Virtual Reality Post Stroke Upper Limb Assessment using Unreal Engine 4

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Abstract—**A person who has suffered a stroke may face upper limb motor impairments. Many daily life's tasks involve the use of the upper limb. Therefore, rehabilitation training is necessary to improve motor ability and recovery of stroke patients. However, a stroke patient may feel bored and unmotivated when doing the same rehabilitation tasks repeatedly for a long duration. This paper presents an evaluation of the performance based on a virtual reality (VR) upper limb assessment method and feedback from forty human subjects. Forty human subjects consist of twenty healthy (control) subjects and twenty post-stroke patients who were invited to join in an upper limb motor rehabilitation program. They participated in four games under VR upper limb assessment, namely, 'Pick and Place' game, 'Mirror Pick and Place' game, 'Hit the Ball' game, and 'Wall Climbing' game. All participants wore a VR head-mounted display (HMD) and used hand controllers to perform the assessment. Based on the four games, the stroke group achieved a better score in the 'Mirror Pick and Place' game compared to the other games. A NASA Load Task Index shows that the 'Hit the Ball' game has the highest task load while the 'Mirror Pick and Place' game has the lowest task load. Feedbacks from subjects highlighted that the system was easy to use and the program was full of engagement.**

Index Terms— **Virtual Reality, Upper Limb, Unreal Engine 4, Assessment**

I. Introduction

Having a functioning limb is very important to any human being. Unfortunately, there are over a billion people worldwide who have a few forms of disability such as stroke, and upper limb disability, and around 15 million people have trouble in using their limbs [1]. Disability disproportionately affects men, older people, and children [2]. Rehabilitation is useful to restore the functionality of the upper limb to go on with basic life [3]. Many types of rehabilitation have been introduced such as conventional therapy, robot-assisted therapy, sensor-based, etc [4].

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The upper limb motor can be restored through physical rehabilitation training in a hospital or rehabilitation centre. Most of the rehabilitation is done with conventional methods in hospitals or rehabilitation centres and it is normally a time-consuming session for stroke patients. A full rehabilitation process may take up a duration ranged from a few months to a few years before recovery [5]. It also depends on the patient's progress and condition. Moreover, if the patients feel demotivated, they may not perform the rehabilitation training according to a prescribed schedule which can slow down the process of recovery [5]. Treatment in conventional rehabilitation is often administered on a one-to-one basis, and healthcare costs are high [6]. Moreover, in the absence of computational sensing and measurement, traditional therapy may result in errors when interpreting evaluation data [7]. Therefore, a home-based rehabilitation [8] application is introduced in this paper.

VR technology is developed mainly for entertainment purposes such as in the gaming industry. This growth of technology has rapidly been adopted in other fields such as education, medicine and automotive industry [9]. It has the advantage of flexibly deployed in scenarios that cater for specific needs [10]. The use of VR technology in the medical field has been researched over the years and greatly improved medical rehabilitation such as upper limb motor impairment [11] rehabilitation, Parkinson's Disease Walk [12] rehabilitation and without the immersive system rehabilitation. The VR technology used in rehabilitation is useful to expedite the recovery progress and it can also motivate the user to do more training during rehabilitation. VR technology allows humans to sense virtual objects in a way that is similar to the objects in the real world [13].

VR rehabilitation could be developed as a non-immersive game platform and it has become popular with the advent of off-the-shelf commercial systems [6]. Microsoft Kinect™ system provides a motion-based control interface, which makes it applicable for motor function rehabilitation and the system is affordable. However, the therapeutic effect of non-immersive VR gaming has not been consistent due to a variety of assessment methods for measuring outcome [6].

VR rehabilitation games are not as complex as VR games developed for entertainment. These VR games are regarded as 'serious games' from the viewpoint of the stroke patients where entertainment is not the primary purpose [14]. Serious games are designed by following a framework of game-based learning methodology for education and rehabilitation [15]. Games designed for stroke rehabilitation are more effective than games designed for entertainment [7].

In this study, we developed an immersive VR application with serious gaming by using a game engine to assess the performance of post-stroke upper limb. The paper is organised as follows: Section II describes the related work of system setup and activities of assessment. Section III describes an overview of the proposed assessment program. Section IV presents data analysis, the result of the study and Section VI presents discussion, conclusion, and limitation of this research study.

II. Related work

The most common hardware and sensor used in the VR rehabilitation were Microsoft Kinect and leap motion sensor [16] because they were cheap and widely available in a non-hospital setting. The Microsoft Kinect has a depth sensor that can track the movement of a patient in 3 dimensions [17]. Usually, it was used in upper limb rehabilitation research to capture a patient's movement in the form of a skeleton. Primarily, the Microsoft Kinect system was developed for normal people to play games but was not specifically designed for use by the disabled or stroke patients [18]. On the other hand, the leap motion sensor was usually used to track finger motion in finger motor rehabilitation. It consists of two cameras and three infrared LEDs, which give a higher accuracy of motion tracking to track finger motion [19]. The leap motion sensor could not track a motion properly if it was used near to incandescent light bulbs or exposed under daylight.

Sevgi et al. [18] used Xbox 360 Kinect to perform upper limb motor rehabilitation for subacute stroke patients for evaluating the effect of VR training. The Xbox 360 Kinect device could recognise and track user movements in real-time without requiring any controller. The patients were divided into two groups after baseline evaluations, namely the control group (healthy individual) and stroke group (stroke patients). All patients from the control group and the stroke group underwent a 60-minute conventional therapy. The control group then joined in game-based VR rehabilitation for another 30 minutes. The patient sat in a wheelchair 1.5m or 2m away from the Kinect sensor. Four VR games were introduced whereby the patient had to perform bilateral shoulder abduction and adduction, elbow flexion and extension movement and flexion and extension movements in both the shoulder and elbow joints. The results showed that the combination of conventional therapy and rehabilitation by a Kinect-based game system benefited stroke patients. However, two limitations of the research work were that the duration for the control group was longer than the normal group, which could affect the rehabilitation outcome; and, the Xbox Kinect system was not made purposely for rehabilitation [18].

Sim et al. [5] designed two VR-based Unity applications for rehabilitation by using a leap motion sensor, Microsoft Kinect and a Mobile-based VR headset. The first application was a finger VR-based rehabilitation system for treating the post-stroke patient. The patient was required to wear a headset which was attached to a leap motion sensor before moving the fingers. The patient was then required to pick up a block and stack them up accordingly in the VR environment. This training would help the patient in improving upper limb motor skill. The second application was Balance & Movement training, which was equipped with Microsoft Kinect and mobile VR Headset. The patient was immersed in the virtual environment through a phone VR headset and had to walk on a 3-meter walkway that was equipped with a handrail to prevent the body from falling. The Microsoft Kinect sensor was placed 4 meters away from a starting point. This training would help the patient in improving leg motor.

Robert et al. [20] designed a VR-based system for rehabilitation to recover hand mobility. The system was created by using the Unity game engine. There were three types of sessions which were mirror, augmented and real feedback for the patient to do the hand and arm exercise. The participant who did the hand exercise should do the extension and flexion of the palm and thumb. The participant who did the arm exercise should put the forearm resting on the table, perpendicular to the body. The participant should slide the forearm on the table, back and forth, brought it close to the body and moved it back to the start position. In the first session (mirror session), the patient could see both hands moving in VR even though he could not move the paralysed arm due to the reflection from the mirror. The participant had weak control over his arm and could only participate in the second session (augmented session). The hand movements of the patient in the second session were amplified whereby the hand movement of the patient in VR increased even if he was only able to move slightly in the real world. The third session (real session) was a real feedback session where hand movement would no longer be augmented. The participant who had regained partial control over his arm only could participate in this session [20].

To the best of our knowledge, there are no studies that cover the reliability and usage of the Oculus Rift devices in virtual rehabilitation applications, specifically that involve seated activities.

III. Methodology

VR devices such as Oculus Rift is the main hardware component for upper limb assessment in the VR environment. The combination of the computer software and the hardware is required for a user to carry out the upper limb assessment training. Fig. 1 shows a block diagram of the proposed VR system.

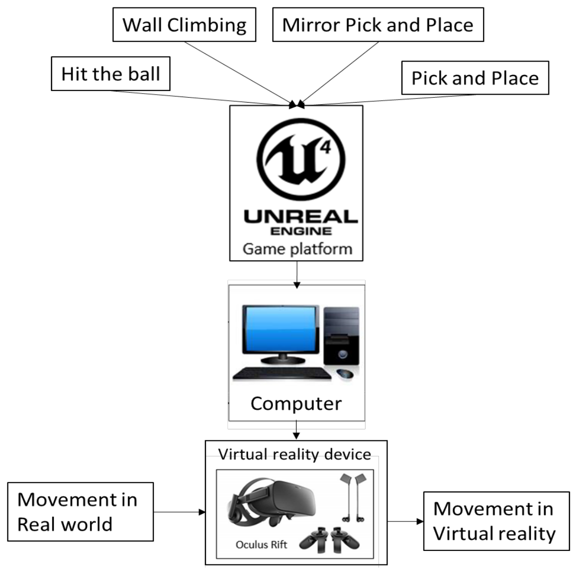

Fig. 1. Proposed Method for Upper Limb Assessment

The training activities include four exercises, which are ‘Pick and Place’ game, ‘Mirror Pick and Place’ game, ‘Wall Climbing’ game and ‘Hit the ball’ game. These training activities are designed for post-stroke therapy. The proposed VR system allows the patient to exercise and hand movement and hand muscle abduction, adduction, flexion, extension and circumduction.

A. Oculus Rift

The Oculus Rift is a ground-breaking VR device and is capable of providing an unparalleled level of immersion in a virtual world [21]. Oculus Rift devices consist of a HMD, a pair of touch controllers and three sensors. It has per-eye displays in a 1080×1200 resolution and operates at 90 Hz; performs 360-degree positional tracking; and is integrated with audio. It can be used as the virtual eye of the user. The touch controller devices and the sensor devices contain a set of infrared (IR) LEDs. The touch controller allows the user to be in contact with the virtual content world through physical movement in the real world and it consists of a haptic sensor. It utilises the low-latency tracking technology to determine the relative position of the headset [22]. The touch controller can be used to grab, hold, select options and so on in the virtual world. Fig. 2 shows a user trying to reach the real and virtual target. The sensors are used to track the movement of the torch controllers and HMD. The sensors must have a clear line of sight to the torch controllers and HMD. Thus, it can translate the movements into VR. Most of the time, two sensors are placed in front of the user and one sensor is placed behind the user so that the sensors can capture the surrounding of the user. The distance between the two sensor devices must be at least 100 cm. The application runs on an RTX 2080Ti desktop computer. Two requirements need to be fulfilled before using VR which are the operating area must be at least 1m in length and 2m in width and no obstacle in the operating area. This is to avoid any unnecessary incidents while operating the VR device.

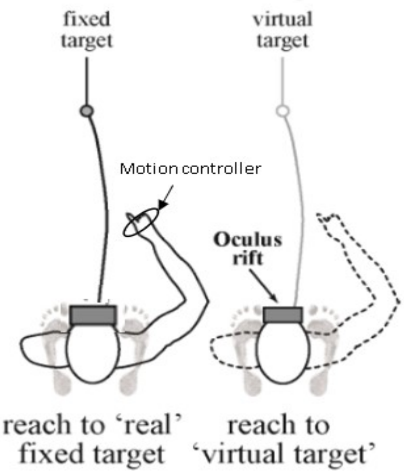

Fig. 2. User Tried to Reach the Real and Virtual Target

B. Unreal Engine 4

These applications are developed using a game development tool called Unreal Engine 4 (UE4, version 4.24). UE4 is a professional AAA game engine created by Epic Games [23] and a great platform to build a virtual environment. The programming language used is C++. All the measurements made in the UE4 are Unreal Unit (uu), where 1 uu in UE4 is equivalent to 1 cm in real measurement. The position of any object in UE4 can be measured in real-time. UE4 has inter-changeable codes with libraries in an object-oriented design framework. It is a computer-generated graphics system [24]

C. Application Interface

The main user interface for these applications comprises four elements, namely the user management module, the storage module, the assessment module and the game module. The management module contains information about the patient and the history of the patient who had used this application. The user is required to fill in information in the application before performing the training. This allows the system to track the patient while performing the training. The required information includes name, age, gender and stroke details. After the required information has been filled in, the information will be displayed as shown in Fig. 3. The storage module can save all the patient information to a file to act as a backup if the data is accidentally deleted. The assessment module can track the patient’s assessment progress. When the patient finishes the training, the data from the game is displayed in the patient profile shown in Fig. 4. The assessment program module provides exercises using game concepts.

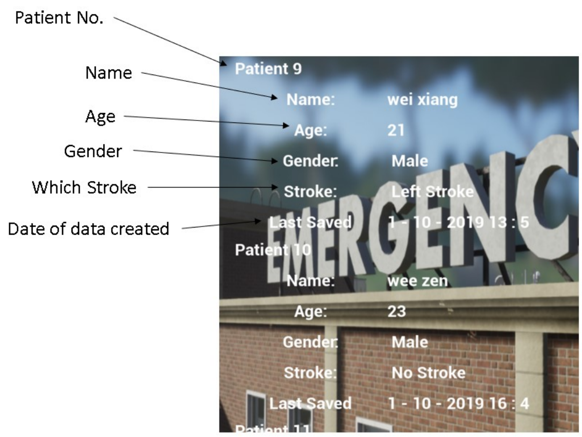

Fig. 3. Management Module Stored the Filled Information

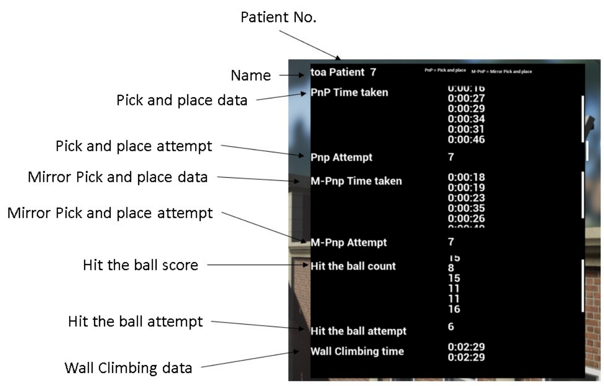

Fig. 4. Assessment Module Displayed the Result of User

D. Subject Selection

There were twenty stroke patients who had fulfilled the inclusion and exclusion criteria identified for the study and twenty healthy people (control people) who have fulfilled the criteria included in the study. The information sheet and form were available in two languages, English and Malay. The consent form seeks approval for the training by the patients' willingness. The inclusion criteria for stroke patients are as follows: their age must in between 30-80 years old, their cerebrovascular accident evidenced by radiological report or physician reports, their stroke with hemiparesis with the power of the upper limb at least 2, they do not have any visual problem and no cognitive impairment as evidence by Mini-Mental State Examination score of more than 24. The exclusion criteria for stroke patients are as follows: they have cognitive impairment with a Mini-Mental State Examination score of less than 24. They have the presence of uncontrolled medical illness that requires actual medical management, and they cannot be enrolled in other studies targeting stroke recovery.

The criteria for the control group are as follows: the age difference of control people and stroke patients is not more than 10. They do not have any surgery records and visual problems. Table I shows the user characteristic of control group and stroke group in this study. The mini-mental examination required no additional equipment and was easy to perform. The Modified Barthel Index can measure physical disability by assessing the behaviour relating to activities of daily living for stroke patients or patients with other disabling conditions.

TABLE I
HEALTHY PEOPLE AND STROKE PATIENT USER CHARACTERISTIC

User characteristics	Control group (N = 20)	Stroke group (N = 20)
Sex (male/female)	15/5	15/5
Age (year)(mean±SD)	33.46±2.47	35.4±1.4
Dominant side (left/right)	3/17	5/15
Disease duration (year) (median)	-	3.5
Montreal cognitive assessment MoCA (median)	28.5	26
Stroke-specific clinical characteristics		
First ever stroke (%)	-	90
Type of stroke (ischemic/haemorrhage)	-	16/4
Lesion side (left/right/both)	-	5/15/0
Mini mental examination (median, range)	-	25[24-26]
Modified Barthel Index (median, range)	-	52.4[44.7-56]

E. Four Games for Upper Limb Assessment

1) Pick and Place (PNP)

The 'Pick and Place' game is designed to evaluate the time taken for the user in completing the game using the affected hand. The PNP task involved many daily life activities and focused on flexion and extension of the upper limb. A user shall pick the cube and place it on another table. The timer will start counting after the user has picked up the first cube from the table. The timer will stop counting when the user has placed all cubes on another table. This game has eight levels of difficulty. At level one, the number of cubes that shall be picked and placed is three. The number of cubes increases by one from one level to another. The stroke patient (user) is instructed to pick up a cube with the affected hand. The user should press the torch controller button to pick up the cube and free the torch controller button to release the cube. Fig. 5 shows the 'Pick & Place' game. The user will advance to the next level of the game if he has passed at present level. The width, height and length of each cube are 13 cm in the VR environment.

Another assessment criterion for evaluating upper limb motor skill is the time taken by the patient to complete the game. The time taken is calculated once the cube has been picked and placed on the table and expressed in seconds. The shorter the completion time, the fitter the upper limb of the patient. The success rate of PNP, S_{RPNP} is determined by measuring the time between picking a cube and placing it on a table. S_{RPNP} is calculated by using (1) and expressed in percentage.

$$S_{RPNP} = \frac{n}{m} * 100\% \quad (1)$$

where, n represents the number of cubes that have been picked and placed on the table within the 20 second and m is the number of cubes that are required to pick and place in the level. Besides, the movement speed of the hand can be measured through the game. The speed of hand movement, S_{PNP} is calculated by using (2) and expressed in centimetres per second (cm/s).

$$S_{PNP} = \left| \frac{u-v}{t_c - t_o} \right| \quad (2)$$

where, u is the total distance travelled of the cube, v is the distance of the cube before moved, t_c value is the time when the cube is placed and t_o is the time when the cube is picked. Arm maximum distance, AMD_{PNP} is calculated by using (3) as the maximum distance between wrist and shoulder in each movement direction and expressed in percentage.

$$AMD_{PNP} = \frac{l_d}{l_u + l_f} * 100 \quad (3)$$

where, l_d is the maximum distance of upper limb can reach in the virtual world, l_u is the length of the upper arm of the user and l_f is the length of the forearm of the user.

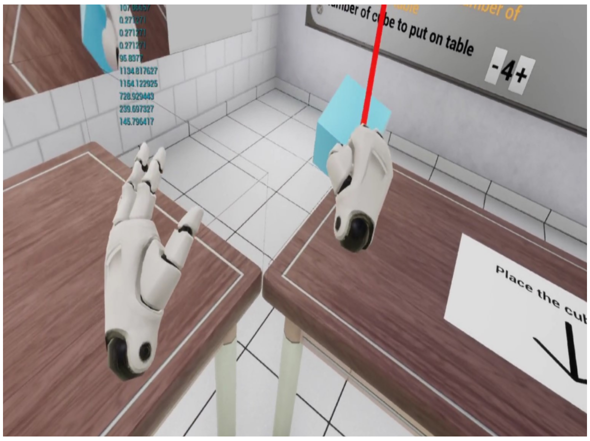

Fig. 5. Right Hand Pick and Place a Cube on the Table

2) Mirror Pick and Place (MPNP)

The 'Mirror Pick and Place' game is developed to promote neuroplasticity by increasing the excitability of the ipsilateral motor cortex which will be projected on the upper limb. In this game, a stroke patient (user) will go on a mirror therapy whereby the user will pick several cubes subsequently from one table to another table. It is different from the PNP game because it does not have mirror therapy. The affected hand will make the same movement as the non-affected hand. The width, height and length of each cube are 13 cm. This game has eight levels. There are three cubes at level 1 of the game. The number of cubes increases by one from level one to level eight. The user will use the non-affected hand to hold the torch controller button to pick up a cube on one table and release the torch controller button to place the cube on another table.

The performance of the stroke patient in the MPNP game is also measured by the time to completion of picking and placing all cubes. The shorter the duration of the completion time, the better the ability motor upper limb of the patient. The time taken is calculated once the cube has been picked and placed on the table and the duration is expressed in seconds. Fig. 6 illustrates the left and right hand selection for grabbing function in MPNP. Fig. 7 shows the right hand controls the grab function and the left hand moves the cube while grabbing it. The success rate of MPNP, S_{RMPNP} can be measured based on the time for each cube to be placed on the table. The S_{RMPNP} is calculated by using (4) and expressed in percentage.

$$S_{RMPNP} = \frac{n}{m} * 100\% \qquad (4)$$

where, n represents the number of cubes that have been picked and placed within the 20 second. and m value is the number of cubes that are required to pick and place in the level. Moreover, the movement speed of the hand can be measured through the game. The hand movement, S_{MPNP} is calculated by using (5) and expressed in centimetres per second (cm/s).

$$S_{MPNP} = \left| \frac{u-v}{t_c - t_o} \right| \qquad (5)$$

where u is the total distance travelled of the cube, v is the distance of the cube before moved, t_c is the time when the cube has been placed and t_o is the time when the cube picked. Arm maximum distance, AMD_{MPNP} is calculated by using (6) as the maximum distance between wrist and shoulder in each movement direction and expressed in percentage.

$$AMD_{MPNP} = \frac{l_d}{l_u + l_f} * 100 \qquad (6)$$

where, l_d is the maximum distance of the upper limb can reach in the virtual world, l_u is the length of the upper arm of the user and l_f is the length of the forearm of the user.

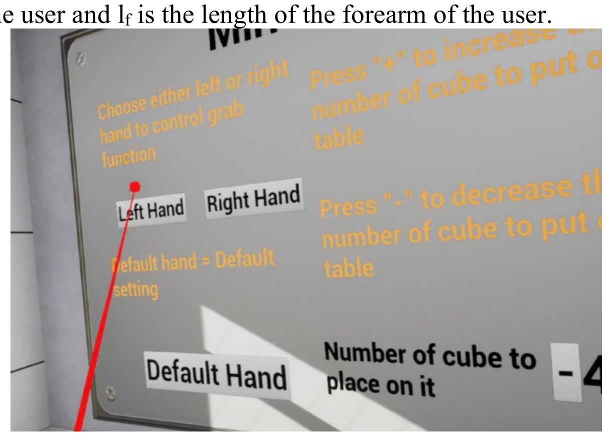

Fig. 6. Left and Right Hand Selection for MPNP

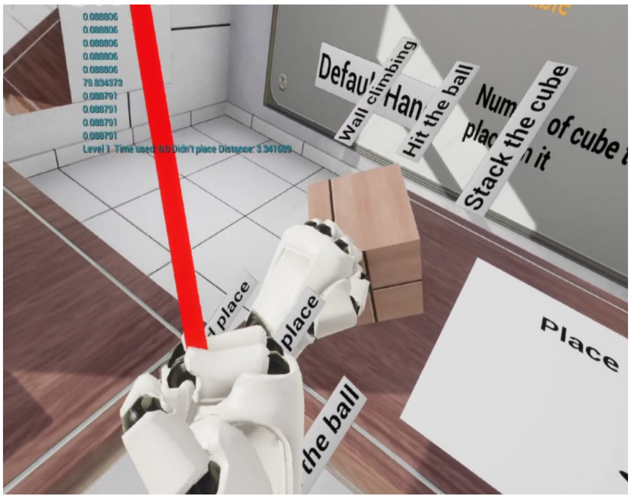

Fig. 7. Right Hand Controls the Grab Function and Left Hand Moves the Cube

3) Wall Climbing (WC)

The ‘Wall Climbing’ game is used in the upper limb assessment sessions. In this game, the user needs to move his or her upper limb vertically, namely movement of adduction and abduction in the VR environment. The WC game is different from real life as the user will not be falling because it does not have a gravity pull. The stroke patient (user) sits on a chair and uses the affected hand to climb the ladder. The ladder has twenty three rungs for the patient to climb. The completion time of this game is measured by the amount of time the user has climbed all rungs of this ladder. In this case, the timer will start counting when the user grabs the first rung of the ladder and stop counting when the user has reached the endpoint or does not grab on a rung of the ladder within thirty seconds. When the user holds a rung of the ladder, the colour of the rung will become red which indicates the rung has been grabbed and the score will be increased by one. In the real world, the user needs to hold the torch controller button to grab the rung of the ladder in VR and likewise, to release the torch controller button to release the rung from the ladder. The user needs to attempt this game five times to record performance. Fig. 8 shows the right hand is grabbing a rung to climb the ladder. Fig. 9 consists of 23 rungs and requires the user to climb to the ending point. The performance is evaluated by using (7) as the average time taken to complete the ladder of five attempts, T_{MWC} expressed in seconds.

$$T_{MWC} = \frac{t_T}{5} \qquad (7)$$

where, t_T is the total sum of time taken from the five attempts. The average time per ladder, T_{APL} is calculated by using (8) and expressed in seconds per ladder (s/l).

$$T_{APL} = \frac{t_a}{23} \qquad (8)$$

where, t_a is the total time used to reach the ending point. The success rate of WC, S_{RWC} will be measured. The S_{RWC} is calculated by using (9) and expressed in percentage.

$$S_{RWC} = \frac{n}{m} * 100\% \qquad (9)$$

where, n is the number of rungs that have been touched within 20 seconds and m is the total number of rungs. The hand movement, S_{WC} is calculated by using (10).

$$S_{WC} = \left| \frac{u-v}{t_c - t_o} \right| \qquad (10)$$

where, u is the final distance of hand after grabbing the new rung, v is the initial distance of hand before grabbing the rung, t_c is the time after grabbing a new rung and t_o is the time before grabbing a new rung.

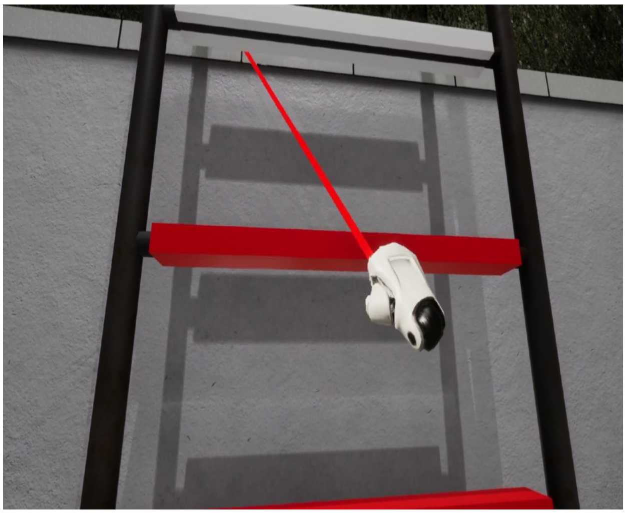

Fig. 8. Grabbing a Rung to Climb Up the Ladder

Fig. 9. The Ladder consists of 23 rungs and requires the user to climb to the ending point.

4) Hit the Ball (HTB)

The 'Hit the Ball' game evaluates the total balls that are hit by the user within 30 seconds. The 'Hit the Ball' game is designed for the extension of the shoulder and elbow joints of the upper limb which involves the movement of extension, flexion, abduction and adduction. In this game, the user moves his or her arm to hit a ball. The user is instructed to use the affected hand to grab the bat and hit the ball in the VR environment. The user will hold the torch controller button in the real environment to indicate holding the bat in the VR. The ball radius is 5 cm and the speed of the ball is set at 40 cm/s. In order to hit the ball, the user has to move the bat to make contact with the ball. A user is given 30 seconds to hit the ball. In this duration, if a ball has been hit successfully, it will disappear and the score of the game will be increased by 1. The user has to attempt this game five times to measure his or her performance. Fig. 10 demonstrates a ball has been hit by using a bat. The performance is evaluated by using (11) which is an average score of five attempts, S_{A5}.

$$S_{A5} = \frac{n}{5} \qquad (11)$$

where, n is the total ball that has been hit by the bat. The average time per ball, T_{APB} is calculated by using (12) and expressed in seconds per ball (s/b).

$$T_{APB} = \frac{30}{n} \qquad (12)$$

where, n is the total ball that has been hit by the bat. Arm maximum distance AMD_{HTB} is calculated by using (13) and expressed in percentage.

$$AMD_{HTB} = \frac{l_d}{l_u + l_f} * 100 \qquad (13)$$

where, l_d is the maximum distance of the upper limb can reach in the virtual world, l_u is the length of the upper arm of the user and l_f is the length of the forearm of the user. The hand movement, S_{HTB}, is measured by using (14) as maximum speed between a point to another point in each movement direction and expressed in percentage.

$$S_{HTB} = \left| \frac{d_t}{t_c - t_o} \right| \qquad (14)$$

where, d_t is the total distance travelled of the limb. The d_t can be obtained by using the current distance of wrist, d_c subtracts the original distance of wrist, d_o, t_c is the time before the hand starts to move and t_o is the time after the hand has stopped moving.

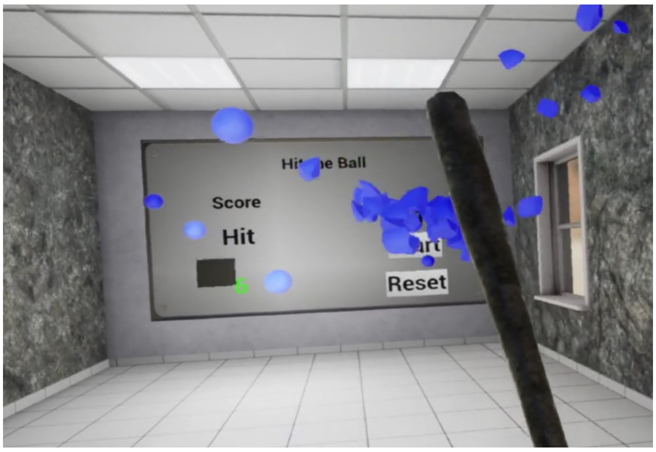

Fig. 10. Hitting a Ball with Bat to Increase the Score

F. *Questionnaire and Feedback from Subject*

Task loads of the games were measured by using the NASA-Task Load Index (TLX) questionnaire after each game session. Each questionnaire score starts from 1 to 10 which indicates from high to worse. The stroke group was required to fill in the NASA-TLX. The NASA-TLX consists of six sections, namely mental demand, physical demand, temporal demand, effort, performance and frustration level that the user needs to fill in with the score from 1 to 10. The mental demand section has a score from 1 to 10 (low to high) and it indicates the mental and perceptual activity that were required during the assessment. The physical demand section has a score from 1 to 10 (low to high) and it indicates the physical activity used in the activity and whether the tasks given are easy or demanding. The temporal demand section has a score from 1 to 10 (low to high) and it indicates the time pressure felt by the user. The performance section has a score from 1 to 10 (good to poor) and indicates the satisfaction of user performance in accomplishing the goal. The effort section has a score from 1 to 10 (low to high) and it indicates the amount of physical and mental use for the user to accomplish the level. The frustration level section has a score from 1 to 10 (low to high) and it indicates the level of stress, discouragement and irritation during the assessment.

The participation was analysed using a subset of 18 questions from the game experience questionnaire, perceived usefulness questionnaire, and perceived ease of use questionnaire. The questions with a score of 1 to 10 indicate from high to worse. ~~Both~~ All three questionnaires were used to assess user experiences and identify opportunities for further development after the end of the experiment.

G. *Experimental Flow*

The torch controllers, sensors and VR HMD are required for all the applications. The user sat in a chair with an armrest. The user had to be familiar with the HMD and torch controllers. Each VR game was explained in-game using Graphics Interchange Format (GIF) and explained by the person in charge. The user was given two torch controller devices to hold with hands. The patient used a pair of torch controllers to interact with the virtual content. Both the HMD and torch controllers were detected by the sensors. Once the user became familiar with the VR devices, he or she started to do VR assessment. The games were played in this sequence: 'Pick and Place' game, 'Mirror Pick and Place' game, 'Wall Climbing' game and followed by 'Hit the Ball' game. After the user finished the training, he or she was required to fill in the given questionnaire and feedback about the application. Fig. 11 shows the flowchart of the process experiments.

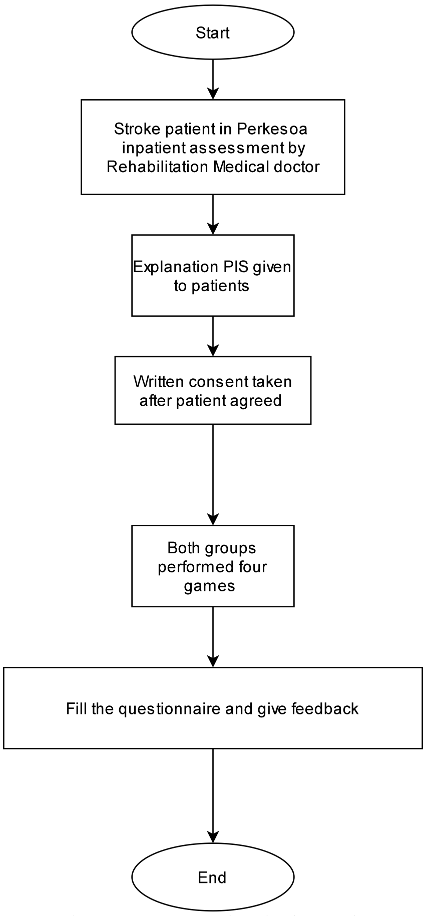

Fig. 11. Program Flow in the Study

IV. Results

A. *Pick and Place Results*

The results from the 'Pick and Place' game throughout all the 8 levels are shown in Table II and Fig. 12. The control group used a shorter time (8.23s±0.41) to complete all levels compared to the control group (24.51s±0.86). Both groups completed all the levels within 10 minutes. There is no difference between the S_{RPNP} of the control group (100%) and the S_{RPNP} of the stroke group (100%). The S_{PNP} of both groups shown in Table III and Fig. 13. The maximum S_{PNP} in the control group is 50.1 cm/s and the minimum S_{PNP} in the control group is 23.80 cm/s. The stroke group maximum S_{PNP} is 13.96 cm/s and the minimum S_{PNP} is 9.79 cm/s. The average minimum S_{PNP} for the control group and stroke group is 30.14 cm/s and 10.66 cm/s. The average maximum S_{PNP} for the control group and stroke group is 48.89 cm/s and 12.39 cm/s. The average AMD_{PNP} is slightly greater in the control group (100%) than the stroke group (64%). Table IV shows the average AMD in each level of both groups. AMD_{PNP} in the control group is 100% in all the levels while the stroke group is able to achieve highest AMD, 70% and lowest AMD, 60%.

TABLE II
AVERAGE TIME TAKEN FOR EACH LEVEL OF 'PICK AND PLACE' GAME

Pick and Place	Control Group (seconds)	Stroke Group (seconds)
Level 1	3.95±0.94	10.05±1.28
Level 2	5.3±1.08	14.90±2.15
Level 3	7.35±0.99	17.90±2.91
Level 4	7.90±1.21	22.40±3.08
Level 5	9.05±1.82	25.85±3.39
Level 6	9.8±1.82	30.20±3.37
Level 7	10.6±1.93	34.40±3.73
Level 8	11.85±1.39	39.20±3.83

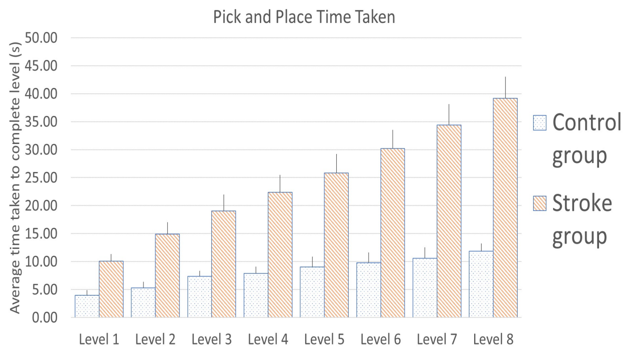

Fig. 12. Average Time Taken for Each Level in the 'Pick and Place'. Error Bars Represent Standard Deviations.

TABLE III
AVERAGE OF MINIMUM AND MAXIMUM HAND MOVEMENT FOR EACH LEVEL IN 'PICK AND PLACE' GAME

Level	Control Group Hand Movement (cm/s)		Stroke Group Hand Movement (cm/s)	
	Min	Max	Min	Max
Level 1	38.89	50.10	11.28	13.96
Level 2	31.34	48.40	10.97	12.70
Level 3	25.93	47.83	10.50	12.03
Level 4	23.80	50.01	9.99	11.97
Level 5	25.03	49.50	9.79	11.83
Level 6	38.89	49.04	11.28	12.32
Level 7	31.34	48.40	10.97	12.21
Level 8	25.93	47.87	10.50	12.07

Fig. 13. Average Minimum and Maximum of the Hand Movement for Each Group In 'Pick and Place'. Error Bars Represent Standard Deviations

TABLE IV
AVERAGE ARM MOVEMENT DISTANCE BETWEEN BOTH GROUP IN PICK AND PLACE

Level in PNP	Control Group Arm Movement Distance (%)	Stroke Group Arm Movement Distance (%)
Level 1	100	64
Level 2	100	67
Level 3	100	70
Level 4	100	65
Level 5	100	63
Level 6	100	62
Level 7	100	61
Level 8	100	60

B. Mirror Pick and Place Results

The average result of the ‘'Mirror Pick and Place' game shown in Table V and Fig. 14. Throughout all the 8 levels, the control group used a shorter time (mean ± SD: 10.04s±0.40) to complete all levels compared to the control group (mean ± SD: 13.16s±0.51). By referring to Fig. 14, the time taken to complete a level has increased as the difficulty has increased. Both groups completed all the levels within 10 minutes. There is no difference between the S_{RMPNP} of the control group (100%) and the S_{RMPNP} of the stroke group (100%). The S_{MPNP} of both groups shown in Table VI and Fig. 15. The maximum S_{MPNP} in the control group is 51.25 cm/s and the minimum S_{MPNP} in the control group is 23.42 cm/s. In the stroke group, the maximum S_{MPNP} is 50.07 cm/s and the minimum hand movement is 23.8 cm/s. The average minimum S_{MPNP} for the control group and stroke group is 27.81 cm/s and 27.71 cm/s. The average maximum S_{MPNP} for the control group and stroke group is 49 cm/s and 48.97 cm/s. The average AMD_{MPNP} is not significantly different from the control group (100 %) and stroke group (100%). Both groups are able to achieve 100% throughout all the levels. Table VII shows the average AMD in each level of both groups.

TABLE V
AVERAGE TIME TAKEN FOR EACH LEVEL IN 'MIRROR PICK AND PLACE' GAME

Mirror Pick and Place	Control Group (seconds)	Stroke Group (seconds)
Level 1	5.05±0.94	6.65±1.42
Level 2	6.80±1.57	9.90±2.31
Level 3	8.95±1.57	10.90±1.86
Level 4	10.50±2.09	12.65±1.95
Level 5	11.10±2.15	14.45±1.85
Level 6	11.85±2.09	15.65±1.53
Level 7	12.65±1.76	16.65±1.93
Level 8	13.95±1.54	18.45±3.05

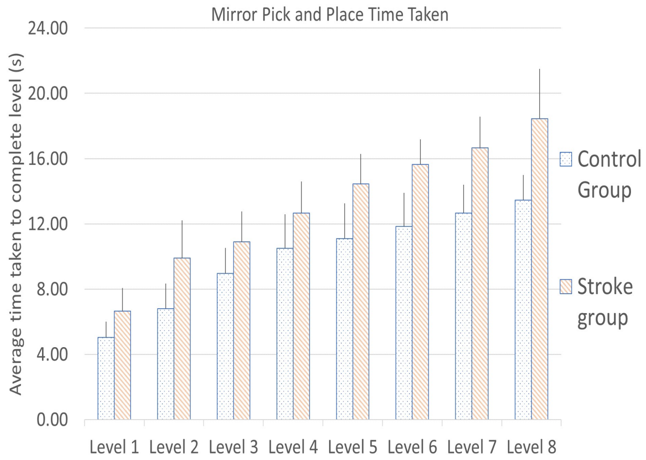

Fig. 14. Average Time Taken for Each Level in the 'Mirror Pick and Place'. Error Bars Represent Standard Deviations

TABLE VI
AVERAGE MINIMUM AND MAXIMUM HAND MOVEMENT FOR EACH LEVEL IN 'MIRROR PICK AND PLACE' GAME

Level	Control Group Hand Movement (cm/s)		Stroke Group Hand Movement (cm/s)	
	Min	**Max**	**Min**	**Max**
Level 1	38.21	51.25	37.93	50.07
Level 2	32.75	47.35	31.80	48.40
Level 3	27.92	47.87	30.68	47.87
Level 4	26.89	50.07	24.89	49.37
Level 5	24.34	51.25	24.47	49.75
Level 6	24.89	49.50	23.80	49.50
Level 7	23.42	47.87	24.47	48.94
Level 8	24.07	46.84	23.67	47.87

Fig. 15. Average Minimum and Maximum of Hand Movement in the 'Mirror Pick and Place'. Error Bars Represent Standard Deviations

TABLE VII
AVERAGE ARM MOVEMENT DISTANCE BETWEEN BOTH GROUP IN MIRROR PICK AND PLACE

Level in MPNP	Control Group Arm Movement Distance (%)	Stroke Group Arm Movement Distance (%)
Level 1	100	100
Level 2	100	100
Level 3	100	100
Level 4	100	100
Level 5	100	100
Level 6	100	100
Level 7	100	100
Level 8	100	100

C. Wall Climbing Result

The average result of the ''Wall Climbing' game shown in Table VIII and Fig. 16. Both groups can complete the game and do five attempts within 10 minutes. The T_{MWC} for the stroke group (mean ± SD: 74.08s±16.74) is significantly longer as compared to the control group (mean ± SD: 34.89s±0.40). The T_{APL} for the stroke group (3.22 s/l±0.12) is slightly longer than the control group (1.52 s/l± 0.07). There is no difference between the S_{RWC} of the control group (100%) and the S_{RWC} of the stroke group (100%). Table IX and Fig. 17 show the average of minimum and maximum S_{WC} of both groups. The maximum S_{WC} in the control group is 26.94 cm/s and the minimum S_{WC} in the control group is 20.64 cm/s. The stroke group maximum S_{WC} is 14.21 cm/s and minimum S_{WC} is 6.53 cm/s. The average minimum S_{WC} for the control group and stroke group is 20.90 cm/s and 6.93 cm/s. The average maximum S_{WC} for the control group and stroke group is 26.5 cm/s and 13.99 cm/s.

TABLE VIII
AVERAGE TIME TAKEN FOR EACH ATTEMPT AND OVERALL TIME TAKEN IN 'WALL CLIMBING' GAME

Wall Climbing	Control Group (seconds)	Stroke Group (seconds)
1st attempt	35.45±3.66	61.53±5.16
2nd attempt	34.53±.3.23	65.53±2.25
3rd attempt	34.93±3.90	65.60±3.25
4th attempt	35.13±3.38	75.07±9.87
5th attempt	34.47±3.58	102.67±10.4
Average from five attempts	34.86±0.57	73.87±14.52

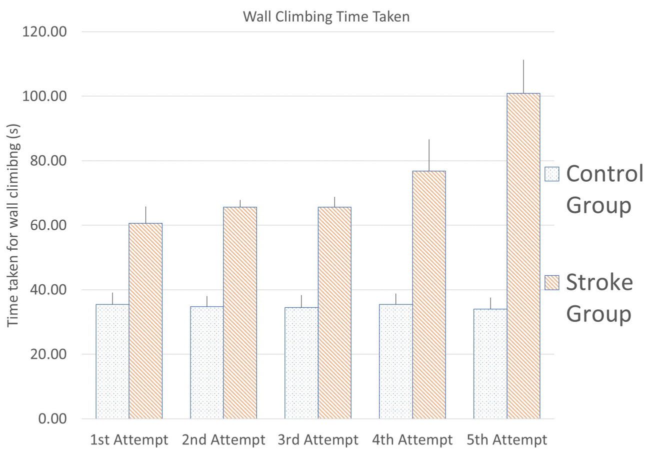

Fig. 16. The Average Time Taken for Each Attempt in the 'Wall Climbing'. Error Bars Represent Standard Deviations

TABLE IX
AVERAGE MINIMUM AND MAXIMUM OF HAND MOVEMENT FOR EACH ATTEMPT IN 'WALL CLIMBING' GAME

Attempt	Control Group Hand Movement (cm/s)		Stroke Group Hand Movement (cm/s)	
	Min	Max	Min	Max
1st attempt	20.13	26.83	7.15	14.65
2nd attempt	20.78	26.34	6.84	13.68
3rd attempt	21.76	25.89	6.88	14.21
4th attempt	21.18	26.94	7.26	13.89
5th attempt	20.64	26.50	6.53	13.51

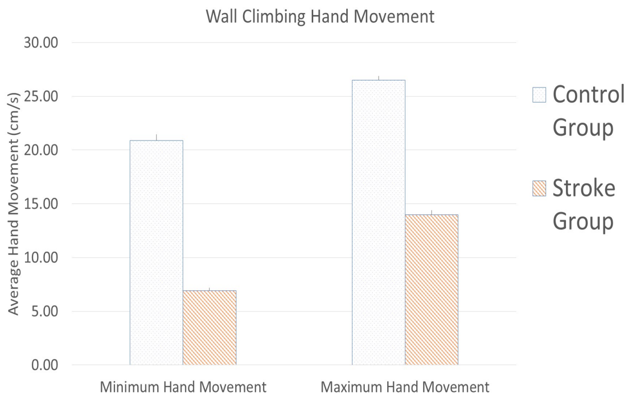

Fig. 17. Average Minimum and Maximum Hand Movement for Both Groups in the 'Wall Climbing'. Error Bars Represent Standard Deviations

D. Hit the Ball Results

The results of the ''Hit the Ball' game are shown in Table X and Fig. 18. Five attempts have been made by both groups to complete the game within a certain time. As expected, the S_{A5} of the control group (mean ± SD: 20.15±0.16) is better than the stroke group (mean ± SD: 15.57±0.37). The T_{APB} for stroke (1.93s/b) is slightly longer compared to the control group (1.49s/b). Table XI and Fig. 19 shows the average minimum and maximum S_{HTB} in 'Hit the Ball' game. The maximum S_{HTB} in the control group is 52.1 cm/s and the minimum S_{HTB} in the control group is 10.5 cm/s. The stroke group maximum S_{HTB} is 35.32 cm/s and the minimum S_{HTB} is 5.97cm/s. The average minimum S_{HTB} for the control group and stroke group is 12 cm/s and 7.04cm/s. The average maximum S_{HTB} for the control group and stroke group is 48.24 cm/s and 21.01 cm/s. The average AMD_{HTB} is slightly greater in the control group (100%) than the stroke group (71%). Table XII shows the average AMD in each level of both groups.

TABLE X
AVERAGE TIME TAKEN FOR EACH ATTEMPT AND OVERALL TIME TAKEN FROM FIVE ATTEMPTS IN 'HIT THE BALL' GAME

Hit the ball	Control Group Score	Stroke Group Score
1st attempt	20.07±0.7	15.07±1.28
2nd attempt	20.27±0.46	15.73±2.22
3rd attempt	20.13±0.36	15.53±3.18
4th attempt	20.33±0.9	15.47±2.36
5th attempt	19.93±0.59	16.07±2.15
Average from five attempts	20.15±0.14	15.57±0.33

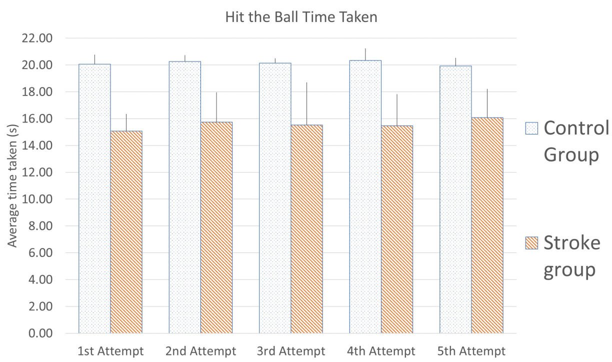

Fig. 18. The Average Time Taken for Each Attempt in the 'Hit the Ball' Game. Error Bars Represent Standard Deviations

TABLE XI
AVERAGE MINIMUM AND MAXIMUM HAND MOVEMENT FOR EACH ATTEMPT IN 'HIT THE BALL' GAME

Attempt	**Control Group Hand Movement (cm/s)**		**Stroke Group Hand Movement (cm/s)**	
	Min	**Max**	**Min**	**Max**
1st attempt	12.6	46.3	8.15	20.6
2nd attempt	11.8	52.1	7.87	35.32
3rd attempt	10.5	43.7	6.9	17.4
4th attempt	13.7	50.4	5.97	15.3
5th attempt	11.4	48.7	6.32	16.4

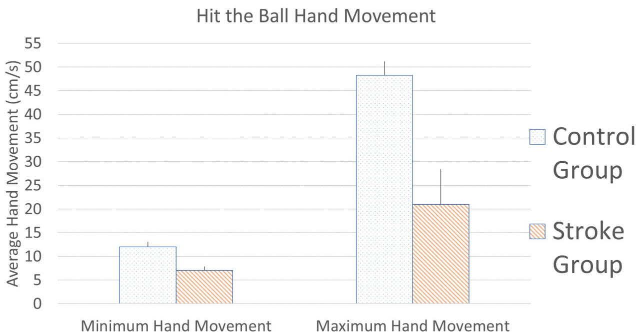

Fig. 19. Average Minimum and Maximum Hand Movement in the 'Hit the Ball' Game for Both Groups. Error Bars Represent Standard Deviations.

TABLE XII
AVERAGE ARM MOVEMENT DISTANCE BETWEEN BOTH GROUP IN HIT THE BALL

Attempt in HTB	**Control Group Arm Movement Distance (%)**	**Stroke Group Arm Movement Distance (%)**
1st attempt	100	78
2nd attempt	100	68
3rd attempt	100	65
4th attempt	100	74
5th attempt	100	70

E. User Feedback and Questionnaires

By referring to questionnaire results in Table XIII, the overall user experience mean score is 13.58±5.17 out of 40. The overall perceived usefulness mean score is 13.29±3.66 out of 40. Fig. 20 shows the users feedback score. The overall perceived ease of use's mean score is 13.55±3 out of 40. By referring to the NASA-TLX score in Table XIV, the overall mean score of the task load in PNP is 8.97±16.69 out of 20. The overall mean score of the task load in MPNP is 4.90±10.83 out of 20. The mean score of the task load in WC is 10.30±21.48 out of 20. The overall mean score of the task load in HTB is 12.23±23.25 out of 20. Fig. 21 shows the PNP task load feedback. Fig. 22 shows the MPNP task load feedback. Fig. 23 shows the WC task load feedback. Fig. 24 shows the HTB task load feedback.

TABLE XIII
USERS FEEDBACK SCORE FOR QUESTIONNAIRES

Questionnaires	**Mean ± Standard Deviation**
User Experience	13.58±5.17
Perceived Usefulness	13.29±3.66
Perceived Ease of use	13.55±3

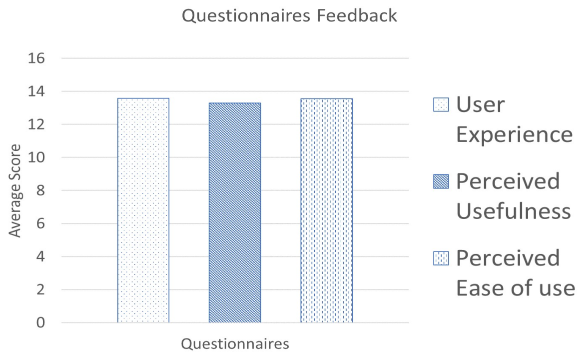

Fig. 20. Users Feedback Score Based on Questionnaire

TABLE XIV
NASA-TLX SCORE FOR EACH VR GAME

NASA-TLX	**PNP**	**MPNP**	**WC**	**HTB**
Mental Demand	6.40± 12.82	6.50± 14.92	5.10± 9.50	12.40± 17.86
Physical Demand	11.30± 20.99	4.10± 9.53	14.10± 23.37	16.50± 30.19
Temporal Demand	9.90± 16.28	7.50± 11.64	13.50± 33.50	5.30± 8.59
Performance	8.30± 17.24	2.50± 5.40	6.70± 13.90	8.90± 17.26
Effort	9.60± 15.57	5.30± 14.08	13.90± 28.87	15.70± 37.71
Frustration	8.30± 17.24	3.50± 9.44	8.50± 19.73	14.60± 28.47
Average	8.97± 16.69	4.90± 10.83	10.30± 21.48	12.23± 23.25

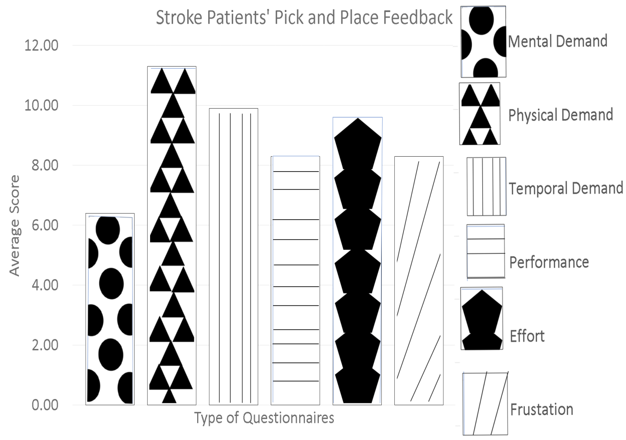

Fig. 21. PNP Feedback of Stroke Patient in the NASA-TLX

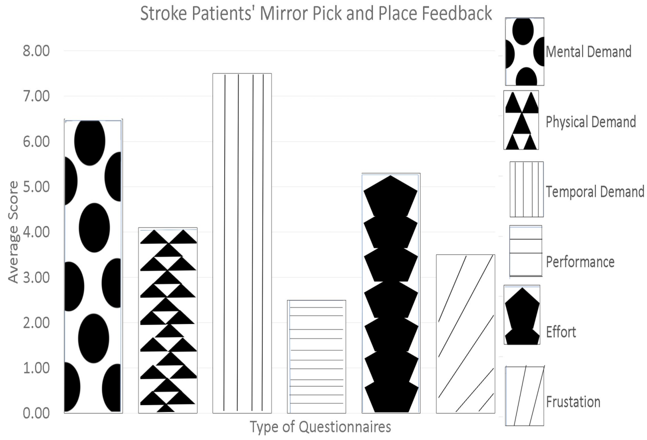

Fig. 22. MPNP Feedback in the NASA-TLX

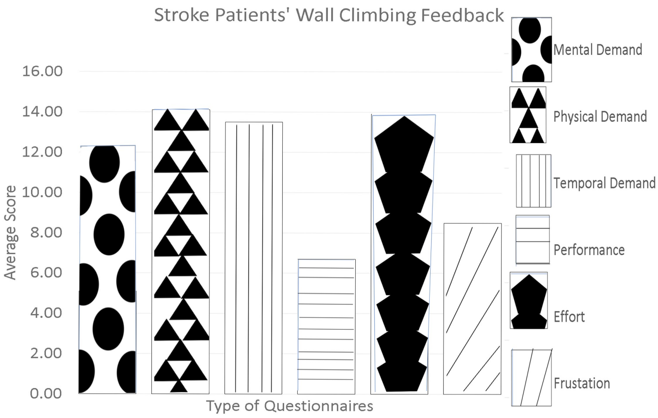

Fig. 23. WC Feedback in the NASA-TLX

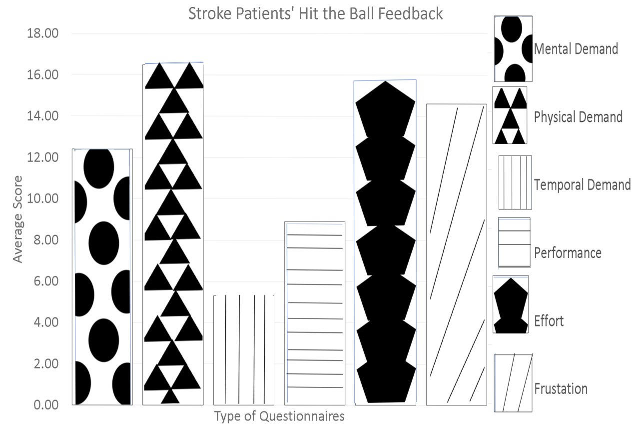

Fig. 24. HTB Feedback in the NASA-TLX

V. Discussion

In the 'Pick and Place' game, the S_{RPNP} between both groups in picking and placing cubes within 20 seconds is 100%. The control group used a shorter time to complete all the levels as compared to the stroke group who used the affected hand to do the task; thus, the stroke group required more time to complete each level. The affected hand moved slower than the non-affected hand. The AMD_{PNP} between the stroke group and the control group has a significant difference as the stroke group is not able to move their hand to the maximum distance based on their upper limb length. The control group's S_{PNP} and stroke group's S_{PNP} have significant differences based on each level of the average minimum and maximum S_{PNP} in the control group are higher than the stroke group.

Based on the 'Mirror Pick and Place' game, the S_{RMPNP} between both groups achieved 100% when the cubes were picked and placed within 20 seconds. The control group and stroke group used the non-affected hand to do the pick and place tasks with mirror therapy; thus, the performance of the stroke group is better than the performance of the stroke group in the PNP game. The AMD_{MPNP} between both groups is the same (100%) as they moved their hand to the maximum distance based on their upper limb length. The control group's S_{MPNP} and stroke group's S_{MPNP} have no significant difference because the average minimum and maximum S_{MPNP} in the control group and stroke group are similar.

In the 'Pick and Place' game and 'Mirror Pick and Place' game, when the level increased, the difficulty increased as the number of cubes required for pick and place increased; thus, the time taken to complete each level for both groups gradually increased. The performance of the non-affected hand is better than the performance of the affected hand. The S_{PNP} and S_{MPNP} are moved in horizontal direction, namely flexion and extension movements. This is because the tables are placed beside and in front of the user. Individual assessment of interaction space (PNP and MPNP) allows the users to get familiar with the controller (i.e., grabs, release). The MPNP used a shorter time to complete compared to PNP because MPNP consists of a mirror therapy concept whereby the user uses a non-affected hand to control 'virtual hand' to pick and place the cubes. Moreover, AMD_{MPNP} is better than AMD_{PNP} because the non-affected hand can extend arm completely.

The 'Wall Climbing' game is the most challenging part in the study. The user needs to climb twenty-three ladders because most of the stroke patients are not able to climb up the ladder and it is dangerous to perform in the real world. Therefore, they can climb up the ladder safely and will not fall in the virtual world. The S_{RWC} for both groups is 100% which means both groups have touched the ladder within 20 seconds. After the third attempt, the time taken to complete the 'Wall Climbing' game has significantly increased. The first, second and third attempts are completed within 65 seconds; however, the fourth attempt is completed with 75 seconds and the fifth attempt is completed with 103 seconds which are longer compared to the first three attempts. Some users have fear of heights, but they manage to finish the climbing. The T_{APL} is significantly different between the control group and the stroke group because the stroke group used the affected hand while the control group used the non-affected hand. The control group's S_{WC} and stroke group's S_{WC} have significant differences based on the five attempts. This game involved the vertical upper limb movements which are adduction and abduction movements.

The presence of time limitations in 'Hit the Ball' led to increasing the movement of users to hit the ball. The balls are spawned randomly because some of the users hit a few of the balls in the same direction. Some stroke patients are not able to hit some balls because their hand is not able to reach a higher height. In the future application, the balls will spawn in order and the ball spawn height will be slightly reduced. The AMD_{HTB} between the stroke group and the control group has a significant difference as the stroke group is not able to move their hand to the maximum distance based on their upper limb length to hit the ball with the bat. The control group's S_{HTB} and stroke group's S_{HTB} have significant differences based on the five attempts. The HTB game involved both vertical and horizontal upper limb movement which are flexion, extension, adduction and abduction movement.

According to the AMD_{PNP}, AMD_{MPNP} and $AMD_{HTB,}$ the stroke group achieved highest AMD in the MPNP game and lowest AMD in the PNP game. This is because the stroke group performed the MPNP game with a non-affected hand and complete the HTB game with the affected hand. This is because non-affected hands can fully extend to its original length while affected hands could not fully extend. Moreover, the stroke group's AMD_{HTB} is higher than stroke group AMD_{PNP}. Thus, the HTB game tends to extend the stroke group's arm more compared to the PNP game.

Based on the minimum and maximum hand movement among the four games, the control group achieved the maximum hand movement in the HTB game, 52.1 cm/s and minimum hand movement in the HTB game, 10.5 cm/s. The stroke group achieved maximum hand movement in the MPNP game, 50.07 cm/s and minimum hand movement in the HTB game, 6.32 cm/s. The control group and stroke group have the lowest minimum hand movement in the HTB game compared to other games. This is because the user could slowly position the hand before the first ball reaches the hit range. The maximum hand movement of the control group is in the HTB game because the user is able to move hand quickly to hit the ball while the maximum hand movement for the stroke group is MPNP because the user is able to play and complete the game using non-affected hand.

According to Table XIII, the average score of all users' questionnaire responses is 13 out of 40. The questionnaire shows the lower the score, the better the user experience. This indicates that users have good experience with the VR rehabilitation system, such as the VR environment is enjoyable for them and the system functioned to their satisfaction. Moreover, the system is very useful for them, enabling them to accomplish their rehabilitation exercise faster and easier. The users are able to operate the VR rehabilitation system easily and the system is friendly for them. Based on users' feedback scores in Table XIV, the MPNP has the lowest task load for the stroke groups because this game required a non-affected hand to do the assessment. The HTB has the highest task load because the users have to target the incoming ball and move their affected hand to hit the ball. The NASA-TLX shows the higher the average score, the higher the task load.

There are several limitations in this study. First, the users must be able to lift their arm above shoulder level, which cannot be done by a large percentage of stroke patients because most of the stroke patients could barely reach shoulder level. This research is carried out with users in middle age. Besides, it is not possible to be generalised without reservation to elder persons because they do not expect to use the new technology. Second, when users use the HMD, some users feel uncomfortable or dizzy after 30 minutes of wearing it. This is because they are not able to get used to it in a short period and it is an expected effect which is motion sickness. In order to prevent motion sickness, the patient must rest between the assessment. Third, the touch controller grab and release button are pressed by using the middle finger and not able to track the finger properly. In the future, the torch controllers can be replaced with the Valve Index controller as the controller is able to track the finger.

VI. Conclusion

In this work, we have successfully implemented four VR games in UE4. We used the Oculus Rift device, HMD to see through the virtual content and interacted with virtual objects with touch controllers. The stroke group achieved a better score in 'Mirror Pick and Place' as compared to the other games. Based on the NASA-TLX, the 'Hit the Ball' game has the highest task load for stroke group while 'Mirror Pick and Place' game has the lowest task load. The users from both groups have feedback good experience in the assessment.

In conclusion, our research bears witness to the ability of VR games to evaluate motor impairments between stroke patients and the control group and offers starting points for further development. This paper could be useful for the researcher who would like to perform the research on upper limb rehabilitation.

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