Contents

1 Introduction

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 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 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 1.

Table 1: 10 principles most relevant to rehabilitation

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

2.2 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.

3 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).

3.1 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).

3.2 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.

4 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.

5 Summary

This review explored the principles of stroke rehabilitation and the mechanisms of stroke recovery. It examines the limitations and challenges associated with conventional rehabilitation approaches, highlighting gaps in accessibility, engagement, and efficacy. In response to these challenges, the review investigates the emerging role of virtual reality (VR) as a promising intervention, emphasizing its potential advantages over traditional therapies in enhancing motor recovery and patient motivation. Finally, the development of the LMC in upper limb rehabilitation was also presented.

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