DEVELOPING A VIRTUAL REALITY-BASED GAMING SYSTEM FOR UPPER EXTREMITY HEMIPARESIS STROKE REHABILITATION

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THESIS CERTIFICATE

This is to certify that the thesis entitled **"DEVELOPING A VIRTUAL REALITY-BASED GAMING SYSTEM FOR UPPER EXTREMITY HEMIPARESIS STROKE REHABILITATION"** submitted by **SAI PRASHANTH PATHI** to the Indian Institute of Technology, Madras for the award of the degree of **Dual Degree (B.Tech and M.Tech)** is a bona fide record of research work carried out by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

Stroke which is caused due to a lack of blood flow or disruption of blood vessels in the brain leaves a patient with several health impairments with *upper extremity hemiparesis* (weakness in the upper limbs) as the most common one. Thus, there is a need for an immediate and apt rehabilitation to help stroke survivors restore their normal health and life. A typical rehabilitation is physiotherapy which involves several exercises followed by standard clinical tests. However, research studies depict that patients tend to lose interest and motivation with time because of the monotonous behaviour of the exercises. As a solution to this inevitable issue, researchers started adopting technologies such as Virtual Reality (VR) to create fun-filled interactive games ("*Serious games*") which allow patients to do exercises while playing.

Serious games for upper extremity hemiparesis rehabilitation involve a wide range of hand movements- reaching, picking objects, grasping, opening and closing of fist, etc. These games are based on parameters like PC/Head Mounted Device (HMD)-modality, Activity Daily Living (ADL) games, different levels, rewards, scoring, reaction time, speed, time of game completion and feedback. However, we still need to consider game challenges like— what should be the language of feedback and the game score to motivate patients, the amount of cognitive component at each game level, and what are the parameters to quantify the patients' hand movement response which is controlled by the games.

Motivated by the needs mentioned above, we developed a Virtual Reality-based Gaming System (VGS) consisting of two games- *Fruit Cutter* and *Space Meteor Shooter*. The *Fruit Cutter* game requires a player to move his/her right hand along X and Y axes and the *Space Meteor Shooter* requires the closing-opening of the right fist. The VGS, a PC-based system connected with Kinect sensor for game interaction is made up of three modules- (1) *Gaming Module*, (2) *Interactive module*, and (3) *Scoring Module*. The first module focused on the game designing on Unity platform. The second module made the games interactive by linking Kinect with Unity, and the last module displayed real-time scoring and feedback based on the player's performance. To understand the feasibility of the VGS, a pilot study was conducted with five healthy participants over three sessions. The results indicated the VGS has the potential to engage players in the games for longer time while motivating them to score higher over multiple sessions and also highlighted the type of games to be used at lower and higher levels.

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1. INTRODUCTION

1.1. STROKE REHABILITATION

Stroke is a major public health risk. It is the most widespread disease in the western world and is one of the main causes for the permanent impairment in humans [30]. It is also the primary cause of adult disability and the third leading cause of death in the United States of America [30]. According to the report of Internet Stroke Centre released in the year 2008, stroke affects over 15 million people per year globally.

Stroke occurs due to the loss of neural tissues in the brain when there is no blood flow to the brain. It may specifically occur as a result of either blocked artery (known as *ischemic stroke*) or disruption of a blood vessel (known as *haemorrhagic stroke*) [1]. It can occur at any point of time in an individual's life causing drastic neurophysiological changes in him/her [5]. For instance, a stroke patient may suffer from asymmetric posture, inability to move or feel on one side of the body, speech and vision deficits, and even cognitive inability [26]. Hence, an immediate rehabilitative treatment and care needs to be aided to the patients for faster recovery.

Stroke rehabilitation is a process by which stroke patients undergo treatment to get back to their normal pre-stroke life. This includes relearning the basic everyday chores and life skills that they are unable to do after stroke. The goal of the rehabilitation is, thus, to restore as much independence as possible by improving physical, mental and emotional states of the stroke survivor. If a patient is medically stable, rehabilitation may begin within one day after the stroke [1]. It is continued for months or years post stroke until the condition improves otherwise, if not treated immediately and consistently, a patient's health may worsen. However, stroke rehabilitation often depends upon several factors, including the ability to tolerate intensity of rehabilitation (hours/stamina), degree of disability, available funding, insurance coverage, and the patient's geographical area.

Often stroke patients rely on physiotherapy conducted in the presence of specialized physiotherapists for rehabilitation. This traditional method involves several repetitive exercises and standard tests like the Fugl-Meyer Assessment (FMA), Wolf Motor Function Test (WMFT), etc. [16,27]. Although patients readily agree to attend these therapy sessions, with time, they tend to lose motivation and interest due to the monotonous exercises and therapy procedure [16]. As a result, despite of spending hours on therapy, recovery rate in the patients seldom do not appear as expected. To tackle this serious problem in the stroke population, scientists and researchers started looking for alternatives or approaches of rehabilitation and therapy that could boost their self-willingness for the exercises. One such contemporary approach took birth in the form of games built by exploiting the modern technologies that are otherwise used for commercial entertainment purposes. Such games used for non-entertainment such as training skills, therapy needs, etc, came to be popularly known as *serious games* [7,8,21]. And, one of the technologies used by these serious games for motor rehabilitation is *Virtual Reality* (VR) [18].

1.2. MOTIVATION

VR technologies were developed for the first time and studied as potential tools for assessment and treatment in rehabilitation in the last decade of the 20th-century. These technology-based applications like VR games provide interactive environment in addition to increased motivation during motor tasks, either with the direct involvement of therapists or remotely at home [4,25]. What can be done with various modern techniques like VR is to make the exercises easier, full of fun and engagement for the patients so that the rehabilitation process can be less hectic. Again, these needs for fun and engagement are fulfilled by interactive games which focus on enhancing tasks by adding elements of enjoyment and stimuli that capture patients' attention. These games further aid the recovery process by providing components of fun to help overcome cognitive limitations, so the patients are capable of focusing on physical rehabilitation. Thus, combination of entertainment sources with practical tasks makes these VR games immensely fascinating, interactive and provides motivation to patients to perform tasks without getting bored. In fact, it has been seen that such games have the capability to reduce the time taken to recover, when used in adjunct with the traditional physiotherapy treatments [2,20].

For rehabilitation of upper extremity hemiparesis in particular, VR games have been developed which involves wide range and types of upper limb movements such as simple reaching, grasping, lateral hand movement, closing and opening of fist, etc. [7]. However, developing games is not enough. For the game to be interactive, sensing devices like Kinect, controllers, hand gloves, etc., are needed so that the patients can feel their presence within the game environment which is very important for engaging them [1,17]. There are VR games such as "Archery" that enabled the patients to move their whole arm [6]. Da silva et al. developed a game named "Spheroids" in which the patients had to move the hands to touch a ball approaching in VR [11]. There are several games related to Activity Daily Living such as supermarket game where the patient has to virtually tour a supermarket and buy things by making hand gestures [19]. These examples of the gaming systems are all lab-based, i.e., a patient has to be physically present with the therapist. However, there are advance remote based gaming systems in VR such as "RehabMaster" which can connect the patient and the therapist remotely [24]. Apart from the stroke-specific designed games, commercial games like Nintendo Wii have also been explored but its efficacy in terms of rehabilitation is not much as that of the stroke-specific games [8, 22]. There are other games which also has cognitive component in it like attention and memory; these are important as stroke patients may have cognitive deficits [14].

In all the examples of VR based games above, the common characteristics that make these successful in rehabilitation are game-design parameters such as scoring, feedback, levels of game and rewards. With the help of scores, time, speed, etc., some secondary factors such as reaction time, longer play duration and levels of enjoyment were quantified [23]. Besides, to study the user usability or satisfiability, survey questionnaires were made which were answered by patients after each session of the games. However, there are challenges that still exist, such as scoring and feedback challenge. It is important to avoid negative scoring and provide positive feedback to the patients even if they perform bad in the beginning. Although remote based systems provide easy access to patients who do not need to travel to hospitals or therapy centres, such systems are expensive and are not affordable to all people, especially in a developing country like India. In spite the fact that games having cognitive component helps in recovering the cognitive ability, we should be careful regarding the amount of cognitive component and be very wise in deciding the levels of cognition. This is important to ensure that the cognitive load for the patients do not become high as overloading of cognition can hinder their performance and hence treatment. Although there are games that require head mounted devices (HMDs) to be worn, many patients may feel heavy and uncomfortable with the HMD on their head. Also, having said that stroke-specific games work better than the commercial ones, it is so because the latter games are targeted at general healthy people.

Thus, looking at the positive sides as well as the challenges, we proposed to build a VR-based Gaming System (VGS) along the similar lines for stroke patients with upper extremity hemiparesis but with the introduction of several parameters and a quantitative research on the nature of games designed for several levels of rehabilitation. The VGS is currently a PC-based system which is connected with Kinect for making it interactive. Concerning about the Indian socio-economic scenario, we built it as a lab-based non-remote system. We built two games to test the feasibility to keep players engaged and also for deciding the type of games to be kept at different levels. Like other games, we too focused on parameters like game score, completion time, reaction time, velocity, feedback, etc. In addition, we defined an Entropy measure as a function of the game space to quantify the randomness of the hand movement enabled by the games in our VGS. We also added sound effects for the game ambiance. Overall, the VGS has three modules: *Gaming Module*, *Interactive module* and *Scoring Module*, which are elaborated in Chapter 3: System Design.

1.3. RESEARCH OBJECTIVES

Based on the motivation in the previous section, the research objectives of this study are as follows:

1. Objective 1: To develop a VR-based Gaming System (VGS) for rehabilitating stroke patients with Upper Extremity Hemiparesis that requires hand movements to interact with the games.
2. Objective 2: To understand the feasibility of the VGS to engage players in making hand movements and the necessity of game-parameters.
3. Objective 3: To test the implication of the VGS on the players' game-performance through a pilot study.

To achieve these objectives, I designed two games in the VGS that required the task of hand movement to aim at the game targets and score high. The system also provided feedback at the end of each game to motivate the players to play again by engaging in the games for a longer time period. Hence, the hypothesis of this current study is that a gaming system like VGS could meet the second and third objectives through the first objective.

The remaining part of my thesis is as follows. Chapter 2: Significance and Background, Chapter 3: System Design, Chapter 4: Methodology, Chapter 5: Results and, Chapter 6: Conclusion and Future Directions.

2. SIGNIFICANCE AND BACKGROUND

2.1. SIGNIFICANCE

Stroke patients who survive brain stroke suffer from deficits in motor movement, speech, cognition, etc. [14]. Motor movement deficits can be in the form of whole-body paralysis or left/right side paralysis (also known as Hemiplegia). Another form of the deficit is Hemiparesis which refers to the inability to move the limbs easily and freely due to weaker limbs on either left or right side of the body [14]. This hemiparesis may again persist only in the upper or lower limb of the body, out of which upper limb hemiparesis accounts for 66% of the post-stroke disorders in the patients [7].

In order to recover their pre-stroke state, patients have to undergo several phases of physiotherapy which involves different kinds of exercises and tests like the standard Fugl-Meyer Assessment (FMA), Box and Block Test (BBT), Wolfram Motor Function Test (WMFT), etc. [16; 27]. However, it is reflected in the stroke literature that the monotonous behaviour of the traditional approach like physiotherapy may lead to boredom in the patients. This boredom in turn may lead to reduced motivation and willingness to engage in the exercises for a longer time [23]. Thus, this came up as a challenge in the rehabilitation strategy; to deal with the same, scientists and researchers started to look beyond the traditional approach. One such modern approach of rehabilitation that has been well adopted by the contemporary researchers is Virtual Reality (VR) based Stroke rehabilitation.

VR-based therapy comes in the form of games. One of the reasons of choosing VR games to engage patients for exercises is that VR induces some characteristics- sense of presence, engagement and motivation [7], which are very crucial for stroke patients. Burke et al. further states that the aim of a rehabilitation-based game should primarily be to encourage engagement followed by reward for every successful outcome [8].

VR not only helps a patient to be physically engaged but also mentally and cognitively active. However, the efficacy of such games depends much upon the design and development phases. These phases involve understanding the need of the patients, their strength and weakness, cognitive ability and also the gaming factors- such as scoring and feedback, rewards and challenges to keep up their motivation level [23]. Besides, determining appropriate parameters to measure the effect of the games on the patients as well as to investigate the improvement of the motor ability, have always appeared as inevitable challenges in this rehabilitation research.

Thus, our current study brings forth the design and development of two VR-based games for upper limb hemiparesis along with the parameters that we have used for measuring the outcomes of patients as well as the efficacy of our gaming systems. The motivation of our work stated in Chapter 1, is based on our literature study presented in Chapter 2. This will be followed by system design and a pilot study conducted to test the utility of our VR games.

2.2. BACKGROUND

Recent decades have seen the evolution of various types of gaming systems along with the development in technology. While the traditional use of these games has been for entertainment purpose, researchers now realize it as educational or training tools (serious games) [21,14] and even rehabilitation aids. Two of the reasons are that such games provide entertainment which is useful in keeping boredom away from the end users and also help in interaction with the games. This interactive nature of the games yields a profound impact by inducing a sense of engagement to the users.

The games that are being looked for purposes other than entertainment alone come in the form of video games, simple computer-based games, Virtual Reality, Augmented Reality based games and so on. Here, we present the literature study particularly on Virtual Reality (VR) based games for Stroke rehabilitation (upper limb hemiparesis).

For upper limb Stroke rehabilitation, VR games have been developed primarily to engage the patients in hand exercises through fun gaming so that they do not feel bored as in traditional physiotherapy [7]. However, literature reflects that VR games alone have no significant effect on the improvement of motor movements in the patients [2,18]. But VR supplemented with physiotherapy have shown remarkable outcomes [2,20]. While the games require the patients to play by making hand movements such as reaching, grasping, lateral movement, rotational movement, etc., the gaming systems require a middleware such as body tracking sensors or devices to track the hand movements [10]. These middleware (Kinect [12,17], HTC-Vive and controllers [17], gloves [1], leap motion [21] etc.) allow the patients to interact with the gaming platforms through which the system is enabled to collect hand movement data. These collected data are then analysed to calculate trajectory, velocity, time, accuracy, etc., to produce comparative results or effects of the exercises and give feedback to the patients and their care takers.

For example, Broeren et al. [6] developed 3D computer games such as “Archery”, “Fish tank”, “Space tennis”, etc., which were based on social activities and enabled the patients to move their whole arm. To play the games, a haptic device was worn and from the data collected, hand trajectories were produced. In the work [7], Burke and team represented hand activities like moving, reaching, releasing objects and grasping through games like “Adaptive ‘whack a mouse’”, “Rabbit Chase”, etc. Da silva et al. [11] used data gloves to capture flexure of finger movements while playing their self-designed "Spheroids" game in which the patients had to move the hands to touch a ball approaching towards the patient in VR. In another work [19], the authors developed 2D VR training for hand movements as well as 3D games like “Soccer”, “Volleyball” and “Supermarket” which necessitated reaching and grasping. A similar game on a local supermarket scene was developed by Lin et al. Besides, some of the games focused on Activity for Daily Living (ADL)such as in the work [1].

While most of the VR based games are PC based, based at a specific location and require the presence of a therapist, there are some gaming system which provide remote connection between therapists and patients via internet connection. For instance, in [6], the system offered a telemedicine service to provide training and feedback to the patients at home via Skype. Another team by Shin et al., came up with a VR based system called “RehabMaster” which could be operated remotely by therapists via LAN [24]. The games in the “RehabMaster” focussed on Eye-hand coordination through their self-designed “Water fire game”, “Goal keeper game”, “Bug hunter game”, “Roller coaster” and “Swimming with dolphins”. This gaming system also used a variety of depth sensors- Kinect, ProLive, etc. [24]. Yet another homebased VR rehabilitation [25] described about use of commercial games Nintendo Wii games for stroke patients. A recent home-based gaming system [4] was developed which consisted of upper limb movement games like moving a teapot and pouring tea into a cup.

Besides the stroke-specific VR-based games discussed above, commercial games such as Nintendo Wii too have been researched upon by researchers [2,20]. Burke et al. used Nintendo Wii Remote games along with the use of Webcam and Nintendo Wii technologies [7]. Saposnik et al. [22] compared the efficacy of VR Nintendo Wii games for stroke rehabilitation with that of recreational games like cards and “Jenga”. Standen et al’s work [25] concentrated on three Nintendo Wii games- “Spacerace”, “Spongeball” and “Balloonpop”, and hand activities such as open and close fist, grasping and finger-extension for hitting a target. However, games designed targeting stroke patients seem to be more effective than that of the commercially available entertainment-oriented games for the general population [8].

So far, we have presented the types of hand movements involved in the 2/3D stroke-specific or commercial VR games for stroke rehabilitation. However, the design of such games is not limited to satisfying the need of the movements alone but also focusses on the cognitive component. This cognitive component in the games is often necessary to help stroke patients recover and maintain their cognitive ability which may get deteriorated due to stroke [2]. For example, Gamito et al. built serious games to train cognitive ability to stroke survivors through games like buying items from a market, finding ways to the virtual market, etc [14]. Recently, Cho and team found that cognitive ability consisting of attention and memory, and performance in ADLs got improved in patients with acute stroke. Their games included “Fishing” and “Picture matching” activities which required cognitive act [9].

So, from the above two components- hand movement and cognition, and the variety of games, we see that the essence of these games is indubitably dependent on game-design factors and parameters of measurement. Burke’s work [7] on optimising engagement in games for stroke patients states that a game with meaning, scores, challenges and feedbacks play a crucial role in optimising the engagement factor. In addition, [8] and [23] highlight the importance of ‘rewards’ in engaging and motivating patients. Particularly in [8], it is stated that quantifying a successful outcome by the patient (numerical scores) is important for keeping him/her engaged and motivated; the feedback can be presented in the form of scores, a dialogue spoken by a virtual character, progress bars and sound. Such games should also have skill levels to keep track of the speed of the patient as well as the game at each higher level. With the help of these parameters, we can also record secondary factors such as longer play duration, levels of enjoyment, etc. [23]. Some of the fundamental measures used in the studies are reaction time (time taken to hit the target), time of game completion, accuracy (number of hits and misses), etc. Besides, to check if the games are effective, intervention on the patients is an important step. However, games should be first tested with healthy individuals prior to experimenting with the stroke patients [23]. Survey questionnaires after every stage of intervention are also important.

Thus, several factors come into picture, prior, during and after development phases of the games made for our target population- stroke individuals. One factor is the source of engagement for which scoring, and feedback are important. Again, deciding the quantitative value of the score and the language of feedback is a challenge in itself because we need to ensure that these do not cause demotivation or negative impact on the patients. The setting up of levels in the game is equally critical because we need to keep in mind about the minimum and maximum ability of the stroke patients so that the games in the higher levels do not cause negative effects like pain or immobility. Regarding the gaming systems based on accessibility, home-based telerehabilitation seems to be good but it is again subjected to the cost of set-up and sensors/devices; it also greatly depends on the geographical and socio-economic environment. Comparisons between the commercial games versus stroke-specific games give us a clear idea about the latter's beneficial power over the other. However, VR games come in handy only when in use with traditional physiotherapy practices. So, we need to take care of the time-duration and measuring parameters to sync with the physiotherapy sessions and to investigate the outcomes of VR with(out) the traditional therapy. Further, the games may be immersive (patients wear Head Mounted Device) or non-immersive (PC based) in nature [7,9, 16]. While immersive games provide a better sense of presence than the PC based games, some patients may object to using the devices as they may feel uncomfortable wearing the device on their heads.

Hence, considering the positive factors of the existing VR games for stroke rehabilitation and also the challenging concerns, we built two games which covered simple hand movements like reaching and closing-opening of fist. In the first game *Fruit Cutter* (adapted from "Fruit Ninja"), we introduced hand-reaching task to reach and slice randomly appearing fruits whereas in the second game *Space Meteor shooter,* a player had to close his/her fist to shoot meteors. With both the games, we tested the players' range of movement, peak velocity, accuracy and time of engagement and reaction time (only in *Space Meteor shooter*). In addition to these factors, we used the Entropy measure as a function of the game space to observe the randomness of the hand movement of the player in of the game in *Fruit Cutter* and that *Space Meteor shooter*. We conducted three trials of gaming sessions for understanding the game-efficacy and the user-outcomes. We also provided feedback and scoring to the users at the end of the games and carried out survey questionnaires. We highlight the design and development phases of the VR-based Gaming System (VGS) along with the above-mentioned parameters in the subsequent chapter, Chapter 3 (System Design).

3. SYSTEM DESIGN

The VR-based Gaming System (VGS) has 3 modules as shown below

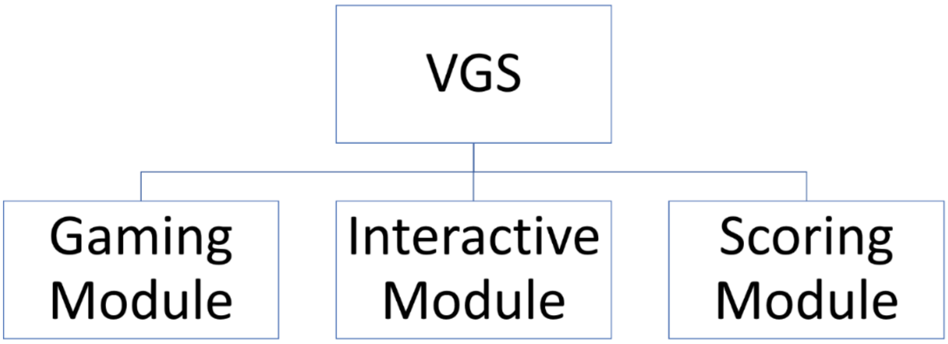

Figure 3-1 VGS Modules

3.1. GAMING MODULE

Gaming Module (GM) is the main module which controls the flow of VGS. This module contains games which use the Interactive Module to allow human-computer interaction. All the data collected are sent to Scoring Module for analysis.

The games were created on the gaming platform, Unity (version: 2018.2.4f1). This is an open source gaming engine that uses object-oriented programming languages, JavaScript and C#.

3.1.1. GAME 1: FRUIT CUTTER

Fruit Cutter game primarily focused on hand extensions. The concept was taken from a popular mobile game "*Fruit Ninja*" (https://fruitninja.com/). In this game, the player must move his hand to slice/cut the fruits which were thrown from random points in the virtual game space. The player scored a point when he/she cut a fruit successfully and; when he/she missed more than a fixed number of fruits (ten), the game ended with the score being displayed.

All the assets used in this game were taken from the Unity asset store. All the game object (fruits) definitions and behaviours were coded in the backend using C#.

The game was designed such that the difficulty of the game could be adjusted by tuning the speed and time gap between the randomly appearing fruits. Since rehabilitation process is continuous and repetitive, this feature would allow us to tune the difficulty level as required to keep the game challenging.

Game Design: The game view was 2D and the fruits (game objects) appeared from random positions on the screen. Fruits were thrown upwards at random angles and since gravitational forces were applied, they followed a projectile trajectory moving the fruits in two directions x(sideway) and y(upward). Right hand of the player was represented and displayed in the game using a virtual tilted right-hand game object which could move all over the game space in 2D. In addition to the visuals, sound and particle effects were added to improve the overall gaming ambiance.

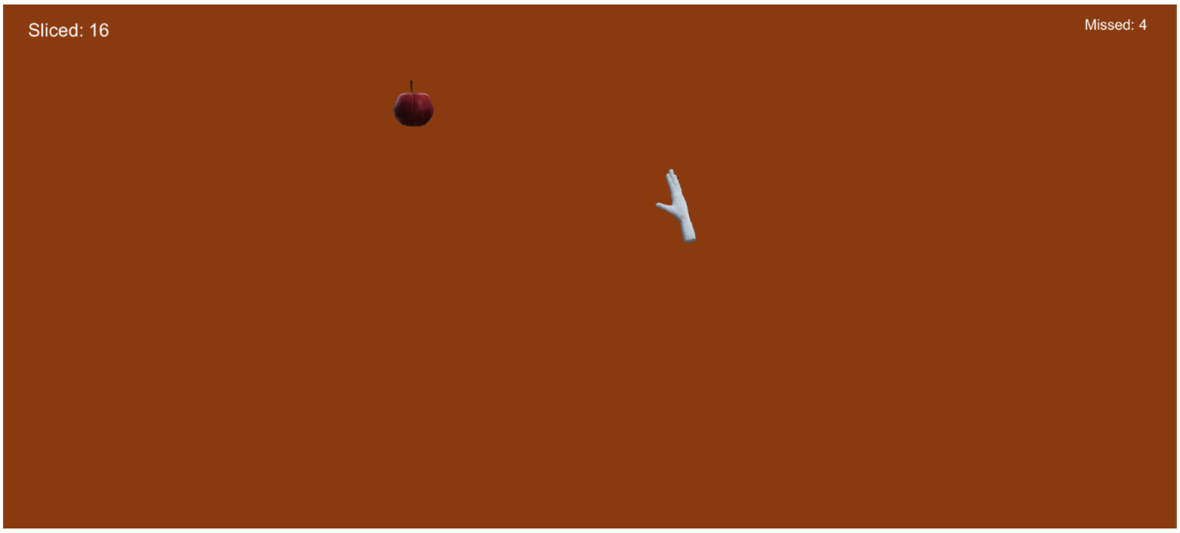

Figure 3-2 Game view of Fruit Cutter

Rules: The objective of this game was to cut the fruits that appeared on the screen by reaching the fruit using virtual hand. Each fruit successfully cut yielded one point whereas each fruit not cut was accounted for the number of missed fruits. The game had a maximum limit of missed fruits; once the player reached that limit, the game ended.

3.1.2. GAME 2: SPACE METEOR SHOOTER

Space Meteor shooter was a first-person shooting game which primarily focussed on hand extensions and fist closure. In this game, the player must shoot down meteors and enemy spaceships heading towards him/her. Each player got a fixed number of bullets using which he/she must shoot down the objects to score and the game ended when the player ran out of bullets.

All the assets used in this game were taken from the Unity asset store. All the game objects' (meteors and enemy ships) definitions and behaviours were coded in the backend using C#.

The game was designed such that the difficulty of the game could be adjusted by tuning the speed and time gap between the randomly appearing meteors and enemy spaceships. Since rehabilitation process is continuous and repetitive, this game feature would allow us to tune the difficulty level as required to keep the game challenging.

Game Design: The game view was 3D and had a scene of 'space'. Meteors and enemy spaceships appeared randomly in the game and moved towards the player. Meteors followed a straight path rotating on their axis whereas enemy ships could have sideward movement too. Right hand of the player was displayed in the game using an aim symbol and this object could move all over the game space. The player must aim and close his/her right fist to release a bullet to shoot a meteor or an enemy spaceship. In addition to the visuals, sound and particle effects were added to improve the overall game ambiance.

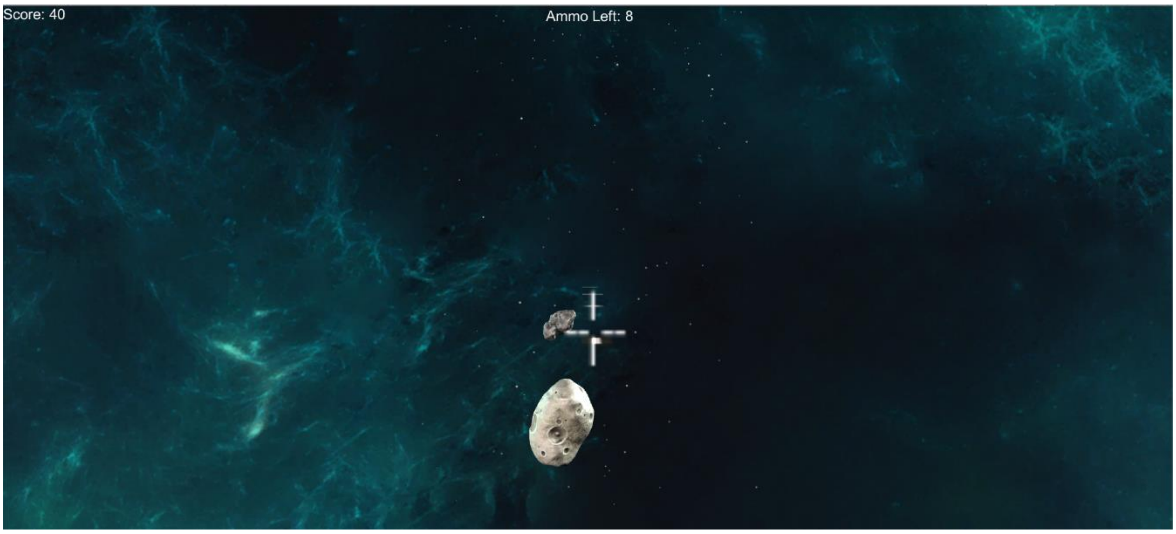

Figure 3-3 Game view of Space Meteor Shooter

Rules: The objective of the game was to destroy or shoot down meteors and enemy spaceships by aiming and closing the right fist; each target destroyed gave 10 points. The player was given only a limited number of bullets (thirty) using which he/she must score high. The game ended when player ran out of bullets.

3.1.3. FLOW OF GAME

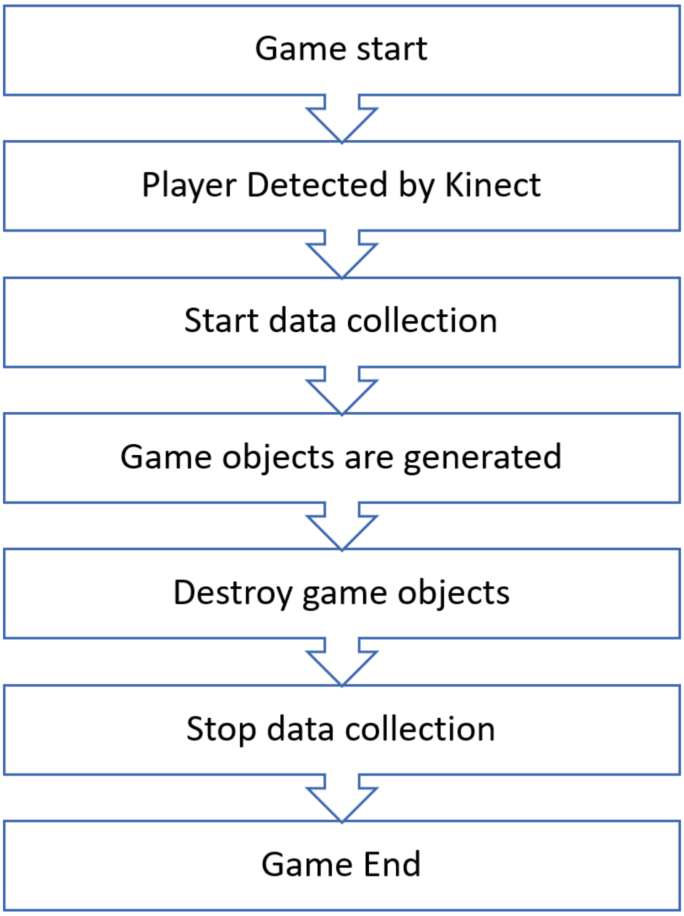

Figure 3-4 Flowchart of VGS games

3.2. INTERACTIVE MODULE

Interactive Module (IM) acted as the bridge which linked the real world to the virtual game world. In order to make the games interactive, Microsoft Kinect v2 middleware [29] was used in IM to track hand movements of a player.

3.2.1. HARDWARE

Kinect is a motion sensing input device produced by Microsoft. It has RGB camera, depth sensor, and multi-array microphone using which it can provide 3D motion capture, facial recognition and voice recognition [21]. It can detect users' motions and gestures and interact with the applications or games without any controller. The Kinect SDK provides skeletal tracking, the capability to extract and track the skeleton image of up to six people moving within Kinect's field of view [21]. Kinect can detect 25 body joints (head, hands, feet, hip centre, etc.) of the human body. Among the Kinect skeleton data (25 joints coordinate in 3D space), the VGS games used those corresponding to the player's *right hand* in order to manipulate the aiming.

3.2.2. CONNECTION

The body tracking functionality of Kinect can be seamlessly integrated with Unity using open source libraries provided by Microsoft Kinect SDK 2.0 for Unity (https://developer.microsoft.com/en-us/windows/kinect). Using this integration, the right-hand position in the real world was represented in the virtual world using a virtual right-hand (*Fruit Cutter)* and an aim symbol (*Space Meteor Shooter*). The coordinate space of real world (Kinect) and virtual (game) world was different; hence, we used a multiplying factor to adjust the game world coordinates as required (in the *BodySourceView* script available in the library). The multiplying factor used for the two games were as follows:

Fruit Cutter: $X_{game} = X_{kinect} * 20;$ $Y_{game} = Y_{kinect} * 10;$

Space Meteor Shooter: $X_{game} = X_{kinect} * 15;$ $Y_{game} = Y_{kinect} * 10;$

3.3. SCORING MODULE

Scoring Module (SM) was the last module of VGS; this module took control when the gaming and interactive modules completed their tasks. This module analysed all the data collected by gaming module and displayed game score, engagement time, peak velocity and provided feedback.

The feedbacks were framed such a way that it used no negative language (in English); these are shown as follows:

Fruit Cutter:

Game Score (GS)	Feedback
GS <= 20	You can do better
20 < GS <= 40	You are playing good
40 < GS	You have played great

Space Meteor Shooter:

Game Score (GS)	Feedback
GS <= 80	You can do better
80 < GS <= 160	You are playing good
160 < GS	You have played great

4. METHODOLOGY

4.1. PARTICIPANTS' DETAILS

In order to assess the second and third research objectives, five healthy participants volunteered for the purpose of the pilot study. Mean age of the participants was 23.4 with standard deviation of 1.949; male to female ratio is 3:2. The same group of participants participated in all the three sessions of the pilot study.

S. No.	Participant ID	Age	Gender	Occupation
1	P1	26	M	Project Associate, IIT Madras
2	P2	22	M	Project Associate, IIT Madras
3	P3	22	M	Student, IIT Madras
4	P4	25	F	Student, IIT Madras
5	P5	22	F	Project Associate, IIT Madras

Table 4-1 Participant Table

4.2. EXPERIMENTAL SETUP

The experimental setup of VGS consisted of a Personal Computer (PC) with a mouse (for the trainer to navigate the system) and a monitor, and a Microsoft Kinect. The distance between Kinect and the player was maintained at 1 metre. The setup is shown the figure below.

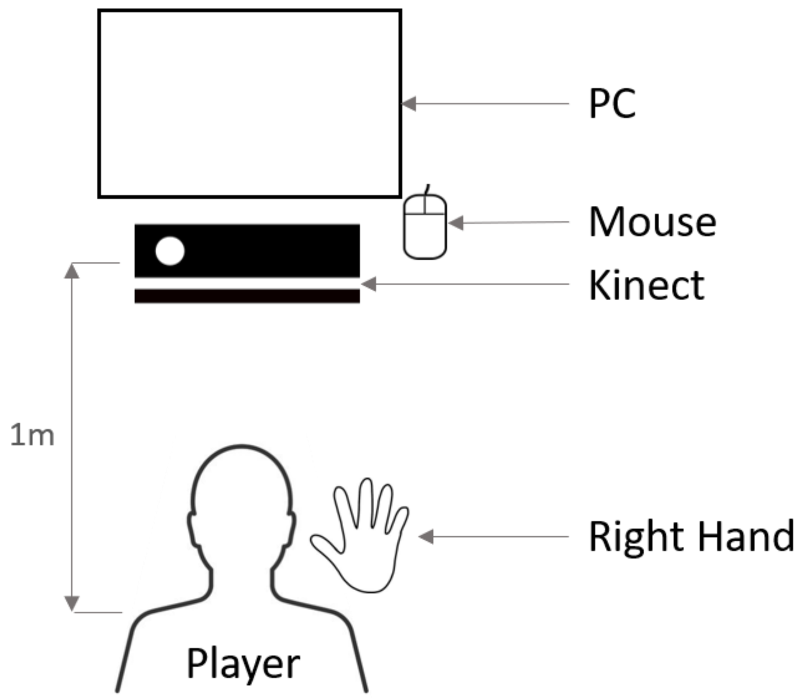

Figure 4-1 Experimental Setup of the pilot study

4.3. PROCEDURE

A total of five healthy participants volunteered to participate in the pilot study which spanned over three sessions. The first session was conducted on 11th April 2019, the second session was conducted after one day (13th April 2019) and the third session after 10 days (24th April 2019).

In Session 1, participants were asked to sit in front Kinect and once they were comfortable and relaxed, a demo and oral instructions of Game 1 were given in English language. After ensuring the participant was clear with the instructions, Game 1 was started. On start, the participant must move his/her right hand in front of the Kinect device to get detected. On detection, he/she could see a virtual hand appearing which represented their right-hand position in the virtual world. On completion of Game 1, the participant was asked to rest for a while. Then, a demo and instructions of Game 2 were given, and Game 2 was started. On start, the participant must move his/her right hand in front of the Kinect device to get detected. On detection, he/she could see an aim symbol appearing which represented their right-hand position in the virtual world. Session 1 concluded on completion of Game 2.

Session 2 and 3 followed the same procedure except a feedback was taken after each game in the final session. Session 1 and 2 took around 10 minutes per participant and Session 3 around 15 minutes as additional feedback survey was taken.

4.4. EVALUATION AND FORMUALE

The collected data were evaluated based on the parameters like game score, engagement time, peak velocity, range of movements, reaction time and entropy measure. The definitions of these evaluative parameters are as follows:

Game Score (GS) is the score attained by hitting the targets- fruits in the *Fruit Cutter* game, and meteors and enemy spaceships in *Space Meteor Shooter*.

Fruit Cutter GS = No. of fruits cut x 1

Space Meteor Shooter GS = No. objects shot x 10

Engagement Time (ET) is the total time taken by a player from the start to the end of the games.

Fruit Cutter ET = Time at the instant when 10 fruits are missed – Time at start

Space Meteor Shooter ET = Time at the instant when 30 bullets are fired – Time at start

Peak velocity (PV) is the maximum velocity of hand movement attained during the gameplay.

PV = Maximum (V_1, V_2, ……. V_n)

Where velocity (V_i) is calculated as:

V_i = (Current hand position – previous hand position) / One time-frame

Range of Movement (RoM) is calculated using the minimum and maximum values of hand coordinates along the X and Y axes.

X_{max} = Largest value of X-coordinate; X_{min} = Lowest value of X-coordinate

Y_{max} = Largest value of Y-coordinate; Y_{min} = Lowest value of Y-coordinate

Least Reaction Time (LRT) is the time between the appearance and destruction of a game object (*Space Meteor Shooter*).

RT = Time at the instance of destruction – Time at the instance of appearance

Entropy Measure (EM) is a measure of randomness and unpredictability. In order to measure entropy, the game space has been divided into a 4×4 matrix (16 regions) as shown below.

Region 1	Region 2	Region 3	Region 4
Region 5	Region 6	Region 7	Region 8
Region 9	Region 10	Region 11	Region 12
Region 13	Region 14	Region 15	Region 16

Figure 4-2 Figure showing the 16 regions used for entropy calculation

Let P_i be the probability of the virtual hand visiting the i^{th} region, then the entropy EM is calculated as follows:

$$EM = -\sum_{i=1}^{16} P_i \log_{16} P_i$$

4.5. STATISTICAL ANALYSIS PARAMETERS

Since, the sample size of the pilot study was very small (five) and there was only one group of participants, we restricted the statistical analysis of the results to basic statistical mythology— 1-sample (paired) t-Test between (session 1 and session 2), (session 2 and session 3), and (session 1 and session 3) for all the parameters. This analysis was done in Microsoft Excel using TTEST function. This TTEST function produced p-values which determined the statistical significance of the parameters between very two sessions.

For example, t-Test for Game Score (GS) between session 1 and session 2 is defined as:

TTEST (GS of 5 participants of session 1, GS of 5 participants of session 2, df, t)

where,

df (degrees of freedom) = number of variables -1 = number of sessions -1 = 3 - 1 = 2

t(type) = paired = 1

5. RESULTS

5.1. RESULTS OF INDIVIDUAL PARTICIPANTS' PERFORMANCE

5.1.1. SESSION 1

Table 5.1 shows the participants' game performance during session 1 for the games—*Fruit Cutter* and *Space Meteor Shooter*.

P. ID	Game 1: Fruit Cutter				Game 2: Space Meteor Shooter				
	Score	Time	Peak Velocity	Entropy	Score	Time	Peak Velocity	Entropy	Reaction Time
P1	15	52.087	627.7860457	0.6826	0	41.98	83.24656473	0.1732	-
P2	9	39.74	443.425618	0.6407	0	28.93	111.231912	0.4608	-
P3	44	117.93	1406.977704	0.8586	110	84.8	75.81791422	0.8105	1.77919
P4	18	59.378	677.1882	0.7089	120	68.069	133.7743365	0.5702	2.058899
P5	29	83.35	975.1952	0.848	40	45.216	69.10591863	0.525	3.100597

Table 5-1 Participants' data of session 1

5.1.2. SESSION 2

Table 5.2 shows the participants' game performance during session 2 for the games—*Fruit Cutter* and *Space Meteor Shooter*.

P. ID	Game 1: Fruit Cutter				Game 2: Space XXX				
	Score	Time	Peak Velocity	Entropy	Score	Time	Peak Velocity	Entropy	Reaction Time
P1	18	51.425	616.5286929	0.709	20	74.426	172.0167116	0.4017	3.132713
P2	25	68.431	841.1405447	0.8323	20	43.342	146.8789207	0.7285	3.338082
P3	35	97.138	1314.958642	0.8881	140	70.32	104.3493311	0.7703	2.090519
P4	18	56.064	642.314	0.7486	70	52.484	152.1104626	0.6384	3.043025
P5	31	84.943	990.8781529	0.913	40	27.901	98.76399646	0.6177	1.936098

Table 5-2 Participants' data of session 2

5.1.3. SESSION 3

P. ID	Game 1: Fruit Cutter				Game 2: Space XXX				
	Score	Time	Peak Velocity	Entropy	Score	Time	Peak Velocity	Entropy	Reaction Time
P1	16	54.352	641.5793648	0.7945	10	82.479	147.7263104	0.4759	2.295826
P2	87	185.48	2251.439011	0.8411	110	120.07	233.5085947	0.6201	2.031389
P3	60	139.48	1669.156	0.7753	110	94.986	149.2777673	0.732	2.310696
P4	17	53.963	623.4425549	0.8109	40	53.98	64.94491676	0.5914	2.521134
P5	77	174.16	2432.982495	0.8126	60	64.466	148.4451117	0.7004	2.327826

Table 5-3 Participants' data of session 3

5.1.4. COMPARATIVE ANALYSIS

This section presents the inter-session comparative analysis of the average values of each parameter based on the pilot study conducted in Chapter 4 for the VGS.

Fruit Cutter game

1. **Average Game Score (GS)**

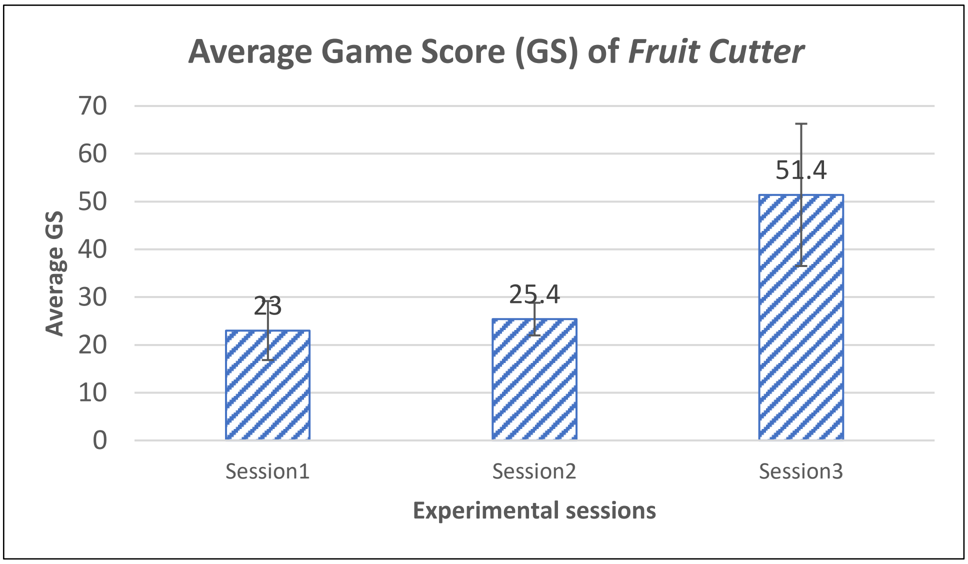

Figure 5-1 Average GS of Fruit Cutter over three sessions

The average GS increased by 10.434% from session1 to session 2, 102.362% from session 2 to session 3 and 123.478% from session 1 to session 3.

2. **Average Engagement Time (ET)**

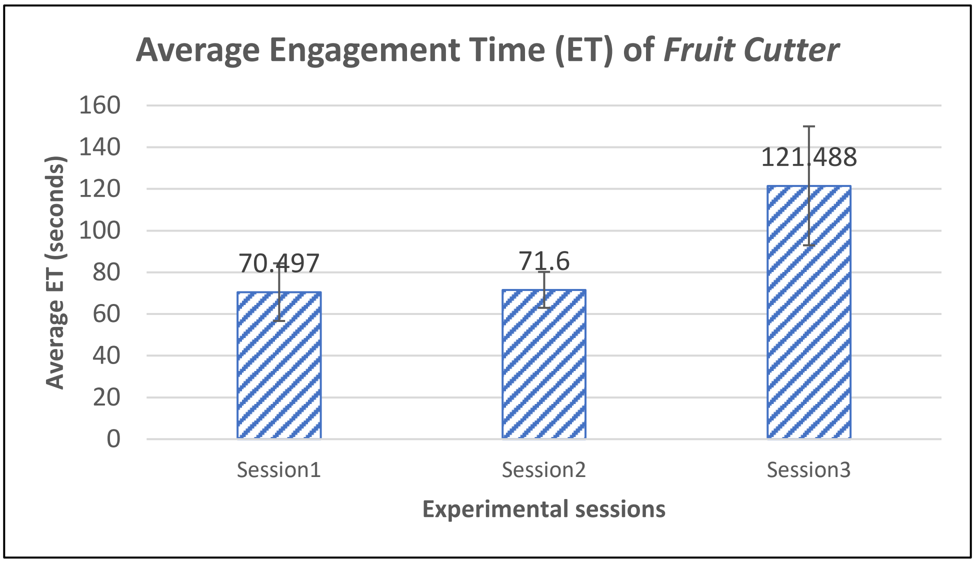

Figure 5-2 Average ET of Fruit Cutter over three sessions

The average ET increased by 1.564% from session1 to session 2, 69.676% from session 2 to session 3 and 72.331% from session 1 to session 3.

3. **Average Peak Velocity (PV)**

The average PV increased by 6.664% from session1 to session 2, 72.921% from session 2 to session 3 and 84.444% from session 1 to session 3.

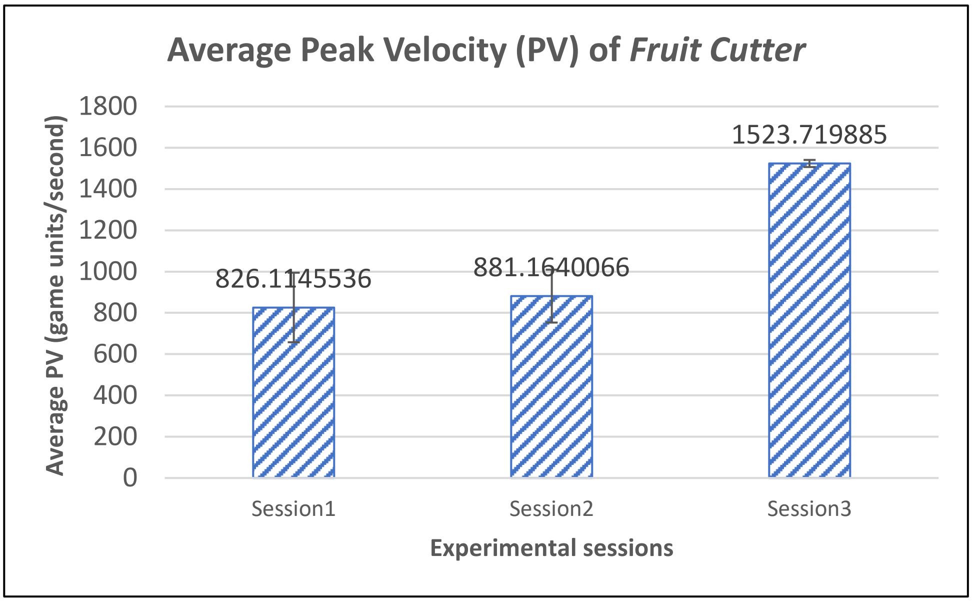

Figure 5-3 Average PV of Fruit Cutter over three sessions

4. **Average Entropy Measure (EM)**

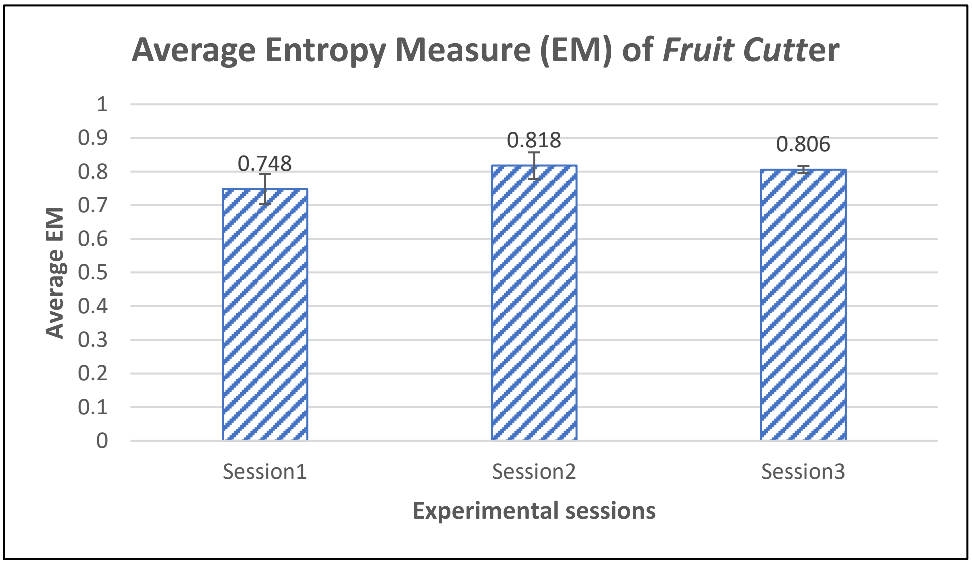

Figure 5-4 Average EM of Fruit Cutter over three sessions

The average EM increased by 9.358% from session1 to session 2, 7.754% from session 1 to session 3. However, it decreased by 1.467% from session 2 to session 3.

5. **Range of Movements (RoM)**

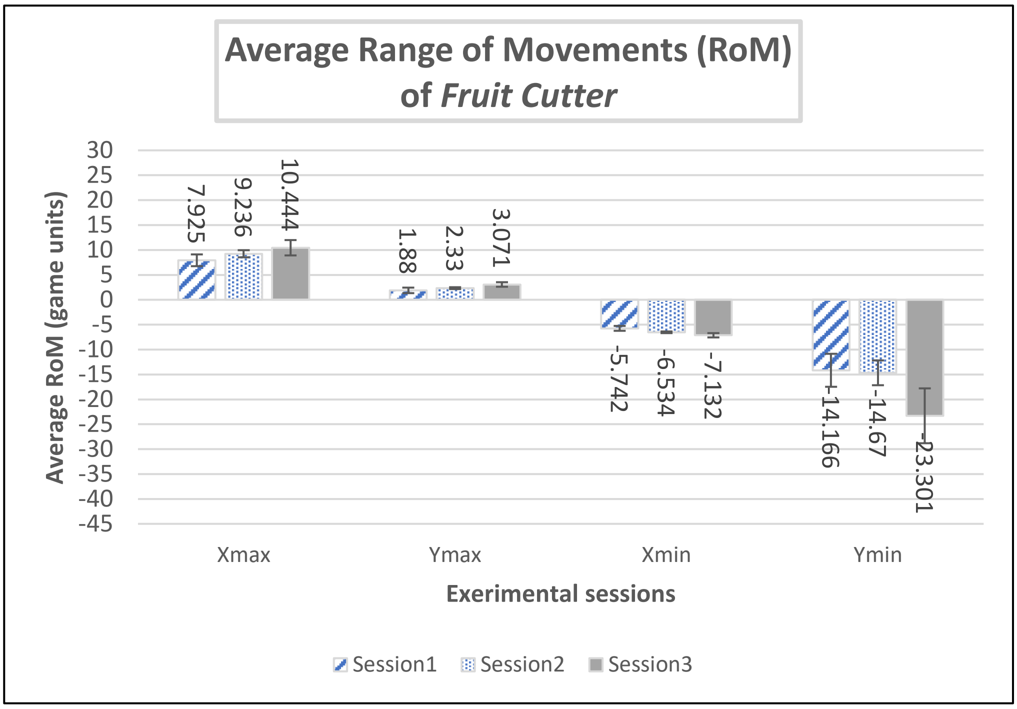

Figure 5-5 Average RoM of Fruit Cutter over three sessions

The average X_{max} increased by 16.542% from session1 to session 2, 13.079% from session 2 to session 3 and 31.786% from session 1 to session 3. The average Y_{max} increased by 23.936% from session1 to session 2, 31.802% from session 2 to session 3 and 63.351% from session 1 to session 3. The average X_{min} increased by 13.793% from session1 to session 2, 9.152% from session 2 to session 3 and 24.208% from session 1 to session 3. The average Y_{min} increased by 3.558% from session1 to session 2, 58.834% from session 2 to session 3 and 64.485% from session 1 to session 3.

Space Meteor Shooter game

1. **Average Game Score (GS)**

The average GS increased by 7.407% from session1 to session 2, 13.793% from session 2 to session 3 and 22.222% from session 1 to session 3.

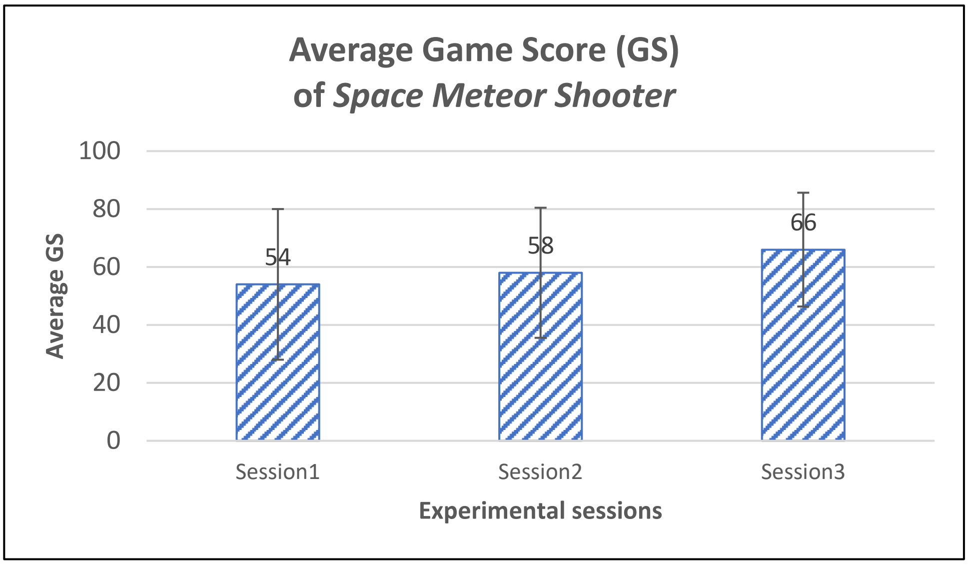

Figure 5-6 Average GS of Space Meteor Shooter over three sessions

2. **Average Engagement Time (ET)**

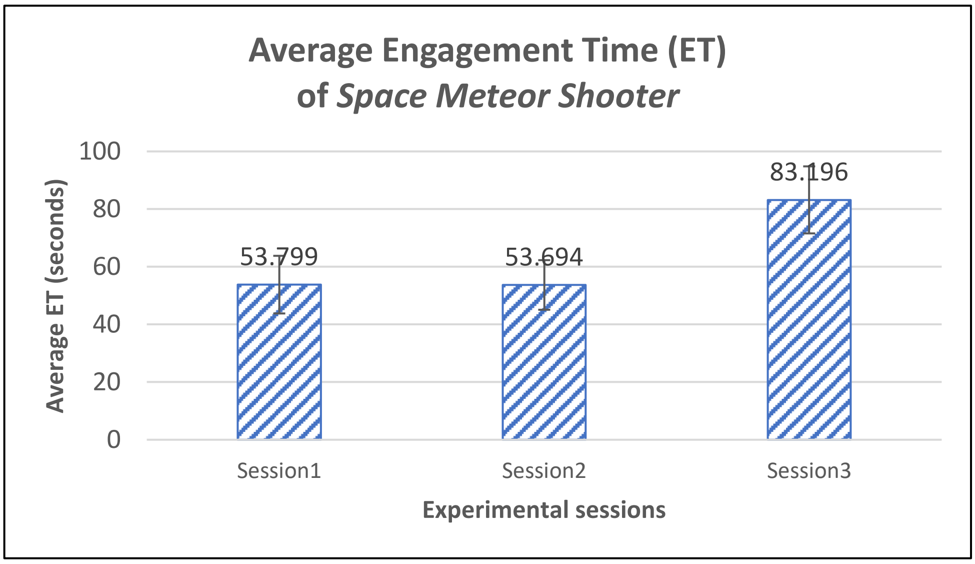

Figure 5-7 Average ET of Space Meteor Shooter over three sessions

The average ET increased by 54.944% from session 2 to session 3 and 54.642% from session 1 to session 3. However, it decreased by 0.195% from session1 to session 2.

3. **Average Peak Velocity (PV)**

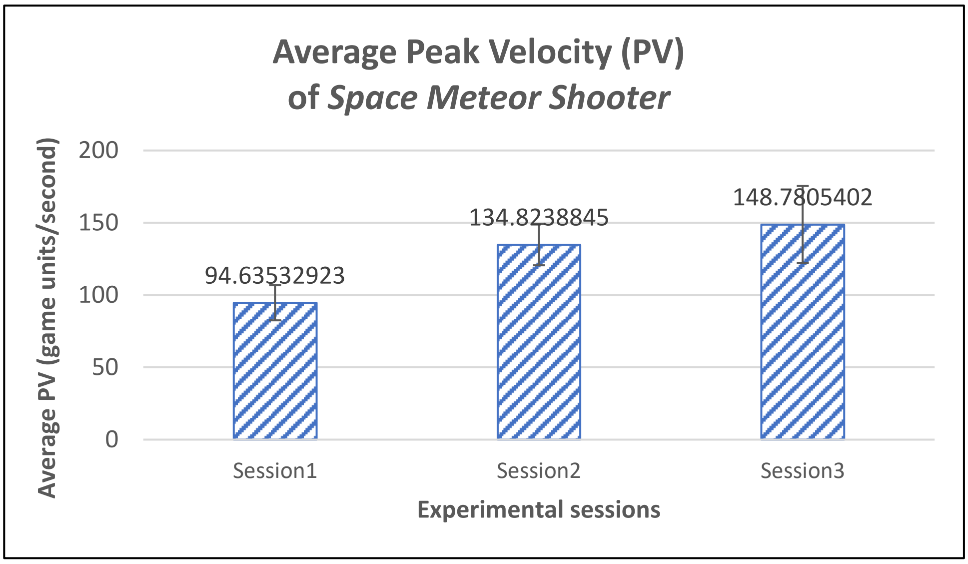

Figure 5-8 Average PV of Space Meteor Shooter over three sessions

The average PV increased by 42.466% from session1 to session 2, 10.352% from session 2 to session 3 and 57.214% from session 1 to session 3.

4. **Average Entropy Measure (EM)**

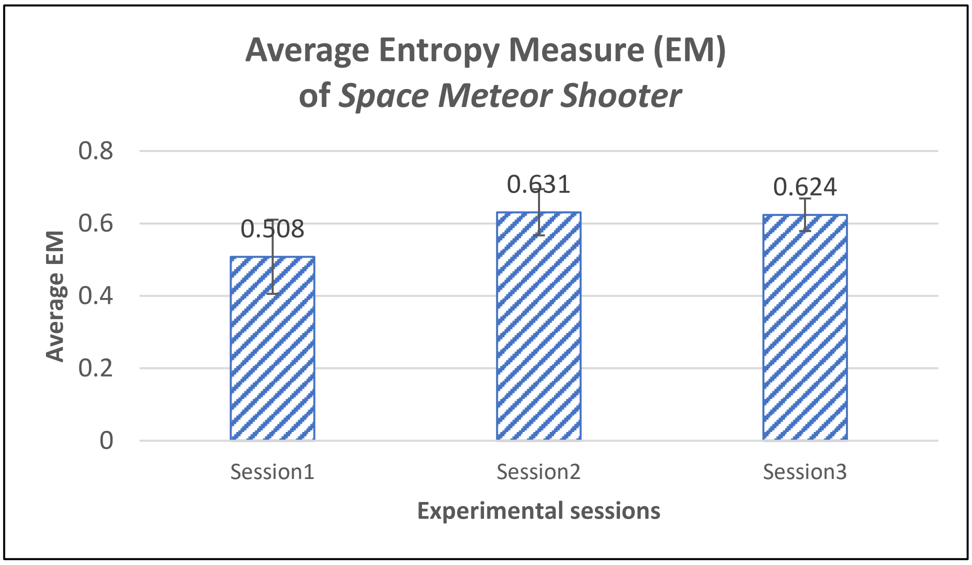

Figure 5-9 Average EM of Space Meteor Shooter over three sessions

The average EM increased by 24.212% from session1 to session 2 and 22.834% from session 1 to session 3. However, it decreased by 1.109% from session 2 to session 3.

5. **Average Range of Movements (RoM)**

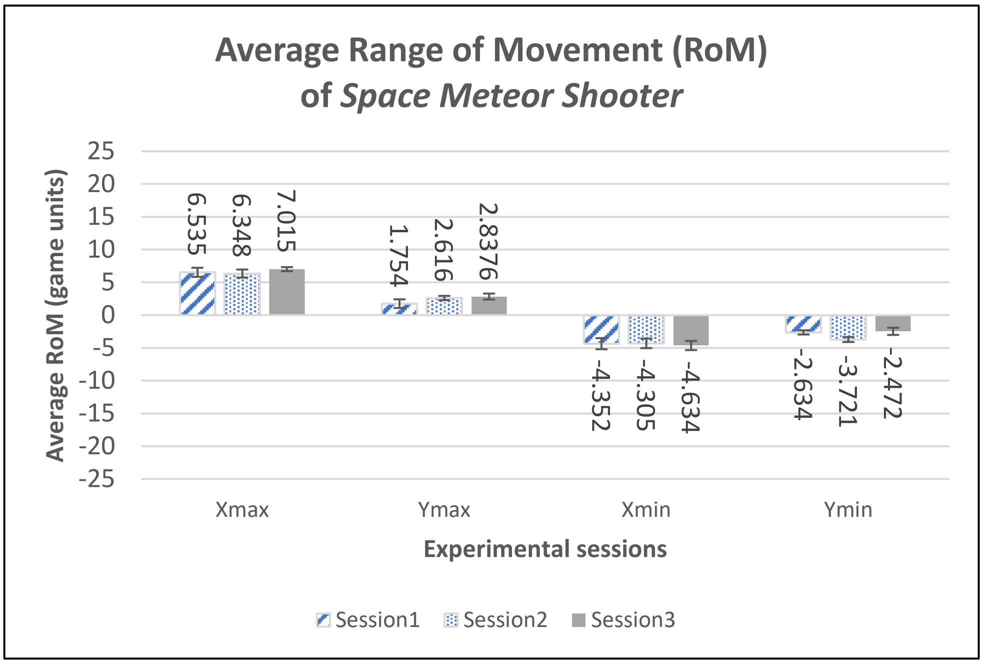

Figure 5-10 Average RoM of Space Meteor Shooter over three sessions

The average X_{max} increased by 10.507% from session 2 to session 3 and 7.345% from session 1 to session 3. However, it reduced by 2.862% from session1 to session 2. The average Y_{max} increased by 49.144% from session1 to session 2, 8.471% from session 2 to session 3 and 61.778% from session 1 to session 3. The average X_{min} increased by 7.642% from session 2 to session 3 and 6.480% from session 1 to session 3. However, it reduced by 1.080% from session1 to session 2. The average Y_{min} increased by 41.268% from session1 to session 2 but decreased by 33.566% from session 2 to session 3 and 6.150% from session 1 to session 3.

6. **Average Least Reaction Time (LRT)**

The average LRT for session 1 contains the values of only three participants as the remaining two participants scored null (Figure 5-11). From session 2 to session 3 the average LRT decreased by 15.166% and 0.671% from session 1 to session 3. All though the average LRT decreased, the average score increased from session 2 to session 3 as well as session 1 to session 3. This indicated that the participants might take longer RT to hit the target for scoring high.

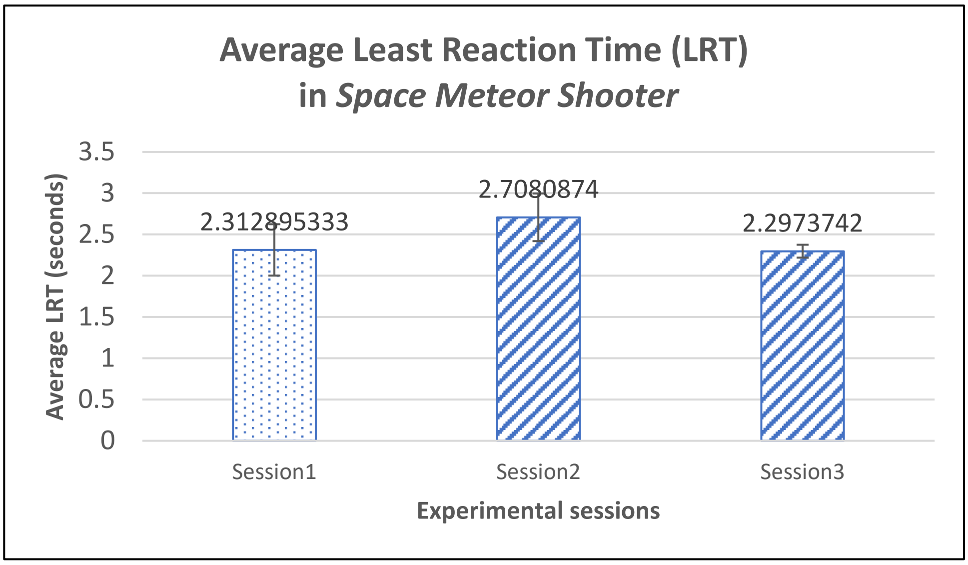

Figure 5-11 Average LRT of Space Meteor Shooter over three sessions

5.2. STATISTICAL ANALYSIS RESULTS

p-values of *Fruit Cutter:*

		1-sample paired t-Test		
		Session1-Session2	**Session2-Session3**	**Session1-Session3**
Game Parameters	GS	0.58152	0.109407	0.134837
	ET	0.896312	0.10077	0.155068
	PV	0.563349	0.120355	0.147692
	EM	0.085793	0.795597	0.317967
	X_{max}	0.381836	0.21264	0.144156
	Y_{max}	0.29662	0.071171	**0.049081**
	X_{min}	0.118625	0.233876	0.116779
	Y_{min}	0.748294	0.134823	0.181354

Table 5-4 1-sample t-Test of Fruit Cutter

From Table 5-4 we see that all the p-values except one are greater than 0.05 which means there is no statistical significance between the sessions of *Fruit Cutter* game. However, the p-value of Y_{max} between session 1 and session 3 is less than 0.05 which means there is statistical significance between session 1 and session 3 for this parameter. The p-values having greater than 0.05 may be due to the fact that our sample consisted of healthy participants also we might except to see the difference if the participants are exposed to games for multiple sessions.

p-values of *Space Meteor Shooter:*

		1-sample paired t-test		
		Session1-Session2	Session2-Session3	Session1-Session3
Game Parameters	GS	0.794295	0.739581	0.71169
	ET	0.992195	0.091116	0.172951
	PV	**0.032116**	0.675765	0.16909
	Least RT	0.951413	0.26771	0.87799
	EM	0.092146	0.852347	0.15352
	Xmax	0.795517	0.330395	0.483893
	Ymax	0.234385	0.581639	0.154544
	Xmin	0.948266	0.630855	0.655164
	Ymin	0.098471	0.189811	0.623288

Table 5-5 1-sample t-Test of Space Meteor Shooter

From Table 5-5 we see that all the p-values except one are greater than 0.05 which means there is no statistical significance between the sessions of *Space Meteor Shooter* game. However, the p-value of PV between session 1 and session 2 is less than 0.05 which means there is statistical significance between session 1 and session 2 for this parameter. The p-values having greater than 0.05 may be due to the fact that our sample consisted of healthy participants also we might except to see the difference if the participants are exposed to games for multiple sessions.

5.3. SURVEY RESULTS

Fruit Cutter

The mean and standard deviation (SD) of the average rating obtained by each question belonging to the *Fruit Cutter* survey questionnaire conducted during session 3 have been provided in the below table. 1 was the least and 5 was the highest rating possible in the scoring system that had been followed for the survey questionnaire.

S. No.	Question - *Fruit Cutter*	Mean	SD
1	The game was enjoyable and full of fun.	4.4	0.547723
2	The game was easy to interact.	4.2	0.83666
3	The game made me feel pressurized.	3.6	0.547723
4	The instructions for playing the game were clear.	4.8	0.447214
5	I felt the feedback positive. It encouraged me to play again.	4.8	0.447214
6	I felt engaged throughout the game.	4.4	0.894427
7	I felt relaxed while playing the game.	3.2	0.83666
8	I tried my best to play the game.	5	0
9	I would like to play again.	4.8	0.447214
10	I would recommend my friend to play the game.	4.6	0.547723
11	I would recommend a stroke patient to play the game.	4.8	0.447214

Table 5-6 Table showing mean and standard deviation of the average rating for each question in Fruit Cutter survey questionnaire

It can be observed that most of the questions have attained a rating over 4. Only questions that have a lesser than 4 are "*The game made me feel pressurized*" and "*I felt relaxed while playing the game",* the rating for these can be improved by reducing the difficulty level which would motivate the players positively.

Space Meteor Shooter

The mean and standard deviation (SD) of the average rating obtained by each question belonging to the *Space Meteor Shooter* survey questionnaire conducted during session 3 have been provided in the below table. 1 was the least and 5 was the highest rating possible in the scoring system that had been followed for the survey questionnaire.

S. No.	Question - *Space Meteor Shooter*	Mean	SD
1	The game was enjoyable and full of fun.	4	1.224745
2	The game was easy to interact.	3.2	0.83666
3	The game made me feel pressurized.	4	0.707107
4	The instructions for playing the game were clear.	4.4	0.894427
5	I felt the feedback positive. It encouraged me to play again.	4.8	0.447214
6	I felt engaged throughout the game.	4.8	0.447214
7	I felt relaxed while playing the game.	3.6	1.140175
8	I tried my best to play the game.	5	0
9	I would like to play again.	4.8	0.447214
10	I would recommend my friend to play the game.	4.6	0.547723
11	I would recommend a stroke patient to play the game.	4.8	0.447214

Table 5-7 Table showing mean and standard deviation of the average rating for each question in Space Meteor Shooter survey questionnaire

The mean and standard deviation (SD) of the average rating obtained by each question belonging to the *Space Meteor Shooter* survey questionnaire conducted during session 3 have been provided in the above table. 1 was the least and 5 was the highest rating possible in the scoring system that had been followed for the survey questionnaire.

It can be observed that most of the questions have attained a rating over 4. Only questions that have a lesser than 4 are "*The game made me feel pressurized*" and "*I felt relaxed while playing the game",* the rating for these can be improved by reducing the difficulty level which would motivate the players positively.

6. CONCLUSION AND FUTURE DIRECTIONS

6.1. CONCLUSION

A Virtual Reality-based Gaming System (VGS) consisting of two games- *Fruit Cutter* and *Space Meteor Shooter* for rehabilitating stroke patients with upper extremity hemiparesis that required hand movements were built. The hand movements consisted of hand extension, hand reaching and closing of the right fist. Thus, the first research objective of this study (Chapter 1) was met.

The results of the pilot study showed that the average game score, engagement time, peak velocity and the range of right-hand movement increased over three experimental sessions for both the games. On the other hand, average reaction time in *Space Meteor Shooter* decreased from session 1 to 3. This indicated that VGS could control the players' response over multiple sessions by improving the game score while engaging for a longer time. Hence, these parameters might be potentially considered as indirect measures of the motor functions of the right upper extremity. Further, the average Entropy Measure over the three sessions showed us about the randomness of the hand movements which was higher in case of *Fruit Cutter* as compared to *Space Meteor Shooter*. This indicated that Entropy Measure might be used to judge the difficulty of a game and can help us select the correct game for each level. So, a game like *Space Meteor Shooter* should be used at a lower game level while *Fruit Cutter* at a higher game level. In this way, the second research objective was met.

Overall, the pilot study reflected an improvement in the average game performance of the participants over three experimental sessions. This means the participants liked to engage in the game for a longer time with the aim to score high. This in turn, indicated that VGS was engaging and motivating. Thus, our third research objective was met.

6.2. FUTURE DIRECTIONS

In this current study, the two VGS games were limited to three hand movements (hand extension, hand reaching and fist closure). However, we can develop more games concentrating on other types of gross hand movements like wrist movement, wrist rotation, etc. and fine movements like gripping, finger curl, etc.

We can further, develop games according to the severity of the upper extremity hemiparesis and different age groups.

At present, we have two independent games which can be extended by adding multiple levels of difficulty. Besides, the VGS is a PC based system which can also be transformed to a Head Mounted Device (HMD) based system.

We conducted our pilot study with five healthy participants. In future, we would experiment with a larger group of healthy individuals followed by stroke patients.

I, therefore, believe that by achieving these future directions, the VGS will have the potential to contribute to the rehabilitation of stroke survivors and also help the therapists in treating the patients with robust real-time feedback from the system.

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