</u>.

1.	General discomfort	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
2.	Fatigue	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
3.	Headache	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
4.	Eye strain	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
5.	Difficulty focusing	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>
6.	Salivation increasing	<u>None</u>	<u>Slight</u>	<u>Moderate</u>	<u>Severe</u>

Figure 5.3: Self-Assessment Manikin [22]

Please rate how you feel at the moment about the physical activity you have been doing.

	1	2	3	4	5	6	7	
I enjoy it								I hate it
I feel bored	1	2	3	4	5	6	7	I feel interested
I dislike it	1	2	3	4	5	6	7	I like it
I find it pleasurable	1	2	3	4	5	6	7	I find it unpleasurable
	1	2	3	4	5	6	7	

Figure 5.4: Physical Activity Enjoyment Scale (Adapted from [23])

5.3.4 Post-Study System Usability Questionnaire [24]

The survey is done after the experiment. This survey originated from an internal IBM project called SUMS (System Usability Metrics) in 1988. The survey is widely used for measuring the satisfaction of a particular product. This product usually includes websites, software, system, or product. It has been revised twice after its initial release in 1988, and the third version is used today. The way to differentiate it is to look at the number of questions; there are 18 questions in version one, 19 questions in version two, and 16 questions in version three. Check Figure 5.5 for a small snapshot [24].

		Strongly Agree					Strongly Disagree			
PSSUQ		1	2	3	4	5	6	7	N.A.	
1. Overall, I am satisfied with how easy it is to use this system.										
2. It was simple to use this system.										
3. I was able to complete the tasks and scenarios quickly using this system.										
4. I felt comfortable using this system.										
5. It was easy to learn to use this system.										

Figure 5.5: Post-Study System Usability Questionnaire [24]

5.3.5 Self-Assessment Manikin [25]

The survey is done after the experiment. Bradley and Lang published a paper titled "Measuring Emotion: The Self-Assessment Manikin and The Semantic Differential" in 1994, where they introduced the Self-Assessment Manikin (SAM) scale. SAM is a non-verbal assessment technique that uses pictures instead of a numerical or linguistic scale. In response to a wide range of stimuli, SAM measures three emotional responses: Valence, Arousal, and Dominance. The stimulus differs from study to study, so each study needs a unique set of questions specific to the study. As shown in Figure 5.6, the scale has five blocks with pictures signifying different levels of emotion [25]. The choices are all five blocks and space between each block, giving a total of nine choices. SAM ranges from a smiling, happy figure to a frowning, unhappy figure when representing the valence dimension, and ranges from an excited, wide-eyed figure to a relaxed, sleepy figure for the arousal dimension. The dominance dimension represents changes in control with changes in the size of SAM: a large figure indicates maximum control in the situation.
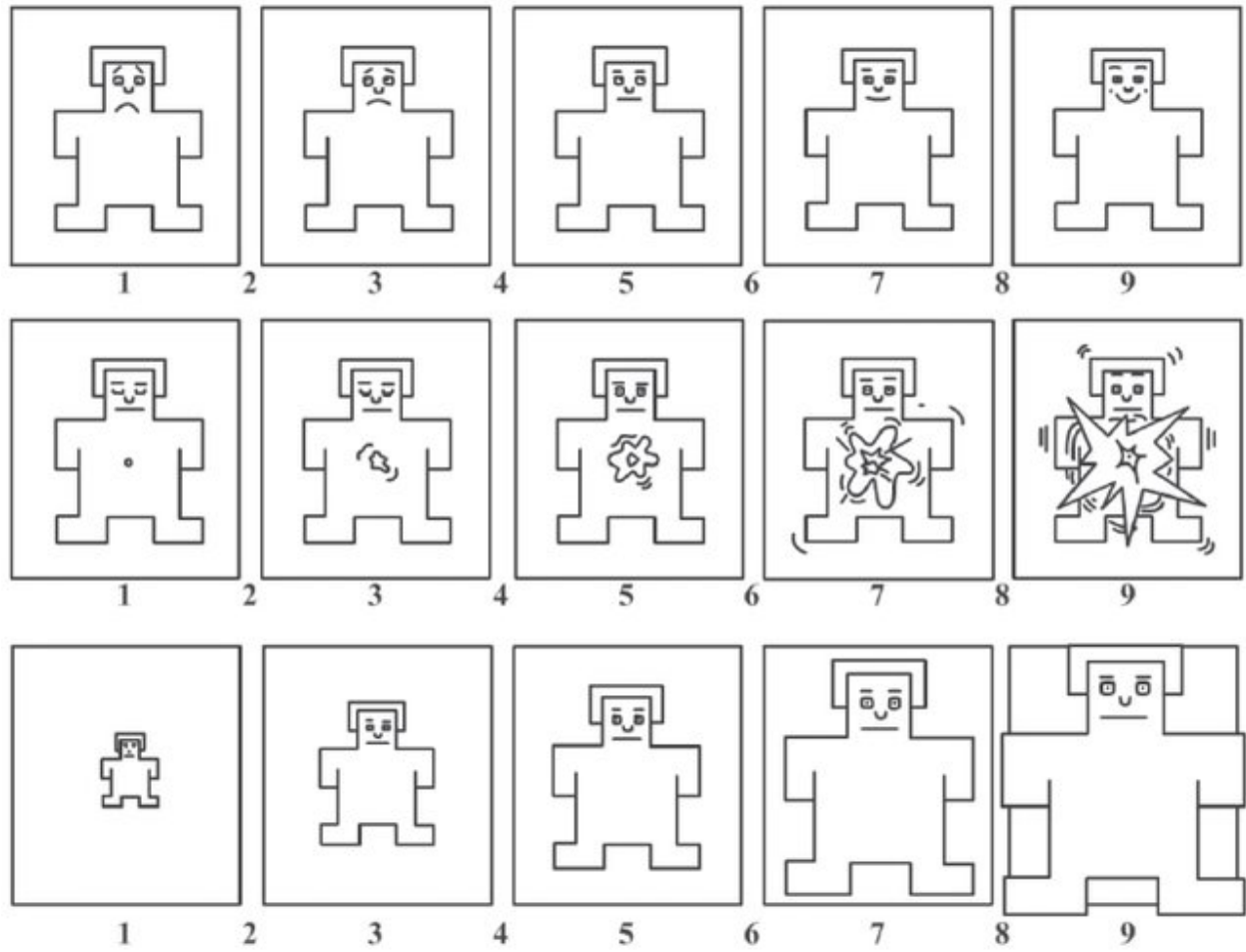
Figure 5.6: Self-Assessment Manikin [25]

Chapter 6

Use Cases

6.1 Concussion Assessment

Concussion is a type of mild traumatic brain injury(TBI). The American Association of Neurological Surgeons (AANS) defines a concussion as "a clinical syndrome characterized by immediate and transient alteration in brain function, including alteration of mental status and level of consciousness, resulting from mechanical force or trauma" [26]. In most cases of concussion, loss of consciousness is common, but there are cases when a person may have suffered concussion without losing consciousness. These can go undiagnosed and later result in the same complications and much more severe concussions [27]. One difficulty presented in concussion diagnosis is the wide range in type and severity of noticeable symptoms. A player suffering from a concussion may experience dizziness, nausea, loss of consciousness, headaches, difficulty concentrating, fatigue, and memory loss. The symptoms may last anywhere from a period of a few hours to weeks on end [28].

Methods to monitor athletes with a concussion include self-reported symptoms, clinician-rated balance performance, and computerized neurocognitive tests [29]. However, these methods are often subjective and may output poor test-retest reliability [30]. The lack of a better method causes the use of these methods.

Virtual Reality (VR) may enhance the management of concussion. Similar to other, new evaluation methods that have enhanced sensitivity to TBI, VR can be designed with increasingly complex tasks to measure subtle motor control [31] or multi-tasking abilities [32]. With the development of technology in full-body tracking, people can simulate real-world scenarios and measure movements more accurately [7]. More importantly, VR can capture elements of performance in which athletes are unaware of being tested. Although visual immersion is only a part of the overall experience of immersion, it is a critical factor, and depending on the body schema, the body image

changes. Visual immersion can even change the space perception and perception of objects [33,34]. Athletes have been found to underperform when they know they are being tested [35]. A lot of the assessment techniques rely on expensive instruments or prolonged and through training for administration. VR is a fairly inexpensive techniques are being developed to enhance the extraction and evaluation of performance-based data [36], which eases and enhances clinician decision-making. VR has been used to evaluate mild TBI in military personnel [37], to treat orthopedic sports injury [38] and has significant potential to evaluate and treat TBI in athletes [39]. The reason of including Double and Triple tasks was inspired by the work of Howell et al. [40]. According to Howell et al. an increase in complexity between two conditions is a result of the necessary increase in sustained attention for completion.

6.2 Promotion of Health

Teenagers and Adolescents are active media users and first to adapt to new types of entertainment. They are susceptible to addiction to these kinds of entertainment and may start to ignore their physical well-being. Vallance et al. talked about the adverse effects of high volumes of sitting (> 8 hours/day) on health [41]. Public health professionals must adopt modern technologies and find ways to incorporate them into their strategies. VR provides a way to combine entertainment and physical activities.

Conner et al. introduced a system for correcting a user's form in real-time while performing a free weight exercise [42]. They used Microsoft Kinect V2 for tracking the body movements. The exercise they chose was Squats, the reason being that squats are easy to track with a rigid and specific set of form specifications. The pilot study showed positive results with participants expressing that the software was beneficial and helped improve their form as they progressed.

Baranowski et al. presented a work where they discussed health promotion and weight-loss in children [43]. They noted that health promotion is effectively behavior change and can be categorized into following: (1) Web-based educational/therapeutic programs (ET), (2) tailored message (TM) systems, (3) data monitoring and feedback (DMF) systems, (4) active video games (AVG),

and (5) interactive multimedia involving games (IMG). They presented findings and available options for each of these categories. The final takeaway was there is no set approach which will work on everyone and this is especially true when comparing between different age groups.

Deutsch et al. presented the feasibility of their system, Virtual Reality Augmented Cycling Kit (VRACK), developed for addressing motor control and fitness deficits of individuals with chronic stroke [44]. They designed a Virtual Environment where the participants were asked to catch another cyclist (virtual). The speed of the other cyclist depended on a Target Heart Rate specified by the participant's physician. Proper indicators were implemented in the Virtual Environment to alert the participant and ensure their safety. They not only found positive results with regards to safety and feasibility but even noticed a transfer of training from the bicycle to walking endurance.

Looking at different studies such as these, we believe SoccerSim VR has the potential to be incorporated into a system whose focus is promoting health. SoccerSim VR needs more testing with different age groups to determine the most suitable age group for this system. Some aids to the players like aim assist may decrease frustration and increase the pleasure of using the system.

Chapter 7

Conclusion and Future Work

The presented thesis is a high-level design guide for highly immersive applications while providing a future-path for human-subject experiments. The results from pilot studies suggest that subjects enjoyed the system. Although initially, the subjects did not start out feeling active and limited their movements as the levels progressed, they got more excited and invested in the system, more immersed in the system. Looking at the pilot data, we can at least say that this idea may help with return-to-play readiness post-concussion for athletes who suffered a concussion in the past and may suffer from performance degradation, and promoting health for non-athletes. Compared to the initial prototype of the system where trigger on hand held controllers did the kicking for the players, this provided much more feeling of immersion.

The use of marker-less full-body motion tracking comes with its own limitations, but as technology advances, we may be able to overcome these limitations. Using multiple Kinects may be useful to reduce the jittering of the foot, which makes it harder to kick. For promoting health addition of assist, a function may be helpful where the trajectory of the ball is determined by the movement of the foot and not precisely by where the ball made contact with the ball. Addition of a real ball with a tracker that can be kicked in a safe room can increase the level of immersion significantly by providing haptic feedback.

Bibliography

[1] Omar Janeh, Odette Fründt, Beate Schönwald, Alessandro Gulberti, Carsten Buhmann, Christian Gerloff, Frank Steinicke, and Monika Pötter-Nerger. Gait training in virtual reality: Short-term effects of different virtual manipulation techniques in parkinsonâĂŹs disease. *Cells*, 8(5):419, 2019.

[2] Mark A Steadman, Chungeun Kim, Jean-Hugues Lestang, Dan FM Goodman, and Lorenzo Picinali. Short-term effects of sound localization training in virtual reality. *Scientific Reports*, 9(1):1–17, 2019.

[3] Frédéric Banville, Pierre Nolin, Thaïna Rosinvil, Eulalie Verhulst, and Philippe Allain. Assessment and rehabilitation after traumatic brain injury using virtual reality: A systematic review and discussion concerning human-computer interactions. In *Virtual Reality for Psychological and Neurocognitive Interventions*, pages 327–360. Springer, 2019.

[4] Shachar Maidenbaum, Ansh Patel, Elisabeth Stein, and Joshua Jacobs. Spatial memory rehabilitation in virtual reality–extending findings from epilepsy patients to the general population. In *Proceedings of the 13th International Conference on Virtual Rehabillitation*, 2019.

[5] Steven Arild Wuyts Andersen, Mads Guldager, Peter Trier Mikkelsen, and Mads Sølvsten Sørensen. The effect of structured self-assessment in virtual reality simulation training of mastoidectomy. *European Archives of Oto-Rhino-Laryngology*, 276(12):3345–3352, 2019.

[6] Coşku Turhan, Gürhan Dönmez, Gazi Huri, and Mahmut Nedim Doral. Simulation training and assessment in fracture treatment. In *Intraarticular Fractures*, pages 403–408. Springer, 2019.

[7] Misha Sra and Chris Schmandt. Metaspace ii: Object and full-body tracking for interaction and navigation in social vr. *arXiv preprint arXiv:1512.02922*, 2015.

[8] Mehmet Ilker Berkman and Ecehan Akan. *Presence and Immersion in Virtual Reality*, pages 1–10. Springer International Publishing, Cham, 2019.

[9] Bottom-up vs. top-down processing, openpsyc. http://openpsyc.blogspot.com/2014/06/bottom-up-vs-top-down-processing.html.

[10] Sungchul Jung and Charles Hughes. Body ownership in virtual reality. *2016 International Conference on Collaboration Technologies and Systems (CTS)*, pages 597–600, 10 2016.

[11] Polona Caserman, Augusto Garcia-Agundez, Robert Konrad, Stefan Göbel, and Ralf Steinmetz. Real-time body tracking in virtual reality using a vive tracker. *Virtual Reality*, 23(2):155–168, 2019.

[12] Filip Drobnjakovic, Jeffrey B Douangpaseuth, Cristian Gadea, Meesam Haider, Dan Ionescu, Bogdan Ionescu, and Lucas Poon. Fusing data from inertial measurement units and a 3d camera for body tracking. In *2018 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, pages 1–6. IEEE, 2018.

[13] Kinect sdk, microsoft. https://developer.microsoft.com/en-us/windows/Kinect/.

[14] Ryuzo Okada and Björn Stenger. A single camera motion capture system for human-computer interaction. *IEICE TRANSACTIONS on Information and Systems*, 91(7):1855–1862, 2008.

[15] Daniel Grest, Volker Krüger, and Reinhard Koch. Single view motion tracking by depth and silhouette information. In *Scandinavian Conference on Image Analysis*, pages 719–729. Springer, 2007.

[16] Paolo Leoncini, Bogdan Sikorski, Vincenzo Baraniello, Francesco Martone, Carlo Luongo, and Mariano Guida. Multiple nui device approach to full body tracking for collaborative virtual environments. In *International Conference on Augmented Reality, Virtual Reality and Computer Graphics*, pages 131–147. Springer, 2017.

[17] F8, facebook. https://www.f8.com/.

[18] Turbosquid. https://www.turbosquid.com/.

[19] Thomas Waltemate, Dominik Gall, Daniel Roth, Mario Botsch, and Marc Erich Latoschik. The impact of avatar personalization and immersion on virtual body ownership, presence, and emotional response. *IEEE transactions on visualization and computer graphics*, 24(4):1643–1652, 2018.

[20] Mar Gonzalez-Franco, Daniel Perez-Marcos, Bernhard Spanlang, and Mel Slater. The contribution of real-time mirror reflections of motor actions on virtual body ownership in an immersive virtual environment. In *2010 IEEE virtual reality conference (VR)*, pages 111–114. IEEE, 2010.

[21] Lynn Hoff, Eva Hornecker, and Sven Bertel. Modifying gesture elicitation: Do kinaesthetic priming and increased production reduce legacy bias? In *Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 86–91, 2016.

[22] Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3):203–220, 1993.

[23] Deborah Kendzierski and Kenneth J DeCarlo. Physical activity enjoyment scale: Two validation studies. *Journal of sport & exercise psychology*, 13(1), 1991.

[24] James R Lewis. Psychometric evaluation of the post-study system usability questionnaire: The pssuq. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 36, pages 1259–1260. SAGE Publications Sage CA: Los Angeles, CA, 1992.

[25] Margaret M Bradley and Peter J Lang. Measuring emotion: the self-assessment manikin and the semantic differential. *Journal of behavior therapy and experimental psychiatry*, 25(1):49–59, 1994.

[26] Concussion, american association of neurological surgeons. https://www.aans.org/Patients/Neurosurgical-Conditions-and-Treatments/Concussion.

[27] William P Meehan III, Rebekah C Mannix, Michael J O'Brien, and Michael W Collins. The prevalence of undiagnosed concussions in athletes. *Clinical journal of sport medicine: official journal of the Canadian Academy of Sport Medicine*, 23(5):339, 2013.

[28] Peter M Rees. Contemporary issues in mild traumatic brain injury. *Archives of physical medicine and rehabilitation*, 84(12):1885–1894, 2003.

[29] Christine M Baugh, Emily Kroshus, Julie M Stamm, Daniel H Daneshvar, Michael J Pepin, and William P Meehan III. Clinical practices in collegiate concussion management. *The American journal of sports medicine*, 44(6):1391–1399, 2016.

[30] Steven P Broglio, Barry P Katz, Shi Zhao, Michael McCrea, Thomas McAllister, CARE Consortium Investigators, et al. Test-retest reliability and interpretation of common concussion assessment tools: findings from the ncaa-dod care consortium. *Sports Medicine*, 48(5):1255–1268, 2018.

[31] Jaclyn A Stephens, Patricia L Davies, William J Gavin, Stewart H Mostofsky, Beth S Slomine, and Stacy J Suskauer. Evaluating motor control improves discrimination of adolescents with and without sports related concussion. *Journal of motor behavior*, pages 1–9, 2019.

[32] Olivia A Galea, Michelle A Cottrell, Julia M Treleaven, and Shaun P OâĂŹLeary. Sensorimotor and physiological indicators of impairment in mild traumatic brain injury: a meta-analysis. *Neurorehabilitation and neural repair*, 32(2):115–128, 2018.

[33] Doug A Bowman and Ryan P McMahan. Virtual reality: how much immersion is enough? *Computer*, 40(7):36–43, 2007.

[34] Shaun Gallagher. Body schema and intentionality. *The body and the self*, 225:244, 1995.

[35] Philip Schatz, Rosemarie Scolaro Moser, Gary S Solomon, Summer D Ott, and Robin Karpf. Prevalence of invalid computerized baseline neurocognitive test results in high school and collegiate athletes. *Journal of Athletic Training*, 47(3):289–296, 2012.

[36] Zhichao Yang, Mohammad H Rafiei, Alexis Hall, Caroline Thomas, Hali A Midtlien, Alexander Hasselbach, Hojjat Adeli, and Lynne V Gauthier. A novel methodology for extracting and evaluating therapeutic movements in game-based motion capture rehabilitation systems. *Journal of medical systems*, 42(12):255, 2018.

[37] Nicolas Robitaille, Philip L Jackson, Luc J Hébert, Catherine Mercier, Laurent J Bouyer, Shirley Fecteau, Carol L Richards, and Bradford J McFadyen. A virtual reality avatar interaction (vrai) platform to assess residual executive dysfunction in active military personnel with previous mild traumatic brain injury: proof of concept. *Disability and Rehabilitation: Assistive Technology*, 12(7):758–764, 2017.

[38] Dustin R Grooms, Adam W Kiefer, Michael A Riley, Jonathan D Ellis, Staci Thomas, Katie Kitchen, Christopher A DiCesare, Scott Bonnette, Brooke Gadd, Kim D Barber Foss, et al. Brain-behavior mechanisms for the transfer of neuromuscular training adaptions to simulated sport: Initial findings from the train the brain project. *Journal of sport rehabilitation*, 27(5), 2018.

[39] Maria Grazia Maggio, Rosaria De Luca, Francesco Molonia, Bruno Porcari, Massimo Destro, Carmela Casella, Ramona Salvati, Placido Bramanti, and Rocco Salvatore Calabro. Cognitive rehabilitation in patients with traumatic brain injury: A narrative review on the emerging use of virtual reality. *Journal of Clinical Neuroscience*, 2019.

[40] David R Howell, Louis R Osternig, Michael C Koester, and Li-Shan Chou. The effect of cognitive task complexity on gait stability in adolescents following concussion. *Experimental brain research*, 232(6):1773–1782, 2014.

[41] Jeff K Vallance, Paul A Gardiner, Brigid M Lynch, Adrijana DâĂŹSilva, Terry Boyle, Lorian M Taylor, Steven T Johnson, Matthew P Buman, and Neville Owen. Evaluating the evidence on sitting, smoking, and health: is sitting really the new smoking? *American journal of public health*, 108(11):1478–1482, 2018.

[42] Caleb Conner and Gene Michael Poor. Correcting exercise form using body tracking. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, pages 3028–3034, 2016.

[43] Tom Baranowski and Leslie Frankel. Let's get technical! gaming and technology for weight control and health promotion in children. *Childhood Obesity (Formerly Obesity and Weight Management)*, 8(1):34–37, 2012.

[44] Judith E Deutsch, Mary Jane Myslinski, Michal Kafri, Richard Ranky, Mark Sivak, Constantinos Mavroidis, and Jeffrey A Lewis. Feasibility of virtual reality augmented cycling for health promotion of people post-stroke. *Journal of neurologic physical therapy: JNPT*, 37(3), 2013.

Appendix A

Surveys

A.1   Demographics Questionnaire

Demographics Questionnaire

Participant #: _____ Date: _____

The purpose of this questionnaire is to collect background information and the information provided is strictly for the purposes of research only.

1. Age: _____

2. Sex: Male   Female   Other

3. What is your current academic standing?   Freshman   Sophomore   Junior   Senior   Graduate Student

4. What is your major? _____

5. Have you ever used a Virtual Reality headset? Yes □ No □

6. Are you currently wearing corrective lenses (contacts or glasses)? Yes □ No □

7. Do you currently have, or have you ever had a heart condition, seizures, or epilepsy? Yes □ No □

8. If you have answered Yes for any of the above conditions, please explain: _____
_____
_____
_____

9. Have you consumed any of the following in the past 24 hours?
   Caffeine   Yes □ No □
   Alcohol   Yes □ No □
   Nicotine   Yes □ No □

10. Indicate the average number of **hours per** *week* you spend using **computers** (personal and work combined): _____

11. Indicate the average number of **hours per** *week* you spend playing the following types of games:

    a. First person shooter games (e.g., Perfect Dark, Call of Duty) _____
    b. Massively multiplayer online games (e.g., World of Warcraft, Age of Empires) _____
    c. Flight simulators (e.g., X-Plane, ProFlight Sim) _____
    d. Sports/racing (e.g., Madden NFL 10, Mario Kart Wii) _____
    e. Military command/strategy (e.g., Tekken Tag, America's Army) _____
    f. Fighting (e.g., Street Fighter IV) _____
    g. Life/business simulations (e.g., The Sims) _____
    h. Fantasy/adventure (e.g., Assassins Creed, Final Fantasy 8) _____
    i. Puzzles/card games/board games (e.g., Solitaire, Settlers of Catan). _____
    j. Social networking games (e.g., Mafia Wars, Farmville) _____
    k. Other: Please specify _____ Hours: _____

For the options listed in Question 11, please indicate with an "X" the type you play most often.

12. Indicate the number of hours **per week** you spend playing games using the following controllers:

   a. Steering wheel _____
   b. Keyboard and mouse _____
   c. Nintendo DS and Nintendo 3DS _____
   d. Gameboy and Gameboy Color _____
   e. Gameboy Advance _____
   f. Touchscreen (e.g., smartphone, tablet) _____
   g. Wii remote _____
   h. Wii accessories (e.g., numchuck, balance board) _____
   i. WiiU gamepad _____
   j. Nintendo 64 controller _____
   k. Nintendo GameCube controller _____
   l. Xbox, Xbox 360, and Xbox One controller _____
   m. PlayStation controller _____
   n. PlayStation Portable (PSP) and PlayStation Vita _____
   o. Xbox Kinect _____
   p. Leap Motion 3D controller_____
   q. Oculus rift _____
   r. Other: Please specify _____ Hours: _____

A.2 Simulator Sickness Questionnaire [22]

No_____   Date_____

SIMULATOR SICKNESS QUESTIONNAIRE
Kennedy, Lane, Berbaum, & Lilienthal (1993)***

Instructions : Circle how much each symptom below is affecting you <u>right now</u>.

		None	Slight	Moderate	Severe
1.	General discomfort	None	Slight	Moderate	Severe
2.	Fatigue	None	Slight	Moderate	Severe
3.	Headache	None	Slight	Moderate	Severe
4.	Eye strain	None	Slight	Moderate	Severe
5.	Difficulty focusing	None	Slight	Moderate	Severe
6.	Salivation increasing	None	Slight	Moderate	Severe
7.	Sweating	None	Slight	Moderate	Severe
8.	Nausea	None	Slight	Moderate	Severe
9.	Difficulty concentrating	None	Slight	Moderate	Severe
10.	« Fullness of the Head »	None	Slight	Moderate	Severe
11.	Blurred vision	None	Slight	Moderate	Severe
12.	Dizziness with eyes open	None	Slight	Moderate	Severe
13.	Dizziness with eyes closed	None	Slight	Moderate	Severe
14.	*Vertigo	None	Slight	Moderate	Severe
15.	**Stomach awareness	None	Slight	Moderate	Severe
16.	Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Last version : March 2013

***Original version : Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology*, 3(3), 203-220.

Simulator Sickness Questionnaire***
Kennedy, Lane, Berbaum, & Lilienthal (1993)***

Validation of the French-Canadian version of the SSQ developed by the UQO Cyberpsychology Lab :

- Total : items 1 to 16 (scale of 0 to 3).
  - « *Nausea* » : items 1 + 6 + 7 + 8 + 12 + 13 + 14 + 15 + 16.
 - « *Oculo-motor* »: items 2 + 3 + 4 + 5 + 9 + 10 + 11.

Please refer to the following articles for more information about the French-Canadian validated version :

BOUCHARD, S., Robillard, & Renaud, P. (2007). Revising the factor structure of the Simulator Sickness Questionnaire. Acte de colloque du *Annual Review of CyberTherapy and Telemedicine, 5,* 117-122.

BOUCHARD, S., St-Jacques, J., Renaud, P., & Wiederhold, B.K. (2009). Side effects of immersions in virtual reality for people suffering from anxiety disorders. *Journal of Cybertherapy and Rehabilitation*, 2(2), 127-137.

BOUCHARD, S. Robillard, G., Renaud, P., & Bernier, F. (2011). Exploring new dimensions in the assessment of virtual reality induced side-effects. *Journal of Computer and Information Technology*, *1*(3), 20-32.

Based on results from Bouchard, St-Jacques, Renaud, & Wiederhold (2009), below are the mean scores reported:
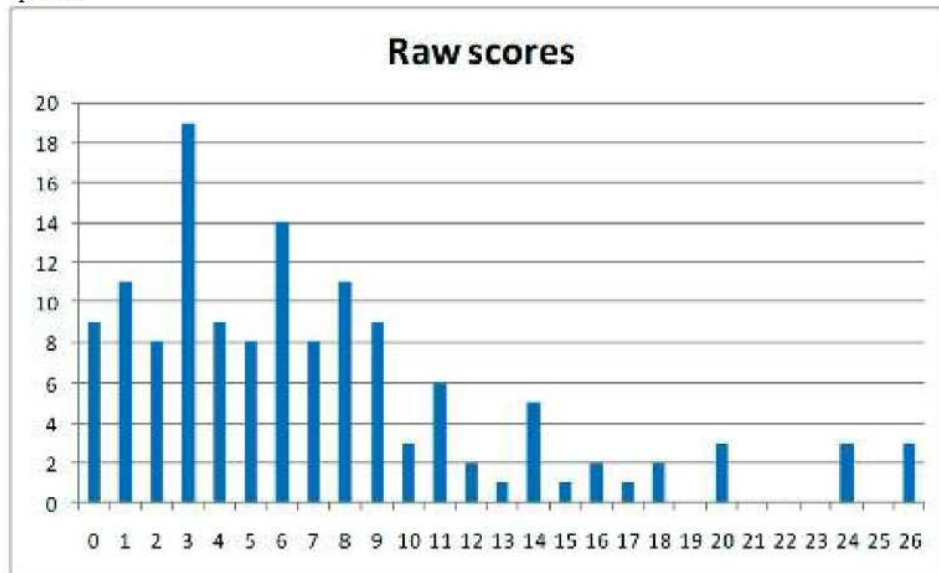
Note. For the original scoring version, consult : Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology, 3*(3), 203-220.

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A.3   Physical Activity Enjoyment Scale [23]

Please enter your participant number: _____

Physical Activity Enjoyment Scale (PACES)

This is a questionnaire to gain insight into how you felt about the physical activity.

Please rate how you feel at the moment about the physical activity you have been doing.

	1	2	3	4	5	6	7	
I enjoy it	1	2	3	4	5	6	7	I hate it
I feel bored	1	2	3	4	5	6	7	I feel interested
I dislike it	1	2	3	4	5	6	7	I like it
I find it pleasurable	1	2	3	4	5	6	7	I find it unpleasurable
I am very absorbed in this activity	1	2	3	4	5	6	7	I am not at all absorbed in this activity
It's no fun at all	1	2	3	4	5	6	7	It's a lot of fun
I find it energizing	1	2	3	4	5	6	7	I find it tiring
It makes me depressed	1	2	3	4	5	6	7	It makes me happy
It's very pleasant	1	2	3	4	5	6	7	It's very unpleasant
I feel good physically while doing it	1	2	3	4	5	6	7	I feel bad physically while doing it
It's very invigorating	1	2	3	4	5	6	7	It's not at all invigorating
I am very frustrated by it	1	2	3	4	5	6	7	I am not at all frustrated by it
It's very gratifying	1	2	3	4	5	6	7	It's not at all gratifying
It's very exhilarating	1	2	3	4	5	6	7	It's not at all exhilarating

	1	2	3	4	5	6	7	
It's not at all stimulating								It's very stimulating

	1	2	3	4	5	6	7	
It gives me a strong sense of accomplishment								It does not give me any sense of accomplishment at all

	1	2	3	4	5	6	7	
It's very refreshing								It's not at all refreshing

	1	2	3	4	5	6	7	
I felt as though I would rather be doing something else								I felt as though there was nothing else I would rather be doing

A.4 Post-Study System Usability Questionnaire [24]

UIUX Trend

PSSUQ Questionnaire PDF Template

On a scale between Strongly Agree to Strongly Disagree, please rate the following statements:

PSSUQ	Strongly Agree					Strongly Disagree			
	1	2	3	4	5	6	7	N.A.	
1. Overall, I am satisfied with how easy it is to use this system.									
2. It was simple to use this system.									
3. I was able to complete the tasks and scenarios quickly using this system.									
4. I felt comfortable using this system.									
5. It was easy to learn to use this system.									
6. I believe I could become productive quickly using this system.									
7. The system gave error messages that clearly told me how to fix problems.									
8. Whenever I made a mistake using the system, I could recover easily and quickly.									
9. The information (such as online help, on-screen messages, and other documentation) provided with this system was clear.									

	Strongly Agree					Strongly Disagree			
	1	2	3	4	5	6	7	N.A.
10. It was easy to find the information I needed.								
11. The information was effective in helping me complete the tasks and scenarios.								
12. The organization of information on the system screens was clear.								
13. The interface of this system was pleasant.								
14. I liked using the interface of this system.								
15. This system has all the functions and capabilities I expect it to have.								
16. Overall, I am satisfied with this system.								

Questions 1 to 16: Overall
Questions 1 to 6: System Usefulness (SYSUSE)
Questions 7 to 12: Information Quality (INFOQUAL)
Questions 13 to 16: Interface Quality (INTERQUAL)

Source: uiuxtrend.com

A.5 Self-Assessment Manikin [25]

Please enter your participant number: _____

Self-Assessment Manikin

Self-Assessment Manikin measures the emotional response to a wide range of stimuli.

Please rate the appropriate emotional response you felt while using the system by looking at the chart at the end.

1. Practice Stage:
   a. Task 1: Valence __   Arousal __   Dominance __
   b. Task 2: Valence __   Arousal __   Dominance __
   c. Task 3: Valence __   Arousal __   Dominance __
2. Stage 1:
   a. Task 1: Valence __   Arousal __   Dominance __
   b. Task 2: Valence __   Arousal __   Dominance __
   c. Task 3: Valence __   Arousal __   Dominance __
3. Stage 2:
   a. Task 1: Valence __   Arousal __   Dominance __
   b. Task 2: Valence __   Arousal __   Dominance __
   c. Task 3: Valence __   Arousal __   Dominance __
4. Stage 3:
   a. Task 1: Valence __   Arousal __   Dominance __