Virtual Reality Interactive Games in Stroke Rehabilitation – a Pilot Study

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Abstract

Stroke is the leading cause of disability in adults. However, stroke survivors can recover some or all of their motor function when supported with rehabilitation. Unfortunately, traditional stroke rehabilitation is costly and patients often lose their motivation in the process due to the repetitive exercises which are regarded as boring. Virtual reality has been considered as an effective intervention in addition to traditional therapy due to recent advances in this technology. Virtual reality in stroke rehabilitation has advantages over traditional rehabilitation in terms of reductions in cost, flexibility in customisation for different individuals, and increasing patients' motivation. In practice, the recovery of mobility, especially walking, is the main priority at early stages of rehabilitation following a stroke. Upper limb rehabilitation, on the other hand, is often undertaken as an outpatient and with home therapy. It is estimated that over 30% of stroke patients do not have a satisfactory recovery in their upper limbs.

This study attempts to develop a Leap Motion controlled virtual reality game for hand rehabilitation. The Leap Motion Controller is a low cost and high precision hand tracking device which can be operated by a free hand. This game requires patients to use their fingers, palms and arms in order to interact with the game environment and practice the exercises in the game. This game consists of 5 exercises: Grab, Pick n Match, Pinch, Navigation and Gesture. Patients can see the actions of their hands on the screen and modify their actions via real time feedback provided by the system in the forms of audio, visualisation, and text. This virtual reality game was evaluated by 5 professional therapists. The positive feedback received demonstrates the feasibility and potential benefits of virtual reality games in hand rehabilitation.

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List of Accompanying Material

Additional materials in Digital Submission:

(1) VR Interactive Game Demos Folder - Video Clip Demo + Screen Capture Demos
(2) Project (VR Interactive Game for Stroke Rehabilitation) Folder – Finished Build and Unity Project
(3) User Testing Results

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Own-work Declaration

Student ID No……………………………………..

Name: Sabina Rong-Sheng Ku

Course/Programme: MSc Medical Visualisation and Human Anatomy

Title of Work: Virtual Reality Interactive Games in Stroke Rehabilitation – a Pilot Study

I confirm that all this work is my own except where indicated, and that I have:

• Clearly referenced/listed all sources as appropriate ☐

• Referenced and added inverted commas to all quoted text (from books, journals, web, etc) ☐

• Given the sources of all pictures, sound, data etc. that are not my own ☐

• Not made any use of the report(s) or essay(s) of any other student(s) either past or present, or lifted extracts from web pages without appropriate referencing ☐

• Not sought or used the help of any external professional agencies for the work ☐

• Acknowledged in appropriate places any help that I have received from others (e.g. fellow students, technicians, statisticians, external sources) ☐

• Complied with any other plagiarism criteria specified in the Course Handbook ☐

I understand that any false claim for this work will be penalised in accordance with the GSA regulations

Signature: ___________________ Date: _______________________

Abbreviations

API	Application Programming Interface
BI	Barthel Index
CAHAI	Chedoke Arm and Hand Activity Inventory
FMAT	Fugl-Meyer Assessment Test
fNIRS	functional Near-Infrared Spectroscopy
IOT	Intense Occupational Therapy
LMC	Leap Motion Controller
MI	Motricity Index
MRC	Medical Research Council Grade
O2Hb/HHb	Oxygenated–Deoxygenated Haemoglobin
PTM	Personalized Training Module
RGS	Rehabilitation Gaming System
ROM	Range Of Motion
SDK	Software Developing Kit
VR	Virtual Reality

Chapter 1 **Introduction**

Stroke is one of the leading causes of death in the world and the UK. Half of stroke survivors live with disabilities. Long term morbidity is a substantial financial burden to individuals and the healthcare system. In the UK, it was estimated that the cost of stroke consumes 5% of the total NHS budget. The cost of direct care, which includes inpatient treatments, outpatient hospital visits, and long-term rehabilitation and care etc, accounts for 50% of the cost of stroke. This can also be seen in other developed countries. As the population is aging, the expense of stroke care is increasing (Dobkin, 2005; Saka *et al.*, 2009; Vogiatzaki and Krukowski, 2014)

The chance of stroke survivors recovering their motor function depends on the nature and severity of the initial deficit. Several studies suggest that early, intensive, and repetitive rehabilitation can help recover lost motor function effectively (Johansson, 2011; Wuang *et al.*, 2011). Conventional stroke rehabilitation requires frequent hospital visits and a dedicated therapist's time and skills. Travelling costs and intense pressure on human resources makes traditional stroke rehabilitation expensive. It is estimated that, in Europe, stroke rehabilitation accounts for 37% of the first year cost of stroke (Kolominsky-Rabas *et al.*, 2006).

1.1 Background

It is estimated that 65% of stroke survivors cannot use their stroke affected hand in their daily activities (Dobkin, 2004). Traditional rehabilitation requires stroke patients to perform repetitive exercises. Such one-to-one administration therapy is costly and the repetition of exercises makes patients get bored and they lose their motivation and commitment to continue with the therapy. Studies suggest that stroke patients can become more motivated by undergoing rehabilitation to recover their motor functions in their home environment and performing activities/exercises chosen by themselves with several interventions lasting 20 minutes in a day rather than one longer therapy session (Dobkin, 2004). Therefore, a new paradigm in stroke rehabilitation is needed to reduce costs and increase patients' motivation.

With recent advances in technology, Virtual Reality (VR) and serious games are used as an assistant technology in stroke rehabilitation and have attracted great attention. The contents of VR and serious games can be tailored to meet patients' statuses and preferences. Patients can choose the activities that they enjoy and the chosen activities can be modified according to their progress in recovery. The system can be installed at home and patients can undergo the intervention at their own pace. Patient progress can be monitored in real time by medical professionals through the Internet and patients can receive real time feedback. The progress data can also be recorded and analysed offline. The data and analysed results can then be exchanged to help understand and design better stroke therapy.

1.2 Contribution of the Study

For this study, 5 tasks were designed and developed using the Leap Motion Controller (LMC) in Unity3D. The hardware setup of the system is simple without being technically demanding and can be installed in most practical environments. The exercises of this game enable patients to use their hands and fingers in intuitive ways. Validation and evaluation by healthy participants suggest that the VR game controlled by the LMC is a promising intervention in hand rehabilitation.

1.3 Objectives of the Study

This study attempts to develop a VR interactive game using Unity3D and Leap Motion for application in stroke rehabilitation of the upper limbs. In this study, a VR interactive game was developed in the Unity3D game engine. The Leap Motion sensor is used to control a virtual hand in several game environments. The exercises of this game are designed to encourage patients to use their affected hands and fingers to complete the tasks designated in the game environments. The study also aims to test the usability of the game through a pilot study. Preliminary results of this pilot study aim to support further developments for the game and implementation on different operating systems and platforms.

1.4 Thesis Organisation

The thesis is organised as follows:

Chapter 2 provides an overview of stroke rehabilitation which includes the principles of stroke rehabilitation, current practice, and the issues of traditional rehabilitation. Chapter 2 also discusses the state of the art of new interventions in stroke rehabilitation: VR. Its advantages over conventional stroke rehabilitation are explored and the applications of the hand tracking device, the LMC, in stroke rehabilitation are also reviewed.

In Chapter 3, the design and implementation of exercises in the form of games for hand rehabilitation are presented. The games developed in this study are controlled by the LMC in the Unity3D platform.

Chapter 4 presents the evaluation of the game.

Chapter 5 provides a discussion on feedback from the evaluation experiment, concludes the study, and outlines the limitations of this project and possible future work.

Chapter 2 **Literature Review**

Stroke is the second and fourth leading cause of death in the world and in the UK respectively. Stroke is also one of the largest causes of long term disability. It is estimated that half of stroke survivors live with disabilities (Stroke Association, 2016).It has been shown that physical activities and exercise have a positive impact on stroke survivors in physical and psychosocial domains. It has been shown that stroke survivors can recover their motor functions and improve their independence through rehabilitation (Billinger *et al.*, 2014). The goal of rehabilitation after stroke is to recover the impaired motor functions of patients through repetitive, intensive rehabilitation training (Cho *et al.*, 2012).This chapter starts with a general review of conventional stroke rehabilitation.

However, traditional stroke rehabilitation has disadvantages, such as high financial cost and being de-motivating for patients etc. Recently, several new interventions, e.g. VR, robotic assistant technology, and video games, have shown their potential benefits in stroke rehabilitation. These new interventions will be discussed next.

2.1 Stroke Rehabilitation

80% of stroke survivors suffer from the loss of or have very limited remaining control of their muscles and movement. Motor impairment caused by stroke can restrict muscle function and mobility in the face, upper limbs, and lower limbs of half of the body. Exercise after stroke has the potential to improve cardiovascular fitness and recover motor functions, such as walking ability and muscle strength (Billinger *et al.*, 2014). The chance of recovery after stroke is determined by the nature, the site and the size of the initial stroke lesion. The long term effect of the stroke depends on the degree of the subsequent recovery (Kolominsky-Rabas *et al.*, 2006; Langhorne *et al.*, 2009; Langhorne *et al.*, 2011). Studies suggest that, although the recovery process is complex and the extent of the recovery varies across individuals, the recovery of impaired functions can be predicted in the first few days after a stroke. Stroke rehabilitation normally contains four stages as following (Langhorne *et al.*, 2011; Billinger *et al.*, 2014):

(1) Assessment: to evaluate the needs of patients in order to set goals and design the intervention. The extent of recovery, social support, and environment should be taken into account at this stage.
(2) Goal: to set a realistic and achievable target for recovery. The goals of initial post stroke rehabilitation are to prevent prolonged inactivity and its corresponding complications, and to recover voluntary control of muscles and basic activities of daily life.
(3) Intervention: activities to achieve the set goal. The design of physical activities and exercise should be designed according to the tolerance, impairment, activity preferences, activity limitations and participation limitations of the individual.
(4) Reassessment: to evaluate the outcome against the set goal.

The first few days and weeks after a stroke is the greatest recovery phase (Stroke Association, 2016). Studies have suggested that an early and intensive rehabilitation might be important to the recovery of stroke patients(Johansson, 2011; Wuang *et al.*, 2011).The most common principles and strategies of stroke rehabilitation for recovering motor function include approaches oriented towards specific activities, frequent and intense practice, and starting early in the first few days or weeks after a stroke (Johansson, 2011; Wuang *et al.*, 2011).

2.1.1 Mechanisms and Principles of Recovery after Stroke

Recovery of motor deficits after a stroke depends on brain plasticity and can be improved by physical therapy and rehabilitation. The goal of stroke rehabilitation is to enable stroke survivors to perform their activities of daily life. The chance of stroke survivors recovering their motor function relies on the nature and severity of the initial deficit. The main focus and challenges of stroke rehabilitation are to optimise brain plasticity and functional reorganisation to reduce motor impairment and relearn lost motor skills. Brain plasticity enables the human brain to respond and adapt to internal and external changes and experiences by changing its structure and function. Through brain plasticity, the human brain can encode experiences and learned skills, including experiences and skills learned through rehabilitation (Kleim and Jones, 2008; Murphy and Corbett, 2009; Cameirão *et al.*, 2010; Garrison *et al.*, 2010). (Kleim and Jones, 2008) summarise the 10 principles which are most relevant to rehabilitation, such as stroke rehabilitation, in Table 2-1.

Table 2-1: 10 principles most relevant to rehabilitation

• Use it or lose it • Use it to improve it • Specificity • Repetition matters • Intensity matters	• Time matters • Salience maters • Age matters • Transference • Interference

From clinical studies and animal studies, the key factors of effective stroke rehabilitation are: the starting time of the initial rehabilitation; the quantity, duration, and intensity of rehabilitation exercises; and the rehabilitation environment (Kwakkel *et al.*, 1997; Jack *et al.*, 2001; Krakauer *et al.*, 2012; Pekna *et al.*, 2012):

(1) Time: In practice, early physical activities within the first day after a stroke can improve walking ability and functional recovery. Getting out of bed within the first 24 to 48 hours after a stroke has shown to be beneficial for the cardiovascular system. However, it might not be suitable for all patients. Animal models suggest the best time to start rehabilitation is within the first 5 days after having a stroke but no more than 30 days later. In this 30 day period of time, there are no adverse effects and

more significant recovery can be seen. After 30 days, no recover associated with rehabilitation can be seen in animal models.

(2) The intensity of the therapy also plays an important role in recovery for stroke survivors. In animal studies, recovery is not seen if the amount of exercise does not exceed a certain threshold.

(3) Duration: It was also estimated that the periods of time resulting in maximum recovery in animal models and human stroke patients are 4 weeks and 3 months after strokes respectively.

(4) Exercise: The exercise/tasks in rehabilitation should be repetitive, goal-oriented, and meet the needs and conditions of patients.

(5) Environment: Studies have provided evidence that an enriched home environment can promote the structural and functional components of neural plasticity and cognitive performance (Pekna *et al.*, 2012).

Therefore, stroke rehabilitation should be early, intensive, and continuous; involve repetitive exercise; and take place in an enriched environment.

2.1.2 Practice of Conventional Stroke Rehabilitation

After a stroke, patients initially undergo rehabilitation in hospital. In early inpatient stroke therapy, the lower limbs are the main focus of treatment in order to recover mobility, posture, balance, and walking ability. The rehabilitation of upper limbs, on the other hand, is more reliant on outpatient and home therapy. Less than 30% of medical professions and 20% of patients agreed that hand therapy in hospital was good (Barrett *et al.*, 2016). To recover the function of upper limbs, patients are required to perform repetitive exercises at home (Alankus *et al.*, 2010). It is estimated that over 30% of stroke patients are unable to have satisfactory recovery in their upper limbs(Lucca, 2009).

However, it is often a challenge for patients to perform the voluntary movements which these exercises require. For upper limb rehabilitation, the interventions in practice for the affected arm are training exercises, impairment-oriented training, functional electrical stimulation, robotic arm assisted rehabilitation and bilateral arm training (Yavuzer *et al.*, 2008).

When patients are stable, they are discharged to various places with different clinical settings, from their home without rehabilitation facilities, to specific units with inpatient rehabilitation facilities. They continue rehabilitation at specialised clinics or at home with a medical professional visiting and supervising. There are several disadvantages for traditional therapy (Yavuzer *et al.*, 2008; J. W. Burke *et al.*, 2009b; Krakauer *et al.*, 2012; Mousavi Hondori and Khademi, 2014):

(1) High Cost: In general, traditional therapy is based on one to one administration, which increases cost. As a result of reducing the cost, the average inpatient stays are decreasing. In the UK, the average inpatient stays were 23.7 and 19.5 days in 2008 and 2010 respectively (Barrett *et al.*, 2016). When stroke patients continue their rehabilitation in a clinic, time is wasted in travelling.

(2) Low Motivation: Traditional rehabilitation requires patients to perform repetitive exercises which are regarded as boring by stroke patients. As a consequence, patients might lose their commitment to stay in the process.

(3) Subjective Assessment: The assessment of the outcomes of therapy and rehabilitation are based on and interpreted by therapists. It is highly dependent on their experience. It could be inaccurate and biased due to its subjectivity.

These interventions are labour intensive, time consuming, and cost in-efficient and make traditional stroke rehabilitation difficult for patients. Evidence also shows that the intensity of traditional rehabilitation is not enough to result in plasticity or to recover motor function (Jack *et al.*, 2001). Several technologies, such as robotic assistant technology, VR, imaging systems, and games, have demonstrated their usefulness and benefits in the applications of stroke rehabilitation. On the contrary to the disadvantages of traditional therapy, these technologies have shown potential advantages over traditional stroke rehabilitation. This will be discussed in the next section.

2.2 New Interventions in Stroke Rehabilitation

The advances in technology in computing, images, the Internet, and sensors, have allowed VR games to become feasible applications in motor rehabilitation after a stroke. In stroke rehabilitation applications, VR systems allows users to engage their mirror-neuron system by interacting with a computer generated virtual environment (Wuang *et al.*, 2011). Game technology enables users to learn and develop skills by playing the game. The motor skill learned from VR can be converted to the real world. Patients with severe motor and cognitive impairment can also learn from VR and transfer it to the real world (Enrique Sucar *et al.*, 2014).

Immersion and presence are the most important aspects of VR. Immersion makes patients feel more engaged in the simulated world. As a consequence, patients are motivated, which is an important factor in rehabilitation (Jack *et al.*, 2001). A highly immersive system normally contains more comprehensive hardware and software so that users can be projected into the virtual environment. Presence, on the other hand, is subjective to the experience of users and the features of the virtual environment system and the contents of the system. The extent of involvement is an indication of presence(Laver *et al.*, 2012; Barrett *et al.*, 2016).

2.2.1 Advantages of Virtual Reality Game Applications

There are several advantages of VR game based stroke rehabilitation compared to conventional therapies. These advantages include (Rego *et al.*, 2010; Laver *et al.*, 2012; Enrique Sucar *et al.*, 2014; Kiper *et al.*, 2014):

(1) Patient centred: VR games can be personalised to meet an individual's requirements. The content can be tailored according to the preference, tolerance and progress of the individual. The dose, intensity and challenge can be adjusted individually.

Furthermore, it can be customised to meet the requirements of different pathophysiologies and patient groups.

(2) Home based: VR game systems can be installed in the homes of patients. The home is an enriched environment which can promote the effectiveness of rehabilitation. They can be used in the hospital and, after discharge, at home without the restrictions of time and location (Cho et al., 2012).Home based rehabilitation requires less dedicated supervision from medical professionals and, without the need for travelling, can reduce the overall cost.

(3) Self-paced: VR game systems are self-paced applications. It makes the schedule flexible and it is possible to perform rehabilitation on daily basis. It is suggested that the best neural recovery period is the first three months after stroke. However, some studies have also shown that significant recovery of stroke patients can be seen in the first six months after a stroke. VR systems can be an option for stroke patients after the traditional rehabilitation period(Jack *et al.*, 2001).

(4) Motivation driven: One of the main issues of traditional stroke rehabilitation is that patients might lose motivation due to repetitive nature of the rehabilitation exercises. VR game systems enable patients to carry out activities which might not be possible in a real environment. They also make repetitive rehabilitation exercises more enjoyable and motivate patients by having entertaining, fun, and interesting content. As a consequence, it promotes the engagement and motivation of patients for performing repetitive exercises. As a result, it improves the outcomes of rehabilitation.

(5) Telemedicine (rehabilitation): VR game systems can be combined with other technologies to form a telemedicine system. Patients and their progress can be monitored through the Internet. The progress data can be recorded and analysed in real time or later. The interpretation of the outcome can be more objective. The data might be helpful for standardising rehabilitation protocols.

(6) Interactive: VR games are interactive systems. Patients can see their movement in the virtual environment through real time feedback. They can modify their movements or imitate the optimised pattern of corresponding movement. VR game systems can enrich the environment where physical activities are carried out. The

feedback provided by VR games can be of multiple modalities. It will promote the engagement of patients and improve the recovery of their motor functions.

However, they also have some disadvantages. For example, the installation is technologically demanding and requires some expertise. Patients might not be familiar with the technology and might not enjoy the content of the VR game system(Enrique Sucar *et al.*, 2014).

A good VR system game for stroke rehabilitation should be able to make patients perform useful exercises, ensures they are correctly performed, and monitor their safety. Monitoring patients' safety and tracking the exercise to make sure it is accurately and correctly performed, is reliant on sensor technology. Advances in sensor technology have shown great potential benefits in stroke rehabilitation. Several bio-sensors have been developed to monitor and record patients' real time physiology status when patients perform tasks for rehabilitation at home. These bi- sensors can record physiological signals such as ECG, EEG, blood pressure, sweat, temperature, and airflow (Vogiatzaki and Krukowski, 2014).

Meanwhile, VR systems should motivate and encourage patients to stay in therapy. As a consequence, they promote the engagement and motivation of patients. As a result, they also improve the outcome of rehabilitation (Khademi *et al.*, 2014; Iosa *et al.*, 2015). To enhance users' experience of VR systems and games in the application of stroke rehabilitation, the application should be able to provide (Alankus *et al.*, 2010; James William Burke *et al.*, 2010; Pirovano *et al.*, 2012):

(1) Meaningful play: The application should follow clinical protocols and its content should be efficient at achieving the goal of the rehabilitation therapy. It is important that patients know the expected goal, the required actions to achieve the goal and whether they have achieved it or not. It is also important to provide feedback in acoustic, visual, and haptic formats which enable patients to be aware and notified of the outcome of playing the rehabilitation games.
(2) Adaption of challenge: The application should be able to adapt to the progress and the goal of individual patients. The difficulty level of the application can be adjusted

according to patient performance. The difficulty levels should fit the skills of each patient. Patients might feel frustrated by applications that are too difficult and get bored by applications that are too easy. A proper level suitable to the current skill of a patient can motivate patients to be engaged in the rehabilitation process.

(3) Positive handling of failure: The application should be able to track the actions of users and assess their performance. Positively handling failure is crucial in stroke rehabilitation. It is very likely that the patient might not handle the application well in the early stages due to a lack of familiarity, limited motor function etc. A good application should handle such failure in a positive way so that patients can be encouraged.

It has been suggested that task-oriented actions executed in a VR environment with visual feedback of virtual limbs enables the reorganization of the affected motor systems by recruiting the mirror neuron system. Several studies have shown that VR is an effective and promising tool for recovering motor function in stroke rehabilitation (Cameirão *et al.*, 2012).

2.2.2 Virtual Reality in Stroke Rehabilitation

It has been suggested that rehabilitation based on VR and interactive games is more effective for recovering upper limb function than for recovering grip strength, walking ability (Laver *et al.*, 2012).

For example, a Rehabilitation Gaming System (RGS) based on VR which can speed up the recovery of upper limb motor function after stroke was reported by (da Silva Cameirão *et al.*, 2011). RGS includes an analysis and tracking system based on vision which detects the movement of the upper limb by colours, two gloves which capture finger flexure and a controller (Personalized Training Module, PTM) which can adjust the difficulty level of the game according to the performance of individuals. There is an avatar which mimics the user in the virtual environment.

The task of this system is to interact with approaching flying spheres with different parameters such as flying speed, range of movement and time intervals between the spheres.

There were two training sessions to calibrate the baseline performance of each individual. In training sessions, the tasks were performed in two fashions, in physical and virtual environments. In the physical environment, patients were instructed to move their arms to specific positions on a tabletop in a random order. In the virtual environment, patients move a simulated arm on a table. PTM adjusted the level of difficulty according to previous performance.

The participating patients were randomly grouped into three groups: RGS, Intense Occupational Therapy (IOT), and Non-Specific interactive Games (NSG) using standard gaming consoles. All patients received standard rehabilitation plus the additional treatment designated by their group. They were assessed in week 1, 5, 12 and 24 using the Barthel Index (BI), Medical Research Council Grade (MRC), Motricity Index (MI), Fugl-Meyer Assessment Test (FMAT) and Chedoke Arm and Hand Activity Inventory (CAHAI). These indices cover the assessment of independence in activities of daily living (BI) to the functional assessment of the paretic arm and hand (CAHAI).

The results show that RGS outperformed the groups of IOT and NSG in terms of the speed of the affected arm and all clinic scales. Furthermore, during the intervention period, those receiving RGS showed a faster recovery in time compared to the other two groups. In their study, it was observed after the 9^{th} week that the speed of the RGS group was significantly higher than the other groups. The authors suggested that the patients in the RGS group developed higher speed skills in order to adapt to the changes in the game's difficulty level.

2.3 Free Hand Interaction

LMC is a hand tracking device which was first available on the commercial market in 2012. LMC tracks the movements and positions of a user's hands and provides real time tracking data. LMC will capture the users' hands in the real world and reflect the change on the monitor. This real time visual feedback enables users to modify and correct their hands' movement in order to complete the tasks in the game. Since it was first available in the market, several practical applications have been developed (Weichert *et al.*, 2013).

Free hand interaction has been evaluated in several applications such as games and VR. Free hand interaction could be a useful assistant tool and an intuitive option in stroke rehabilitation for patients without or with limited hand function (Khademi *et al.*, 2014). LMC is a hands free device which captures and tracks the movement of a user's hands without the need of gloves and markers.

Brain cortex activation during the performing of a task in a VR environment was investigated by (Petracca *et al.*, 2015; Moro *et al.*, 2016) using a multiple-channel functional Near-Infrared Spectroscopy (fNIRS). In their study, a LMC was used to track hand movement and allow interaction with a virtual environment. The activities in the brain's prefrontal cortex (PFC) can also be observed during the controlling of the upper limbs. fNIRS was used to visualise the change of concentration in oxygenated–deoxygenated haemoglobin (O2Hb/HHb) while performing a task.

The task in their study was to keep a virtual ball in a virtual pathway while making sure that the ball did not fall from the path. The participants in the experiment were asked to apply different level of force to the virtual ball at different game levels. The level of difficulty in the game depends on the parameters in the game, such as the weight of the ball and the inclination and friction of the virtual pathway. The experimental data of fNIRS showed significant activation of PFC during the performance of the task. However, the level of difficulty had no significant impact on the activation of PFC. The results showed that VR can induce plasticity and can be a new approach of stroke therapy.

A LMC combined with a haptic interface device was used in a bilateral rehabilitation study (Xu *et al.*, 2015). In bilateral upper limb rehabilitation, patients try to use both healthy limbs and paretic limbs to perform motor tasks. The function of LMC is to detect the motion information of the healthy hand. The haptic interface device, on other hand, assists the paretic hand in completing the training task. The motor task in their experiment is grip-reach-release. The task is to use a healthy hand to move and hold a virtual plate with several virtual blocks on it. The haptic interface device helped the paretic hand to grip a block and move it to virtual braces and release it. Preliminary data analysis of their study focused on execution time, motion trajectories and applied force. These results from healthy subjects demonstrate the feasibility of LMC's application in upper limb rehabilitation.

(Khademi *et al.*, 2014) combined the LMC with the game Fruit Ninja to evaluate its feasibility and usefulness in stroke rehabilitation. The game Fruit Ninja was modified so that the motions of the hands replace mouse input. The original game required players to slice different types of fruit on the screen as fast as they can without missing three pieces of fruit. Players also had to pay attention to avoid bombs. In LMC modified version, players had to slice the fruit within a 1 minute time frame without hitting a bomb or missing three pieces of fruit.

14 stroke patients participated in their study. The experimental results demonstrated that, statistically, the Fruit Ninja scores were significantly correlated with clinical scores such as the Fugl-Meyer score and the Box and Blocks Test score. It indicated the feasibility of free hand interaction technology in stroke rehabilitation.

(Iosa *et al.*, 2015) integrated a LMC into a video game for elderly stroke patients requiring hand therapy. In addition to conventional therapy, a LMC controlled video game was included in rehabilitation. It showed positive and promising results, with the hand mobility of patients being significantly improved. The authors suggested that LMC controlled video game contributed to the high participation level in the rehabilitation sessions. Authors also concluded that the LMC was a useful tool even for aged populations.

Another example employing LMC in hand rehabilitation was reported by (Matos *et al.*, 2014). In their experiment, participants tried to open one of their hands as wide as possible to grab an apple and then drag the apple into a basket. When the apple was dragged to the basket with their hand still open, the apple remained in their hand. When their hand was closed, the apple dropped into the basket. The level of difficulty is related to the extent which participants had to open their hand in order to grab the apple.

(Charles *et al.*, 2014) proposed a VR system with three hand rehabilitation tasks. A LMC was used to control and interact with the simulated environment. The system was presented to professional clinicians/therapists to evaluate the usefulness of the VR system in clinical practice. The tasks in the VR were: picking a cotton ball, stacking blocks, and the nine hole peg test. The participants were instructed to pick up a ball from the table and release it into a container in the "picking a cotton ball" task. In the "stacking blocks" task, users were instructed to build a tower by stacking the blocks given to them in the virtual environment. In the "nine hole peg test", the standard equipment of this test was provided. The participants filled in a questionnaire for feedback after completing the tasks. The results showed that the proposed VR system was a promising intervention in hand rehabilitation which could be used at home and could also help to motivate patients, especially younger people.

LMC is also used as a tracking device in the StrokeBack project (Vogiatzaki and Krukowski, 2014). The games developed in their project include throwing a paper ball to a target circle in the screen (mixing the real and virtual world) and control the movement of avatar in simulated environment. Initially Microsoft Kinect was the tracking device. However, they found LMC can provide more accurate tracking data of palms and fingers for providing an immersive user interface and generating an enriched, immersive gaming experience with virtual and augmented reality.

2.4 Summary

This Chapter reviewed the principles of stroke rehabilitation and the mechanisms of stroke recovery. It also pointed out the challenges and issues of conventional stroke rehabilitation. It further investigated the feasibility of VR as a new promising intervention in stroke rehabilitation and its advantages over conventional therapy. Finally, the development of the LMC in upper limb rehabilitation was also presented.

The next Chapter will explore the process of game development in this study and present the developed exercises and the method of evaluation.

Chapter 3 Methodology

This chapter presents the methodology followed for the implementation of a gaming interface which offers a series of exercises for hand rehabilitation with the LMC. In this chapter, emphasis is given to the material used in this project and the contribution of the design and development stages towards the achievement of the objectives of this thesis.

3.1 Material

The game is designed and developed in the Unity3D game engine and uses the LMC API. The hardware required in this game is a LMC and a windows based-PC (desktop or laptop).

3.1.1 Unity3D

Unity3D is a game engine allowing game developers to develop 2D and 3D applications for multiple platforms such as mobile, VR, desktop, Web, Console and TV. It has four different license schemes, Personal, Plus, Pro, and Enterprise, each corresponding to a difference in price point and available features (*Unity - Game Engine*, 2016). This project uses the Personal licence scheme. The latest revision of Unity available to download is 5.4, at the time of writing this thesis. The revision of Unity used in this project is 5.3, which is the version used by DDS. The scripts are developed in C#.

3.1.2 Leap Motion Controller

The LMC, as shown in Figure 3-1, tracks the positions of a user’s hands. It can track up to two hands and 10 fingers at the same time with an accuracy of up to 0.01mm and a frame rate of up to 300fps (frame per second). The LMC employs 3D optical sensor technology based on stereo vision. It consists of three IR (Infrared red) LEDs (light emitting diodes) and two IR cameras as seen in Figure 3-1. The viewing angle of the LMC is about 150 degrees. The tracked positions are related to the centre point of the LMC, the position of the middle IR LED as seen in Figure 3-1 (c) (Weichert *et al.*, 2013).

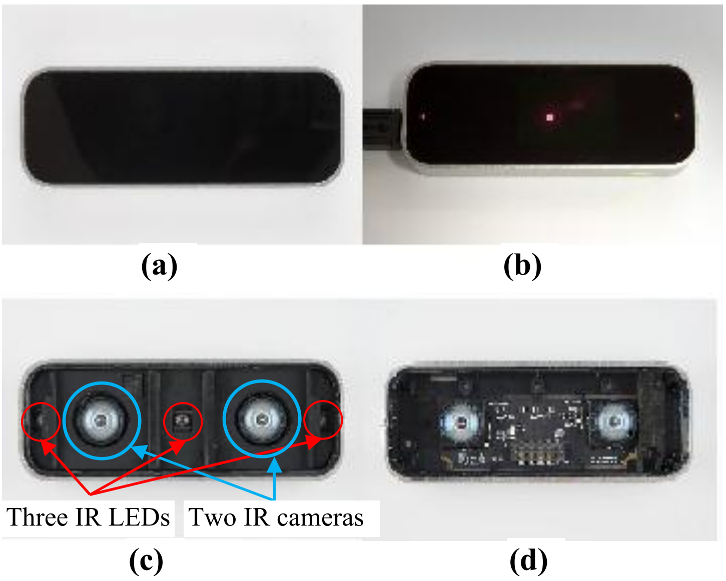
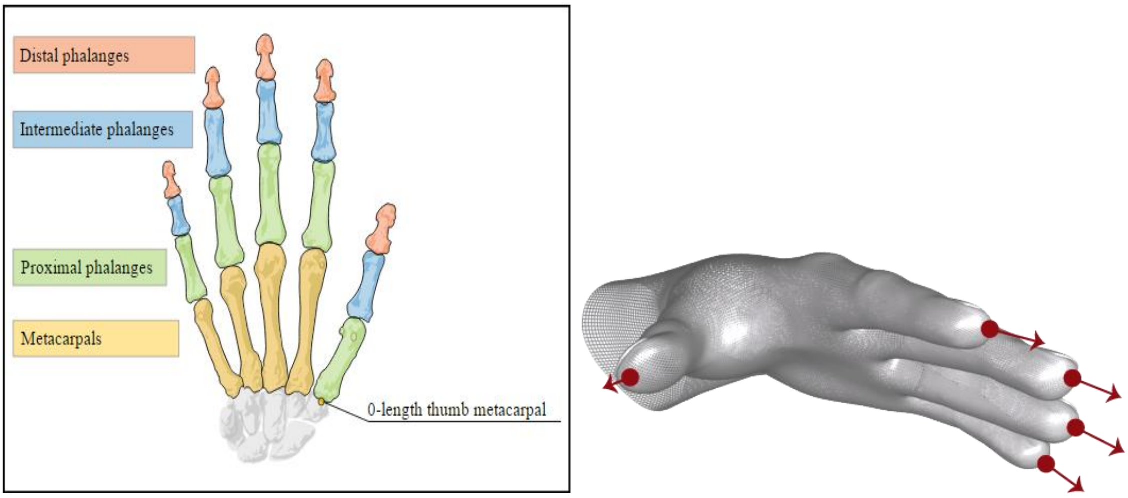


Figure 3-1: (a) Leap Motion Controller. (b) Leap Motion Controller connected to a computer via USB. It can be seen that 3 IR LEDs are turned on. (c) Leap Motion Controller internal structure after removing its cover. (d) Schematic view.

3.1.3 Leap Motion Tracking Model and API

The LMC detects the positions of a user's hands and fingers using a model of their hands. The Leap Motion hand skeletal model can be seen in Figure 3-2 (a). Tracking data of Leap Motion includes finger direction as shown in Figure 3-2 (b). Both figures are from: https://developer.leapmotion.com/documentation/csharp/devguide/Intro_Skeleton_API.html (*Introducing the Skeletal Tracking Model — Leap Motion C# SDK v2.3 documentation*, 2016) and https://developer.leapmotion.com/documentation/csharp/api/Leap.Finger.html respectively.

In the skeletal model, each finger is assigned to a number: 0, 1, 2, 3, 4 for thumb, index, middle, ring, and pinky finger respectively. Each finger, except the thumb, consists of 4 bones: metacarpal, proximal phalange, intermediate phalange, and distal phalange. With this model, Leap Motion can track the joints and bones of each finger (GRUBIŠIĆ *et al.*, 2015).



(a) **(b)**

Figure 3-2: (a) Leap Motion hand and finger skeletal model. This figure is adapted from Leap Motion website https://developer.leapmotion.com/documentation/csharp/devguide/Intro_Skeleton_API.html (*Introducing the Skeletal Tracking Model — Leap Motion C# SDK v2.3 documentation*, 2016). (b) Leap Motion hand tracking for finger direction. This figure is adapted from Leap Motion website https://developer.leapmotion.com/documentation/csharp/api/Leap.Finger.html.

The frame is the most important object of the LMC API. The LMC tracks and reports the positions, velocities and directions of a user's hands and fingers (Figure 3-2) in the frame. The Leap Motion API defines a class representing each of the primary tracked objects. Figure 3-3 shows the tracking model defined by Leap Motion. This figure is adapted and modified from:

https://developer.leapmotion.com/documentation/java/devguide/Leap_Tracking.html
(*Tracking Model — Leap Motion Java SDK v3.1 documentation*, 2016).

The scripts of the game are developed in C# and the LMC Application Programming Interface (API) for Unity which is included in the Leap Motion Software Development Kit (SDK). Hand images and assets used in the game are provided in the Leap Motion Unity Asset Version: 3.0.0. Both can be found in https://developer.leapmotion.com/orion(Developer.leapmotion.com, 2016a). Leap Motion API guideline can be found in (Developer.leapmotion.com, 2016b).

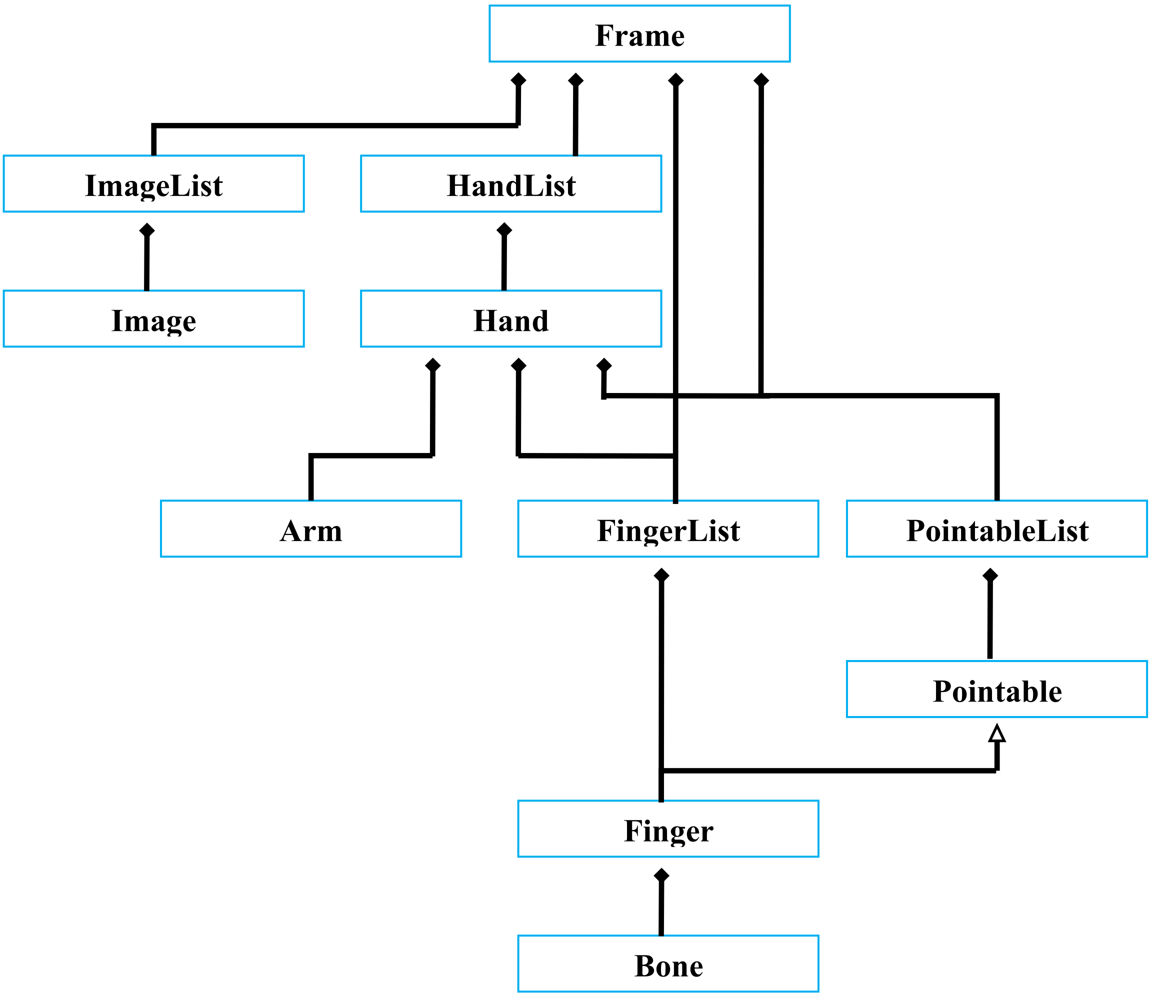


Figure 3-3: Tracking model defined by Leap Motion using objects. This figure is adapted and modified from the Leap Motion website (*Tracking Model — Leap Motion Java SDK v3.1 documentation*, 2016).

While developing the scripts, several game demos, coding examples, and discussions were used as a learning resource. These can be found from the following websites and discussion forums(Karamian, 2015; *GitHub, leapmotion/LeapMotionCoreAssets*, 2016; Leap Motion Community, 2016).

Unity scripts developed in this project use and interpret the tracking data from the LMC to allow users to use their hands to interact with the game environment. Due to time constraints, not all of the tracking data are used in the game. The scripts of this game mainly measure the change of hand and finger positions and classify hand gestures by analysing the tracking data from the LMC. The classes and the corresponding methods and properties used in developing the scripts are listed in Table 3-1.

Table 3-1: The classes and their methods and properties used in the scripts of game.

Class	Methods	Properties
Frame	• Frame () • Hand (int id)	• CurrentFramePerSecond • Hands
Hand	• Finger (int id) • Hand ()	• Fingers • GrabAngle • GrabStrength • IsLeft • IsRight • PalmPosition • PinchDistance
Finger	• Finger ()	• IsExtended • Length • TipPosition

The LeapHandController prefab provided by Leap Motion is the anchor point for tracking the data of hands and fingers. The hand images are provided in the Leap Motion SDK. To show the hands on the screen, four prefabs (CapsuleHand_L, CapsuleHand_R, RigidRoundHand_L and RigidRoundHand_R) were added to LeapHandController.

Examples can be seen in Figure 3-4(*Hand Assets — Leap Motion Unity SDK v3.1 documentation*, 2016).

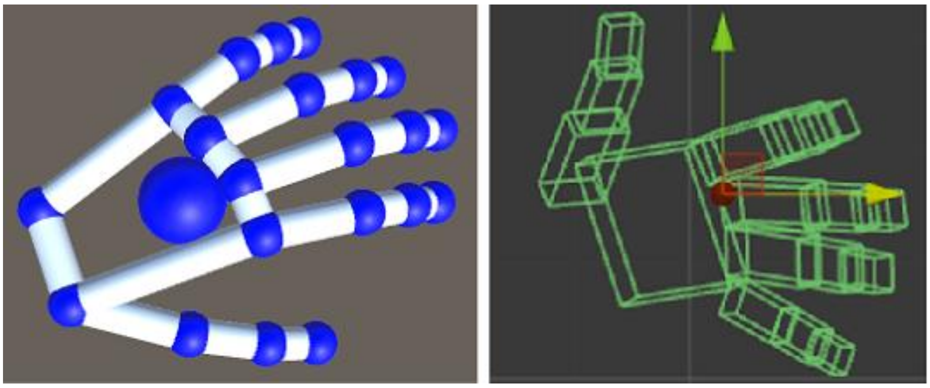


Figure 3-4: Hand models used in this game. These prefabs are provides by Leap Motion. This figure is adapted from the Leap Motion website.

The sound effect files used in this game were downloaded from the website http://soundbible.com/(Koenig, 2016). These sound effects include the effect of beeps, dropping an object onto a wooden floor, crowd applause etc. The images used in this game were downloaded from the Unity assets store https://www.assetstore.unity3d.com/en and the website https://www.google.co.uk(Google, 2016). These images are used for the background of the game, buttons, blocks etc. They are royalty free to use.

3.2 VR Interactive Game Design for Stroke Rehabilitation

This study is focused on the development of a game for hand rehabilitation which stroke patients can benefit from. Hand function recovery can benefit from three types of exercises, Range Of Motion (ROM) exercises, strengthening exercises and endurance exercises. These exercises have different goals and purposes. For example, the aim of ROM exercises is to improve the flexibility of joints and relieve hand stiffness. ROM exercises normally don't require strength exertion during the exercise (GRUBIŠIĆ *et al.*, 2015). The extent of recovery in a hand can be measured using four parameters: range of motion, speed of motion, fractionation of movement, and strength of movement (Jack *et al.*, 2001).

The aim of the present study is to develop a VR interactive game for stroke patients at the early stage of hand rehabilitation. At the early stage of rehabilitation after stroke, patients might not be able to perform finger extension using active movement. Therefore, passive movement is carried out by external devices such as robotic prostheses. It is accepted that joint and muscle mobility can be improved by passive movements which, on the other hand, can also reduce muscle tone (Lambercy *et al.*, 2007). However, passive movements are not sufficient for good recovery. Recovery of muscle strength and coordination relies on the active movements of patients. After the strength and coordination of muscles are improved, patients are expected to perform more accurate muscle activation and coordination. To regain the strength of an affected hand, patients normally require more training exercises with changes in load and resistive forces (Lambercy *et al.*, 2007). Leap Motion can be operated with empty hands. Therefore, it is suitable for stroke patients with weak hands. However, it also limits the strength of exercise. The exercises designed in this VR interactive game focus on improving the range of motion, speed of motion, fractionation of movement, and coordination of fingers.

The purpose of this game is to provide stroke patients with another option for hand rehabilitation. As the rehabilitation progresses, patients can regain control and the use of their affected hand. As a result, they can use their affected hand to perform the activities of daily life. The exercises of this study for hand rehabilitation follow the principles of:

- Range of motion exercise: This exercise is for improving the flexion and extension of fingers. This exercise encourages patients to open or close their affected hand as much as possible. Such gross movement does not require any precision.
- Fractionation of movement exercise: As the rehabilitation progresses, patients are encouraged to practice exercises which require more accurate control and

coordination of their fingers so that they can relearn the skills required for activities of daily life, such as grasping a bottle, moving objects, and holding a key etc.

- Speed of motion exercise: This exercise is for encouraging patients to move as fast as they can.

3.3 Software Implementation with Leap Motion API

Based on these principles, 5 exercises were developed for this game. They are: (1) Grab, (2) Pick n Match, (3) Pinch, and (4) Navigation and (5) Gesture. Pinching is the most desired hand function which patients would like to recover (Lambercy *et al.*, 2007). A brief description of each exercise in terms of exercise tasks, exercise measurements, and the focus of training can be found in

Table 3-2.

Table 3-2: Content of exercise, Measurement and Training focus of each task.

Exercise	Task(s) of exercise	Measurement	Focus of Training
Grab	• Users open and close their hands to the maximum extent possible for them	• Extent of hand opening and closing	• Fingers
Pick n Match	• Users move their hands to pick up blocks and drop blocks into a basket • Open and close hands with some degree of accuracy	• Position of palm • Extension and flexion of fingers	• Fingers • Arms
Pinch	• Users pinch with two f their fingers. The default finger is the thumb • Control and coordinate fingers accurately to perform each pinch successfully	• Distance between the fingertip positions of the thumb and the other fingers	• Fingers
Navigation	• Control the direction of a ball's movement by moving hands • Control hands to move them in a vertical or horizontal direction	• Position of palm	• Wrists • Upper arms • Hands
Gesture	• Users use 5 fingers to perform a gesture. 5 predefined gestures are One finger point, Y letter, OK, Thumb up and V letter • Control and coordinate 5 fingers accurately to perform each gesture successfully	• Combination of finger tip position, length of fingers, and extension of fingers	• Fingers

Table 3-3 lists each exercise in terms of its feature, the format of feedback, and the level of difficulty. In general, the feature detection of each exercise is based on Leap Motion tracking data. The formats of feedback of each exercise include text, audio and visual. These different forms of feedback allow users to visualise their performance and enhance their experience. In this pilot study, each exercise has only one level of difficulty. However, the level of difficulty of each task can be modified according to the parameters, such as distance threshold, as described in Feature detection in Table 3-3.

Table 3-3: Feature and Feature detection, Feedback and Level of difficulty of each task.

Exercise	Feature detection	Level of difficulty	Feedback
Grab	• GrabAngle property of Leap Motion API • GrabAngle is zero when the hand is fully open. On the other hand, it is equal to pi when it is fully closed • GrabAngle is transferred to 100% and 0% for fully open and close respectively for visual feedback	• Not available in this task	• Text • Audio • Visual (colour, radius and bar)
Pick n Match	• PalmPosition and property of Leap Motion API • The distances between all available blocks and the position of palm and distance threshold determine the pickup block • The number of fingers extended determine release of block	• Threshold of distance between palm position and block	• Text • Audio • Visual (colour)
Pinch	• TipPosition property of Leap Motion API • Correct pinch is detected when the finger corresponding to the shortest distance to the thumb is another finger. The shortest distance is smaller than the threshold	• Threshold of distance between thumb tip and other finger tip	• Text • Audio • Visual (indication of fingers)
Navigation	• PalmPosition property of Leap Motion API • Difference of vertical positions and horizontal positions of two measured points are estimated • Direction corresponding to the lager absolute value of difference is moving direction when this value exceeds a threshold	• Threshold of difference • Speed of ball moving • Any direction • Encounter position between ball and cube.	• Text • Audio • Visual (colour)

Gesture	• TipPosition, IsExtended and Length properties of Leap Motion API • Gesture is detected by positions and extension of each finger and length of fingers are used as threshold	• more complex gestures	• Text • Audio • Visual (indication of fingers)

Although each game is designed with different principles, patients can choose any of them in any order and without any limitations. The goal of the game is to encourage users to use their affected arms, hands and fingers. All interactions in the game are based on the movement of hands and fingers, from the start to the end of the game. For example, in order to practise one of the exercises, users are required to move their hands and fingers towards the button corresponding to the exercise they want to practise and then press that button.

3.4 Flow Control and Game Algorithm

This game contains 6 Unity scenes which correspond to 5 exercises and one selection menu. The scenes contain scripts, text, sound, images and LeapHandController with different functions and purposes as shown in Figure 3-5. For example, sound objects provide feedback (e.g. press the button) and validation (a valid action, e.g. successfully pick up a block).

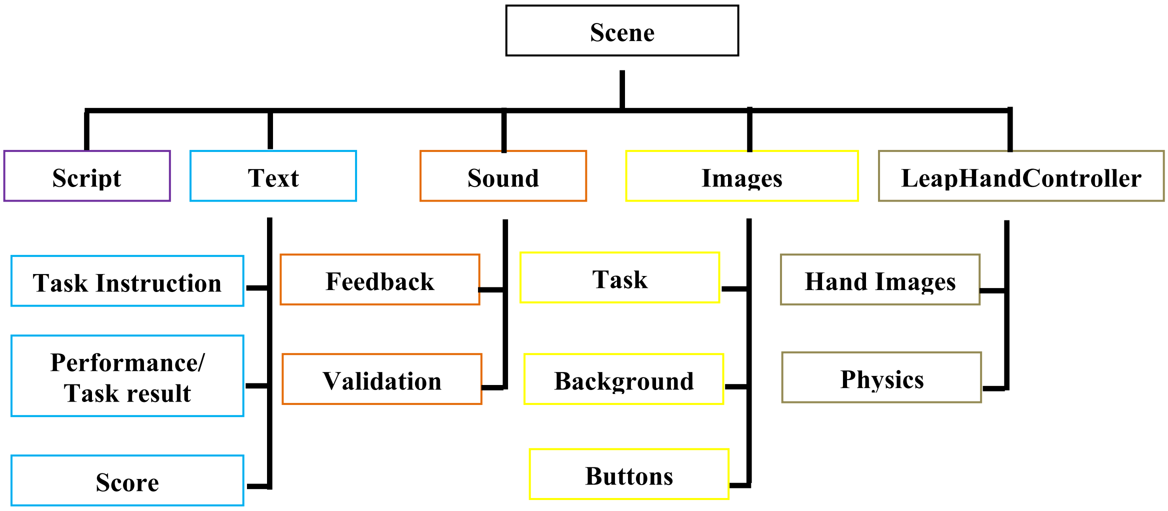


Figure 3-5: The organisation of each scene and their functions/purposes. This game has 6 scenes. Each scene contains objects such as script, text, sound, images and LeapHandController prefab.

Figure 3-6 is a flowchart representation of the game. A more detailed description of the task algorithm is as follows:

After an exercise is selected, the game initialises the selected exercise and goes through setup of the task. The script detects the activities of users by interpreting the tracking data provided by the LMC. If the task is performed correctly, the game updates and provides feedback to users. If the task is done incorrectly, the game keeps examining the tracking data and interprets users' activities until done correctly. The game repeats these steps until the current section is finished. When the current section is finished, users can repeat the same exercise by restarting the same exercise or go back to the main menu to select another exercise or exit the game.

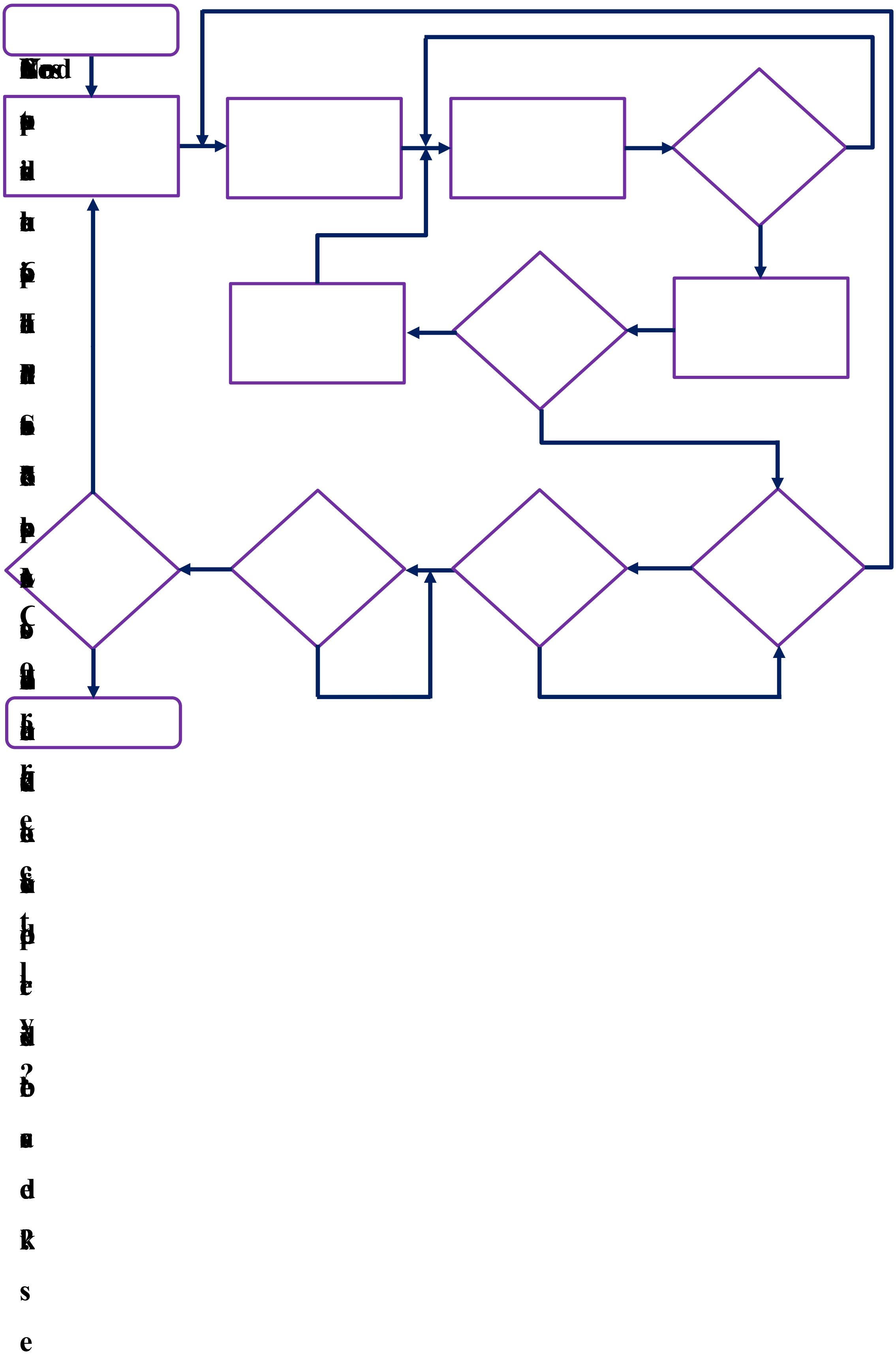


Figure 3-6: Generalized flow chart of game algorithm.

3.5 Evaluation of Experiment for Game Testing

This section describes the evaluation experiment and evaluation data analysis.

3.5.1 Experiment Setup

The core of the hardware of the present study is the LMC which can be used with a PC or attached to a VR headset. In general, Leap Motion can be combined with a 2D monitor, a 3D stereoscopic display or a head mounted display (GRUBIŠIĆ *et al.*, 2015). In this study, LMC is configured with a laptop with a 2D monitor. A laptop (Asus, S400C) with, Intel i3 processor, 4GB RAM, 250GB SSD (Solid State Drive) and 14-inch LED touch screen, was used to run this game and connected to the LMC. The frame rate was in the range of 110 to 115 frames per second (the value was obtained by using CurrentFramesPerSecond). The hardware setup of the experiment is shown in Figure 3-7.

Figure 3-7: Hardware setup of evaluation experiment. (a) LMC is connected to a laptop via a USB port and placed in front of the laptop. (b) A participant practising the Pick n Match exercise.

3.5.2 Participants

5 healthy participants (2 females, 3 males, ages between 17 and 50) participated in the experiment to evaluate this VR interactive game. Two of them are professional therapists.

Two of them are PhD students from the Physiotherapy department of the University of Glasgow. One is a student. They are all right handed.

Before the evaluation experiment, a brief explanation and demonstration of the game was presented to the participants. They were also given manuals for the game. In the experiment, participants practised the exercises in the game in no particular order and were allowed to spend as much time as they wanted to explore the game. After the practice session, the participants were given and asked to fill in a 5 points Likert-scale questionnaire with two sets of subjective questions regarding their opinions on the game and the feasibility of using the game in stroke rehabilitation. The questionnaire also allowed the participants to write down any of their own further comments. We were particularly interested to know: (1) their overall views on the game; (2) their overall views on the usability of the game for people after stroke.

3.5.3 Questionnaire

The game was tested and assessed by the participants using one questionnaire of two question sets. The first question set is listed in Table 3-4. The questions are for getting the participants' opinions on the tested VR game (Q1 to Q3) and ascertaining their previous experience in games and technology (Q4 to Q6).

Table 3-4: The questions of the first question set for the participants who took part in the experiment to evaluate the game developed in this study.

Question (Overall views on the game)	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Agree
When using the game I understood what I was supposed to do					
I would be interested in trying more games / practising more activities on the system					
Using the system and practicing activities was fun					
I have played games on a personal computer or game console					
I have played games or applications in Virtual Reality environment					
I feel comfortable using technology					
Additional Comments:					

The second question set is for getting the participants' opinions on applying the tested VR game to people after stroke in terms of ease of use, improvement of motivation, and effectiveness. The questions are listed in Table 3-5.

Table 3-5: The questions of the second question set for the participants who took part in the experiment to evaluate the game developed in this study.

Question (Overall views on the usability of the game for people after stroke)	**Strongl y Agree**	**Agree**	**Neither Agree nor Disagree**	**Disagre e**	**Strongl y Agree**
The system and activities would make rehabilitation more interesting					
The system is easy for people after stroke to use					
The system and activities will motivate People after stroke to practice their upper limb rehabilitation.					
People after stroke could use the system at home to practice the upper arm and get better					
The system has the potential to help people after stroke recover					
Using the system will improve people after stroke' hand and upper arm ability					
I would be happy to let people after stroke use this system without supervision					
I can see this system being useful for other groups who have upper limb problems					
Additional Comments					

3.5.4 Data Analysis

Frequency analysis of the questionnaire was performed based on the participants' answers. In addition, the answers were further converted into scores, Strongly Agree (5), Agree (4), Neither Agree nor Disagree (3), Disagree (2) and Strongly Disagree (1). The mean score and standard deviation of each question across the participants was estimated. The target users of this game are people after stroke, therefore, their opinions and comments were important and valuable. Their comments will be taken into account to support future developments of the game.

3.6 Summary

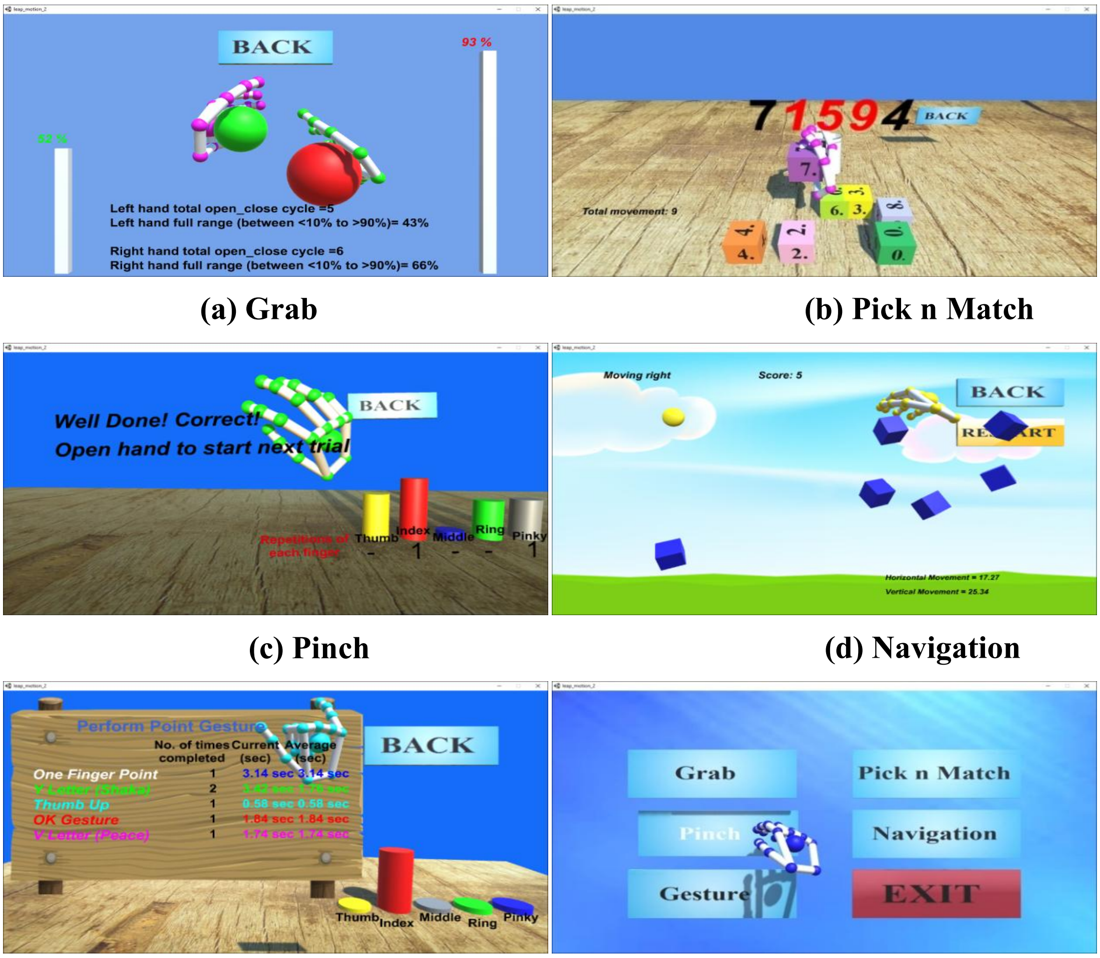
This chapter presents the implementation of a VR interactive game using the LMC. The design concept of the game is illustrated. The hardware setup and the scripts' development were also explained. The developed exercises are fully described. The questionnaire used to evaluate the game is also presented in section (3.5.3). In the next Chapter, the outcomes of the game and the evaluation results will be discussed.

Chapter 4 Results and Evaluation

This chapter presents the outcomes of the developed game and its evaluation.

4.1 Game Contents

Figure 4-1 shows the screenshots of 6 scenes in this game. (a) to (f) represent the exercises Grab, Pick n Match, Pinch, Navigation, Gesture, and the Main Menu respectively.



(a) Grab (b) Pick n Match

(c) Pinch (d) Navigation

(e) Gesture (f) Main Menu

Figure 4-2: Screenshots of 6 scenes in this game. (a) Grab. (b) Pick n Match. (c) Pinch. (d) Navigation. (e) Gesture. (f) Main Menu.

A brief description of each scene can be found in Table 4-1. Table 4-1 describes what to do in each task and the expected feedback from the task.

Table 4-1: Descriptions of 6 scenes in the game.

Scenes	Description
Grab (a)	• Users open and close their hands • Radius and colour of the ball in the hand changes in response to the extent the hand is opened/closed • Vertical bar on the side indicates the extent the hand is opened/closed • An audio sound is played when users perform a full open/close cycle (going from at least 10% to at least 90% open and vice versa)
Pick n Match (b)	• Users move their hands to pick up numbered blocks (one at a time) by closing their hand and drop blocks (one at a time) into a basket by opening their hand • If the number on the block dropped into the basket is included in the task number (a black, 5 digit number in the middle of the screen), the corresponding digit in the task number changes from black to red • Total number of movements (times when blocks are picked up) is displayed • Audio sounds are played whenever users pick up a block or drop a block
Pinch (c)	• In each trial, users are instructed (through text on the screen) to perform a two finger pinch with their thumb and one of their other four fingers. The thumb is the default finger which is used in every pinch. • The number of times each finger has been used to pinch (excluding the thumb) is displayed on the screen • Cylinders on the lower right corner of the scene indicate the figures which need to be used in the current pinch • An audio sound (applause) is played when the correct pinch is performed and detected
Navigation (d)	• Users controls the movement of a ball by moving their hands up or down (for vertical movements) or right and left (for horizontal movements) • The task is to make the rotating cubes disappear by using the ball to hit the cubes • The ball turns grey and can't be controlled when the user's hand is out of the scene. The cubes turn green when they make contact with the ball • The direction of the ball's movement, the number of cubes which have disappeared (score), and whether the user's hand is moving horizontally or vertically are all displayed onscreen • Audio sounds play when the ball makes contact with the cube and when the cube disappears

Gesture (e)	• Users performs one of 5 predefined gestures in the game: one finger point, Y letter, thumb up, OK and V letter • The number of repetitions of each gesture, and the time and average time required to perform the gesture are shown • Cylinders on the lower right corner of the scene indicate the suggested positions of each finger for performing the current gesture • An audio sound (applause) is played when the correct gesture is performed and detected
Main Menu (f)	• Users select the exercise they would like to practice or exit the game by moving their hand to the corresponding button and pressing it • An audio sound is played if one of the buttons is pressed • The text of the pressed button turns white and the button moves away

Apart from the Main Menu scene, each scene also contains a BACK button which users can press to go back to the Main Menu and select a different task. The Navigation scene has a RESTART button which enables users to restart a new section of Navigation task.

4.2 Evaluation

As mentioned previously, a frequency analysis of the questionnaire was performed based on the participants' responses and these responses were also converted into scores, from 1 to 5: Strongly Agree (5), Agree (4), Neither Agree nor Disagree (3), Disagree (2) and Strongly Disagree (1). The first and second question sets can be found in Table 3-4 and Table 3-5 on pages 35 and 35 respectively. The first and second question sets are referred to as Q1 and Q2 respectively. Questions in the first set are referred to as Q1-1 to Q1-6 for questions 1 to 6 respectively. The same applies to questions in the second set.

4.2.1 Overall Views on the VR Game

Table 4-2 presents the frequency analysis and the mean scores (μ) and standard deviations (σ) of each question of the first question set. Participants had very positive feedback on this part, all responded and reported that the system was easy and interesting to use (μ=5 and σ = 0 in response to "When using the game I understood what I was supposed to do", "I would be interested in trying more games / practising more activities on the system", and "Using the system and practicing activities was fun").

Additionally, the participants described the game as interactive, engaging, and motivational, as highlighted by participants' comments like "*All Good, Well done; The interactivity, the system is very interactive and engaging for the us*er*; Very easy to use, The games with a goal were the best (pick n match); Really motivational + likelihood to adhere exercises + improve rehabilitation; Cheap, easy to use*"). However, the participants also suggested improvements for some interfaces and features of the system "*The UI could be more streamlined, i.e. less intrusive menu buttons in the game; The dancing digit bars were a little distracting and decreased the obviousness of their purpose; manoeuvring between different activities appears more tricky so possibly difficult for stroke patients; The skeletal hand looks a bit scary - could it be displayed in a more life-like way?*"

Table 4-2: Frequency analysis and mean scores and standard deviation of 6 questions of the first question set. The number of participants is 5 (*n*=5). The questions are, Q1: When using the game I understood what I was supposed to do; Q2: I would be interested in trying more games / practising more activities on the system; Q3: Using the system and practicing activities was fun; Q4: I have played games on a personal computer or game console; Q5: I have played games or applications in Virtual Reality environment; Q6: I feel comfortable using technology.

	Question Set 1					
	Q1	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**
Strongly Agree	5	5	5	3	1	1
Agree	0	0	0	2	0	4
Neither Agree nor Disagree	0	0	0	0	0	0
Disagree	0	0	0	0	2	0
Strongly Agree	0	0	0	0	2	0
Mean (μ)	5	5	5	4.6	2.2	4.2
Standard Deviation (σ)	0.00	0.00	0.00	0.55	1.64	0.45

4.2.2 Usability of the VR Game for Patients after Stroke

The second question set focused on getting opinions from participants on how useful they thought the VR game would be for people after stroke. The feedback from participants on this part demonstrates that they felt confident with the system and considered it to be a very promising solution for people after stroke. The mean scores and standard deviations of the second questionnaire can be seen in Table 4-3. The results show a positive view from professional therapists with regards to using this VR game for stroke rehabilitation. All participants strongly agreed that the system and its activities would make rehabilitation more interesting (Q2-1, μ=5 and σ = 0). 80% of participants strongly agreed with the following questionnaire statements: “People after stroke could use the system at home to practice the upper arm and get better”, and “The system has the potential to help people after stroke recover” (Q2-4 and Q2-5, μ=4.8 and σ = 0.45). All participants also agreed that “The system and activities will motivate people after stroke to practice their upper limb rehabilitation.”, “Using the system will improve people after stroke’s hand and upper arm ability”, and “I can see this system being useful for other groups who have upper limb problems” (Q2-3, Q2-6 and Q2-8, μ=4.6 and σ = 0.55). However, some participants showed a neutral response to the statement: “The system is easy for people after stroke to use.”, and “I would be happy to let people after stroke use this system without supervision” (Q2-2, μ=4.2 and σ = 0.84; and Q2-7, μ=4.4 and σ = 0.89). Question number 2 “The system is easy for people after stroke to use.” reported the lowest score, with one of the participants commenting that ease of use depended on the “*nature / severity of stroke*”.

Overall, the participants had very positive comments on the usability of the VR game for people after stroke and even for other rehabilitation purposes, such as “*This technology + Upper Limb (UL) exercise programme has the ability to improve adherence, motivation + progress through rehabilitation. It has excellent clinical implications + there are so many possibilities to improve*”, “*The game and sensor were very exiting! I could see it being used in a clinical setting for a large number of disables and not just stroke.*”, “*How resource* *intensive is the system? Could the games be too demanding for hospital computers / users PCs*"?

Table 4-3: Frequency analysis and mean scores and standard deviation of 8 questions of the second question set. The number of participants is 5 (*n=5*). The questions are, Q1: The system and activities would make rehabilitation more interesting; Q2: The system is easy for people after stroke to use; Q3: The system and activities will motivate People after stroke to practice their upper limb rehabilitation.; Q4: People after stroke could use the system at home to practice the upper arm and get better; Q5: The system has the potential to help people after stroke recover; Q6: Using the system will improve people after stroke' hand and upper arm ability; Q7: I would be happy to let people after stroke use this system without supervision; Q8: I can see this system being useful for other groups who have upper limb problems.

	Question Set 2							
	Q1	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**
Strongly Agree	5	2	3	4	4	4	3	3
Agree	0	2	2	1	1	0	1	2
Neither Agree nor Disagree	0	1	0	0	0	1	1	0
Disagree	0	0	0	0	0	0	0	0
Strongly Agree	0	0	0	0	0	0	0	0
Mean (μ)	5	4.2	4.6	4.8	4.8	4.6	4.4	4.6
Standard Deviation (σ)	0.00	0.84	0.55	0.45	0.45	0.89	0.89	0.55

4.2.3 Concern of Usability of the VR Game for Patients after Stroke

The user testing does not mean to get exclusively quantitative feedback, but also intends to gather feedback from participants for improving the VR Game system for Stroke Rehabilitation. Therefore, it was very important to get physiotherapists with experience in stroke rehabilitation involved in the testing in order to collect their valuable feedback. Most of these comments are related to the design of the interface and are listed below:

(1) *"The system should provide arm support, something that patients can use to put their forearm on, otherwise they would get tired."*
(2) *"The interactivity, the system is very interactive and engaging for the user."*
(3) *"The UI could be more streamlined, i.e. less intrusive menu buttons in the game"*
(4) *"Very easy to use, The games with a goal were the best (pick n match)"*
(5) *"The "dancing" digit bars were a little distracting and decreased the obviousness of their purpose."* (see Figure 4-1 (c) and (e), cylinders located right lower corner.)
(6) *"Some of the screens were a bit busy for the eye. They may need to be simpler for those who have had a stroke."*
(7) *"Manoeuvring between different activities appears more tricky so possibly difficult for stroke patients."*
(8) *"The skeletal hand looks a bit scary - could it be displayed in a more life-like way?"*

These comments and feedback are a valuable resource in the development of a more effective and suitable VR game for post-stroke patients. All feedback will be taken into account for future development.

4.3 Summary

This chapter first describes the activities and outcomes of the VR interactive game. This game was tested by 5 participants, 4 of whom are professional therapists. The feedback of these participants is encouraging and all participants pointed out that the exercises in the game were easy to understand and easy to practice. The Leap Motion Controller being an unconventional input device meant that participants found the exercises especially fun and were interested in practising them. Furthermore, although the participants had different levels of experience with video games, VR, and technology, they all found the VR interactive game of this study very accessible and easy to use. They also commented that it could motivate patients to practice rehabilitation exercises. Moreover, they were impressed by its cost, convenience, and its ability to be used in a home environment without supervision. However, they also indicated some design issues and concerns with the game which will be discussed in the next Chapter.

Chapter 5 **Discussion and Conclusion**

This study has developed 5 exercises for hand rehabilitation in a VR environment based on the Leap Motion Controller, a non invasive interactive device for hand motion capture, and Unity3D. Users can thus practice these exercises with free hands and see the motion of their hands in a digital environment. These exercises have been validated and evaluated by able-bodied subjects, mainly physiotherapists with experience in Stroke Rehabilitation. The results demonstrate that these exercises allow users to interact with the VR environment by using their free hands.

This chapter discuss the feedback from the evaluation experiment, concludes this study, and also outlines the limitations and future work of this study.

5.1 Discussion

Participants provided valuable feedback about the user interface and the design of the game. These comments can be summarised in terms of the game's user interface, game feedback, and task goals of the exercises.

(1) Game user interface: One of the challenges of designing this game was the inclusion of a BACK button in each exercise. This button is required to allow users to go back to the main menu to select an exercise. However, this button was easy to accidentally press when practising exercises. For this reason, some exercises (Pinch and Gesture) had no BACK button in their original design, instead allowing users to go back to the main menu by closing their hand for some time. However, it also had some pitfalls:

a. Some patients might not be able to keep their hands closed.
b. It might confuse users.
c. To prevent unintentionally returning to the main menu, the game only goes back when it detects users keeping their hand closed continuously for some time (a certain threshold). Selecting a proper threshold is important. If the threshold is too

short, it could easily result in a false positive. On the other hand, if it is too long, users might stop keeping their hand closed before reaching the threshold.

Therefore, the BACK button was put back in later.

(2) Game feedback: The game is designed to provide real time feedback in different formats/modalities. However, some of the participants pointed out that some of the feedback might distract users and/or might not be suitable for stroke patients. For example, the participants mentioned that in the Pinch and Gesture exercises, the cylinders could distract users and were not suitable for patients. They also mentioned that some of the sound effects might not be suitable for patients.

(3) Task goals of exercises: In general, the Pick n Match exercise was the most popular exercise. This might be due to it having a clear goal. Some participants suggested integrating real life scenarios into the task. This will be one of the next steps of this study.

(James William Burke *et al.*, 2009a) suggested that users can be frustrated due to the poor design of a game's interface and poor feedback. The design of a game's interface should be effective, clear, consistent, well organised, and unobtrusive. As VR game environments are 3D, making the user interface more effective and friendly needs more consideration in terms of 3D geometry, especially regarding depth (z axis).

(Jack *et al.*, 2001) suggested that motor learning in rehabilitation can benefit from intense feedback and training in a VR environment. It was also suggested that less feedback could increase the level of challenge for patients (Lange *et al.*, 2011). For this reason, this VR game attempts to provide as much feedback as possible, and in different ways, to increase the immersion of users. The comments from the participants addressed the importance of users' needs and the need to keep feedback relevant to the task. Feedback will therefore be modified in the future development of this game.

Also, VR games for stroke rehabilitation should provide meaningful gameplay. It is important that patients know the expected goal of each exercise, how to achieve the goal, and whether they have achieved the goal (Alankus *et al.*, 2010; James William Burke *et al.*, 2010; Pirovano *et al.*, 2012). Apart from Pick n Match and Navigation, the goals of the other three exercises are not clearly defined. Therefore, integrating the exercises into a real life simulated environment is one of the priorities of future development.

5.2 Limitations of this Study

There are several limitations of this study due to constraints in time.

(1) Experimental setup: The Leap Motion Controller is the device used to control the game's virtual hands in the digital 3D game environment. However, due to the time restrictions of the study and the availability of hardware, the LMC was configured with a PC and a 2D display and could not be configured with a 3D display or a head mounted device.

(2) Participants: Due to time limitations, this game was not tested by stroke patients. However, it was validated and evaluated by a small group of professional therapists who provided very valuable feedback and comments. This study is a proof of concept. It is assumed that users are experienced in computer use. Therefore, patients with less experience with computers might not have the same perception of the exercises as the professional therapists.

(3) Data collection and analysis: This game only displays tracking data as real time feedback to users while they practice the exercises and does not record or store data for online and offline analysis.

(4) Game development:

   a. Functionality: Due to the limitation of time, the game developed in this pilot study only focuses on the functionality of the exercises. The overall functionality can be considered in some ways as incomplete. For example, the level of difficulty cannot be changed. The exercises are also fixed and cannot be customised to adapt to the statuses of different users. Also, the developed scripts do not fully use the tracking data of Leap Motion to explore its full potential and merits.

b. Platform: The game is developed for windows based PCs only.

(5) Measurement of effectiveness: Due to time constraints, this study cannot measure the effectiveness of using this game in hand rehabilitation.

5.3 Future Work

The VR Game for Stroke Rehabilitation was well received by the user testing participants, who reported that the VR game was easy and fun to practice and will motivate people after stroke to practice as part of rehabilitation. The reported results and feedback of the initial user testing are very positive, and the participants in the user testing all enjoyed the 3D interactive activities in the VR game. Some participants have even pointed out the possibility of using the VR game in the rehabilitation of other medical conditions. In addition, the use of VR applications or games for stroke rehabilitation has been demonstrated as a valid approach in literature. As future work, I intend to continue improving the VR game in steps as follows:

(1) Exploring Leap Motion in depth: There are more tracking data available which are provided by the LMC. More time and further study is required to investigate the usefulness of the data in rehabilitation.

(2) Expansion of in game exercises and the simulated VR environment: To design more daily life scenarios in the system and the corresponding activities/exercises in these scenarios. For example, holding a key and inserting it into a key hole to open a door. Lifting a water bottle, opening it and drinking it. Users would also be able to select the scenarios they are interested in practising.

(3) Data acquisition and telemedicine: The system should record patient progress data and activities data for therapists to analysis and evaluate patient progress. Furthermore, therapists can monitor patient progress and interact with patients in real time through an Internet connection.

(4) Cooperation with the medical profession and potential target patients: Rehabilitation is a multi-disciplinary field, resulting from the collaboration of multiple professions.

A feasible and practical rehabilitation intervention requires different efforts from many disciplines.

(5) Including other biosensors and VR technologies: the system can bring more benefits to patients if it adapts more biosensor technologies which can detect the physiology of patients while they are engaged with the system. Physiology status monitoring can provide real time feedback and information to users and clinicians in remote locations for monitoring and analysis purposes.

(6) It is also required to conduct more experiments with target users and with a larger group of participants.

5.4 Conclusion

The evaluation results show that VR using the Leap Motion free hand tracking controller is a feasible intervention for hand rehabilitation for people after stroke.

The VR interactive game designed in this study for stroke rehabilitation is space efficient, of a low cost, and easy to setup. It is suitable for clinical and home environments. The free hand feature allows people after stroke to practice hand rehabilitation at any time. The exercises are flexible in terms of their duration and the intensity of repetitions. Although the target users are people after stroke, it can be applied to any individuals requiring hand rehabilitation.

5.5 Final Note

The participants involved in the user testing for this pilot study gave very positive feedback about the functionality of the LMC controlled VR interactive game and they considered it to be a very promising intervention for people after stroke. They also commented that it could be used for people with other medical conditions requiring hand rehabilitation and that it had the potential to be commercialised and used in healthcare settings. Therefore, further research and development should be carried out on this VR interactive game in order to improve it and make it viable for people in need of stroke rehabilitation.

(word count: 11,738)

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Appendices

Appendix-1: Participant Information Sheet

1. Study title and Researcher Details

- MSc. Medical Visualisation and Human Anatomy
- **Virtual Reality Interactive Games in Stroke Rehabilitation – a pilot study**
- Principal investigator: Sabina R.S. Ku
- Supervisor: Dr. Lorna Paul, Dr. Daniel Livingstone & Dr. Matthieu Poyade

2. Invitation paragraph

You are being invited to take part in a research study. Before you decide it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

3. What is the purpose of the study / testing?

The background and aim of this study is to research Virtual Reality (VR) and Games technologies that may be used in future by stroke patients to improve hand and upper-arm mobility / ability

This is a preliminary evaluation of technologies, and an initial design in which users are able to choose the tasks they are interested in from a set of simple tasks.

The duration of the testing is around 10-15 minutes.

4. Why have I been chosen?

This study is looking for the users with an interest in post-stroke rehabilitation.

5. Do I have to take part?

It is up to you to decide whether or not to take part. If you decide to take part you are still free to withdraw at any time and without giving a reason'.

6. What will happen to me if I take part?

The duration of the testing is around 10-15 minutes. You will be asked to complete a questionnaire anonymously.

7. Will my taking part in this study be kept confidential?

All data collected will be dealt with in confidence and that anonymity will be preserved.

All information which is collected about you during the course of the research will be dealt with confidentially*. You will be identified by an ID number and any information about you will have your name and address removed so that you cannot be recognised from it.

8. What will happen to the results of the research study?

The data and the results of the research will be used to evaluate the performance of the Serious Game in VR environment for Stroke Rehabilitation.

9. Who is organising and funding the research?

Digital Design Studio at The Glasgow School of Art in collaboration with the Laboratory of Human Anatomy, University of Glasgow; and Institute of Health and Wellbeing, University of Glasgow

10. Who has reviewed the study?

The project has been reviewed by the Digital Design Studio Ethics Committee.

11. Contact for Further Information

If you have any questions/concerns, during or after the investigation, or wish to contact an independent person to whom any questions may be directed or further information may be sought from, please contact:

Sabina Ku

c/o Digital Design Studio at The Glasgow School of Art

Address: The Hub, Pacific Quay, Govan Road, Glasgow G51 1EA

Phone: 0141 566 1450

S.Ku1@student.gsa.ac.uk

If you have any concerns regarding the conduct of the research project that they can contact the Digital Design Studio Ethics Officer, Dr Daniel Livingstone.*

Appendix-2: Consent Form

Title of Project: Virtual Reality Interactive Games in Stroke Rehabilitation – a Pilot Study

Name of Researcher: Sabina R.S. Ku

1. I confirm that I have read and understand the Participant Information Sheet/Plain Language Statement for the above study and have had the opportunity to ask questions.

2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.

3. I agree / do not agree (delete as applicable) to take part in the above study.

Name of Participant	Date	Signature
Name of Person giving consent (if different from participant, eg Parent)	Date	Signature
Researcher	Date	Signature

Appendix-3: Instructions for User Testing

Instructions for Leap Motion Controlled VR Interactive Game for Stroke Rehabilitation

The Leap Motion is used to control virtual hands in several game environments. The sensor should be placed in a stable position in front of and central to the screen (laptop screen or monitor). Place your hand at least 2inches above the sensor with the palm facing the sensor. The tip of the middle finger should align with the dim red spot in the middle. If you see the images of your hand showing on the screen, it is set and ready to go.

When the program starts, you should see 5 buttons on the screen which represent the 5 game tasks and the exit button. Move the hand on the screen towards the button which corresponds to the game task you want to practise. Once the button is pressed, you will hear a 'click' sound. The text on the button will become white and the button will move away from you.

1. Grab: The Grab task allows you to practise opening and closing your hand. In this task, please perform the activities of opening and closing your hand. You will see the colour and radius of the ball in the onscreen hand change to correspond to the extent your hand has opened. A vertical bar will present the same information. Text on the screen will inform you of the number of times you have performed an equivalent cycle of opening or closing your hand and the percentage of these cycles which are a result of you fully opening or closing your hand.

2. Pick n Match: In the Pick n Match task you will see the task number, a 5 digit number shown in black in the middle of the screen. The task is to select and move the blocks which possess a digit in the task number. Move your hand towards the block you want to pick up. Grab it and move your hand towards the basket underneath the task number and release it. The corresponding number will change from black to red. The blocks can be picked up in any order, regardless of which order the numbers appear in the task number.

3. Navigation: In this task, you will see a ball and 11 rotating blue cubes. The task is to make the blue cubes disappear by moving the ball to touch the cubes. The ball can move vertically (up or down) or horizontally (right or left). If you want the ball to move up, move your hand up. The other three directions follow the same rule, except you move your hand down, right, or left.

4. Pinch: The Pinch task requires you to perform a pinch with two of your digits. The default digit used in all pinches is the thumb. You will be instructed to use one of your other four digits (index, middle, ring and pinky) through the text shown on the screen.

When the system detects the correct pinch, you will hear a cheering sound and text will appear to inform you that you have successfully made the correct pinch.

5. Gesture: The Gesture task is similar to the Pinch task. The difference is that the pinch task only involves two fingers while the gesture task involves 5 fingers. This task will require you to perform one of 5 pre-set gestures: one finger point, Y letter (Shaka), OK gesture, thumb up and V letter (Victory). When the system detects the correct gesture, you will hear a cheering sound and text will appear to inform you that you have successfully made the correct gesture. You will also be provided with the time in which it took you to make the correct gesture.

Note: 1.All tasks have a BACK button on the screen. Pressing this button will take you back to the main menu. 2. If you feel that you have lost control of Leap Motion or it does not behave as you expect, the easiest way to fix the issue is to move your hand away from the Leap Motion sensor and to then put your hands back over the Leap Motion sensor.

Appendix-4: Questionnaire for VR / Serious Game in Stroke Rehabilitation User Testing

1. **Overall views on the game**					
Question	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
When using the game I understood what I was supposed to do					
I would be interested in trying more games / practising more activities on the system					
Using the system and practicing activities was fun					
I have played games on a personal computer or game console					
I have played games or applications in Virtual Reality environment					
I feel comfortable using technology					
Additional comments:					

(To Be Continued on the 2nd page)

Questionnaire for VR / Serious Game in Stroke Rehabilitation User Testing

2. Overall views on the usability of the game for people after stroke					
Question	Strongly Agree	Agree	Neither Agree Nor Disagree	Disagree	Strongly Disagree
The system and activities would make rehabilitation more interesting					
The system is easy for people after stroke to use					
The system and activities will motivate People after stroke to practice their upper limb rehabilitation.					
People after stroke could use the system at home to practice the upper arm and get better					
The system has the potential to help people after stroke recover					
Using the system will improve people after stroke' hand and upper arm ability					
I would be happy to let people after stroke use this system without supervision					
I can see this system being useful for other groups who have upper limb problems					
Additional comments:					

What do you think are:

1) **The best features of the system**
2) **The poorest features of the system**
3) **Barriers to people after stroke using the system**