Virtual reality in the rehabilitation of the upper limb after stroke: the user's perspective

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ABSTRACT

Virtual reality provides a three-dimensional computer representation of a real world or imaginary space through which a person can navigate and interact with objects to carry out specific tasks. One novel application of VR technology is in rehabilitation following stroke, particularly of the upper limb. Our research group has built a system for use in this field, which gives the user the ability to interact with objects by touching, grasping and moving their upper limb. A range of user perspectives has been tested with healthy individuals and with people following stroke.

1. INTRODUCTION

Virtual reality (VR) provides a three-dimensional computer representation of a real world or imaginary space through which a person can navigate and interact with objects to carry out specific tasks. It can either be *immersive*, where the user feels physically present in the virtual environment (VE), typically using a head-mounted display (HMD) or *non-immersive*, where a handheld interface allows interaction with objects on a computer screen. In its immersive form, visual, auditory and tactile sensory aspects of the VE can be delivered to the individual through visual display units and speakers within the HMD unit (Rose et al, 1996). A tracking system links head movements so that the image in the VE is updated in synchrony with head movements, giving an impression of looking around from within the VE. In addition to this, a representation of the user's upper limb can be generated within the VE using sensors on the arm and a dataglove on the hand (McDonough et al, 2003) so that the user can interact with objects as though they were real (Kozak et al 1993).

One novel application of VR technology is in rehabilitation following stroke, particularly of the upper limb. Recovery of upper limb function is a major problem, with 30 – 66 % of stroke survivors no longer being able to use the affected arm (van der Lee et al 1999). This can be explained in part by the site of injury in the cortex (Kandel et al, 1991), which can cause limb paresis that limits active practice with the arm in the real world (Chae et al, 1998). Other factors are low levels of interaction between the patient and the environment (Tinson, 1989; Mackey et al, 1996), ineffective therapy techniques (Kraft et al 1992), and the very small percentage of time actually spent practicing tasks (Tinson, 1989). The use of VE technology has been advocated for this problem as it can be manipulated to avoid the physical constraints that would prevent a patient practicing in the real world. The ability to practice is very important as it has been shown in the rehabilitation literature that early (Wade et al, 1985; Chae et al, 1998; Johansson, 2000) intensive (Langhorne et al, 1996; Kwakkel et al, 1997; Kwakkel et al, 1999) practice of active functional tasks (Dean and Mackey 1992, Smith et al, 1998; Smith et al, 1999) in an enriched environment (Bennett 1976; Rosenzweig, 1980, Ohlsson & Johansson, 1995; Grabowski et al. 1995) leads to more positive outcomes for upper limb rehabilitation, by modifying neural reorganisation of the cerebral cortex (Thompson et al, 1996; Traversa et al, 1997).

The specific advantages of both non-immersive and immersive VE technology in people following stroke are: the ability to view and correct the movement of the affected arm; to explore, interact and make errors, which provides the facility for motor learning. Tasks can be chosen to enable success that would not be possible in the real world; and their difficulty can be increased, over time, to mirror real world tasks. Immersive VE technology has the additional advantage of increasing the feeling of being 'present' in the VE and this greater degree of 'realism' may be an advantage in rehabilitation of people following stroke. Indeed effectiveness of a VE has often been linked to the sense of presence reported by the user, where presence is defined as the subjective experience of being in one place or environment, even when one is physically situated in another (Witmer and Singer, 1998).

Although there is much potential for the use of immersive VE in clinical applications, there are problems that could limit their ultimate usability. Some users have experienced side effects during and after exposure to an immersive VE. There have been some reports of users experiencing transient reduced binocular vision after wearing head-mounted displays (Mon-Williams et al, 1993). Other symptoms include disorientation and balance disturbances, and nausea. Many of these effects can be attributed to delays between the sampling of head and limb positions and the presentation of an appropriate image through the HMD. This incongruity between visual cues through the HMD and vestibular motion cues can produce sickness symptoms, similar to motion sickness, including disorientation, sweating, nausea and headache. It should be noted that there is considerable variation in the extent to which people in a VE have been found to suffer from these problems (Kolanski, 1995). Susceptibility to side effects can be affected by age, ethnicity, experience, gender and physical fitness, as well as the characteristics of the display, the virtual environment and the tasks (Lewis and Griffin, 1997).

The majority of published work on the use of VR technology for rehabilitation of motor deficits following stroke (n=11) in the upper limb (Burdea et al, 1997, Holden et al, 1999, Myers and Biering, 2000, Jack et al, 2001, Piron et al, 2001, Broeren et al, 2002, Deutsch et al, 2002; Holden & Dyer, 2002; Merians et al, 2002), and lower limb (Deutsch et al, 2002; Brown et al, 2002) have used non-immersive technology. No specific side effects have been noted in relation to the use of non-immersive VR with people after a stroke. Therefore the introduction of patients to immersive virtual reality environments, for assessment, therapy or rehabilitation, needed to be carefully tested in order to identify any safety or ethical issues.

Further questions that needed to be addressed in exploratory work of this system were: the specification of the tasks for the system from the users perspective; and the amount of effort and degree of immersion experienced using immersive VR during tasks in people following stroke.

Therefore the aim of this project was:

a) To ascertain the views of potential users of a virtual reality rehabilitation (VRR) system with respect to the type of task to be practised.
b) To establish the specification of these tasks to encourage arm and hand movement in people following stroke
c) To assess the interaction of the user, in both the healthy and stroke populations, in terms of their experience of presence in the virtual environment and their perceived exertion.
d) To investigate the rate of self reported side effects from use of the VRR system in both healthy and stroke users.

2. SECTIONS

2.1 Equipment: UUJ Virtual Reality Rehabilitation System

Our research group has built a system for use in stroke rehabilitation, which gives the user the ability to move around a world composed of familiar objects and to interact with these objects by touching, grasping and moving their upper limb. The user wears a head-mounted display (HMD) giving visual and audio cues and a data glove that facilitates manual interaction in the virtual world (see Figure 1).

A magnetic sensor system provides real-time 6-degrees of freedom (position and orientation) tracking of up to four points on the user's body. A VE has been created with a series of reaching and grasping tasks (based on the views from people following stroke, see Section 2.2); the patient sees a number of easily recognisable objects and also stylised representations of their arm and hand in the VE which replicates the movement of their upper limbs in the real world. The sensors attached to the upper limb are positioned carefully in order for the virtual arm to be correctly articulated. Three of the sensors are attached to the major upper limb joints (shoulder, elbow and wrist) and the fourth is attached to the HMD to facilitate the sense of immersion in the VE – as the patient moves their head their view of the VE changes accordingly.

Figure 1. *User wearing a head-mounted display (HMD) giving visual and a data glove that facilitates manual interaction in the virtual world.*

2.2 Identification of Tasks: Focus group interviews

To date three focus group interview sessions have been conducted by the research team. Participants were recruited from two local stroke clubs. The composition of the group members can be seen in Table 1 below, which details the individual's age, sex and relevant stroke characteristics.

Table 1. *Focus group participants.*

Group	Number	Sex (M=male, F=female)	Age (years)	Time since stroke (years)	Right/Left (R/L) stroke	Upper limb movement ✔=yes ✕=no
A	1	M	72	12	L	✔
	2	M	78	2	R	✔
	3	M	52	15	L	✔
	4	M	65	2	R	✔
	5	M	61	1	L	✕
	6	F	75	15	L	✕
B	7	F	78	7	R	✔
	8	F	62	9	R	✔
	9	M	63	6	L	✔
	10	M	73	3	L	✔
	11	M	62	12	R	✔
C	12	M	72	5	L	✔
	13	M	81	9 months	R	✔
	14	M	60	10	L	✔
	15	M	75	15	L	✔
	16	M	65	2	R	✕
	17	M	67	11	R	✔

Following the introductions and opening explanations of the project, participants were guided to discuss and give responses to the following questions:

1. What sort of activities can you do with your stroke arm?
2. What would you like to be able to do with your stroke arm?
3. What type of exercises / tasks do you think people with a stroke should be practicing with their arm?
4. How many of you had any form of therapy after your stroke?
5. Can you remember how much time was directed to getting movement back in your arm?
6. Do you think you would like to use a virtual computer system to help you practice arm movements?

The interviews were tape recorded and reviewed by the researchers. The main themes in relation to the above questions are summarised in Table 2.

Table2. *Summary of participant responses during focus group sessions.*

Question	Response summary
1 What sort of activities can you do with your stroke arm?	Reaching tasks Everyday actions
2 What would you like to be able to do with your stroke arm?	To hold objects To be able to use arm in getting dressed
3 What type of exercises / tasks do you think people with a stroke should be practicing with their arm?	Based on everyday actions Working above shoulder level A minority noted fine finger movements
4. How many of you had any form of therapy after your stroke?	The majority of participants had some form of therapy following their stroke, delivered via a mixture of in and out patient settings and ranging between 6 weeks and 5 months duration.
5. Can you remember how much time was directed to getting movement back in your arm?	The majority of participants reported the focus of therapy to be on the lower limb and walking practice. A minority remembered practising upper limb exercises.
6. Do you think you would like to use a virtual computer system to help you practice arm movements?	15 of the 17 participants stated they would like to try using a virtual computer system. A few were concerned as to their lack of knowledge about computers.

From the information gleaned from the focus group interviews the design of the UUJ VRR system, as described above, has attempted to incorporate the features that potential users would like to see in a rehabilitation system for the upper limb. In summary these are:

- Everyday activities
- Reach and retrieve actions
- Working above shoulder level
- A few wanted to focus on fine finger movements

A limitation of the above analysis is that at the time of interview most of the participants were between 2 and 15 years after having their stroke. Therefore the individual's recollection of how much therapy they received and how much of that was directed towards the rehabilitation of their upper limb specifically may not be reliable. Also, due to the chronic nature of most of these participants stroke, the type of exercises they would want to practice is likely to influenced and may be more limited in comparison to a group of people in the acute phase after stroke. It is planned to continue this analysis with focus group interviews with people in the acute phase and investigate of they have different ideas or perceptions. The VRR system may then need to be modified to incorporate alternative tasks.

2.3 Specification of Tasks

Functional tasks have been designed to incorporate a range of levels of difficulty for reach, grasp, release and manipulative components. The tasks engage both individual joint movements and the use of the whole arm and some require fine upper limb and hand motor control. They have been carefully designed so that complex tasks (such as grasping an object and moving it from one position to another) can be divided into a number of smaller sub-tasks. A wrist extension task has been designed to focus particularly on the movement at this joint (see Figure 2). It is likely to be functionally useful to promote wrist extensor activity as it impacts on grip strength and the dynamic positioning of the hand for grasping objects.

(i) Reach and Retrieve Task. This task has 7 levels of difficulty and will be tailored for each individual patient. The components of the task are 1) reach for a near green square object on a table in the VE, 2) then reach for and grasp a red cup in the centre of the table and 3) finally place the red cup on top of a yellow square object on the table. The tasks can be chosen depending on the patient's motor dysfunction, for example if the patient has difficulty reaching forward with the arm, the target for reaching 1) is increased in size and the distance to reach reduced. As the patient's reaching function improves, this task can be made progressively more difficult by reducing the size of the objects and increasing their distance away from the patient. The level of difficulty of the task can also be increased by increasing the number of objects that the patient has to touch, and by randomly ordering the placement of objects on the screen. Actual grasping of the cup 2) can either be produced on screen by simply touching the cup with any part of the hand (grasping is not required) to higher-level function where the hand must grasp around the cup in order to hold it.

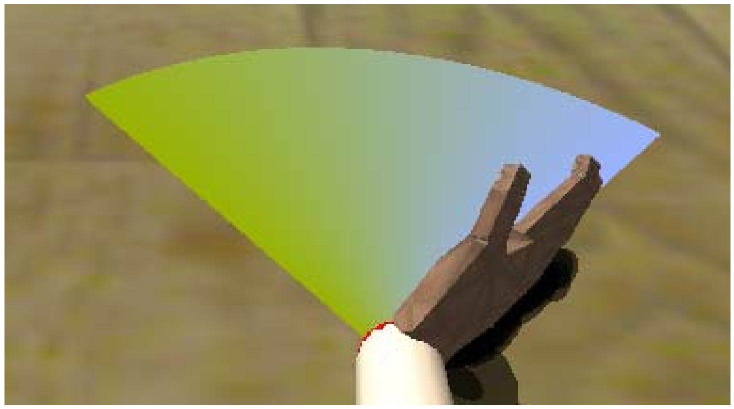

Figure 2. *View of the wrist extension task.*

(ii) Wrist extension. As noted above, the VE system can also be used to facilitate wrist extension practice. On screen the patient views a red task bar, each time they produce a flicker of wrist extensor muscle activity the colour of the task bar changes incrementally to green, if they carry out 10 successful repetitions the task bar changes to green completely, this can be repeated many times and alteration of the number of repetitions to complete can be reset depending on the users ability. The settings for this task can be changed so that only a very minor amount of movement starts the task, or the patient must produce moderate or full range of wrist extension in order to completely move the full red to the full green task bar.

Each sub task is accompanied by a set of audible instructions delivered via the earphones on the HMD and a pre-recorded demonstration for the user to view prior to attempting the task. The time taken to complete each task can be monitored, as can the patient's movements as they are engaged in achieving their goals. A specially designed graphical user interface (GUI) has been incorporated to allow straightforward initialisation of the system, configuration of individual tasks and scripting of whole sessions (see Figure 3), the goal being that this complex system should be usable by physiotherapists and other non-computing personnel.

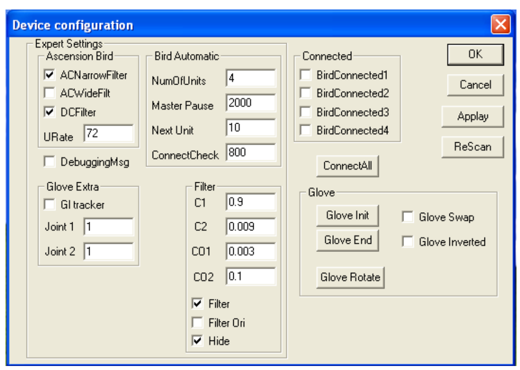

Figure 3. *System Initialisation and Task Configuration Dialogues*

2.4 User experience of the UUJ VRR system: Subjects

For this part of the study both healthy volunteers and people after stroke were recruited in order to assess their experience of using the VRR system. *Inclusion criteria* for those following stroke was: first stroke with a motor impairment of the upper limb as a primary deficit, muscle strength greater than 2/5 on the Medical Research Council (MRC) scale; stable medical condition; ability to communicate; good cognitive ability as indicated by a score greater than 15 on the Mini Mental State Examination (MMSE, Folstein et al 1975), Motricity Index score (Wade, 1992) greater than 26 indicating either activity of the shoulder or elbow and beginnings of prehension in the hand. *Exclusion criteria:* Patients with significant dysphasia; severe symptomatic arm pain; poor muscle strength (as determined by a score of less than 2/5 on the MRC scale of shoulder girdle muscle strength), an unstable medical condition, poor cognitive status (as defined by the MMSE, Folstein et al 1975) and severe visual-spatial neglect (The Line Cancellation Test, Albert 1973). Informed written or witnessed verbal consent was obtained from all recruited patients and healthy adults.

Each person undertook a VR session in which the HMD, dataglove and motions sensors were applied and they worked through a short series of exercises for the upper limb, which included reach to target tasks, a wrist extension task and a reach and retrieve of an object task. Features that have been designed into the system were evaluated, i.e. the audible instructions and pre-recorded demonstrations, the options to add or remove objects and to adjust distances and the height of objects in relation to the user. (see Figure 4 below).

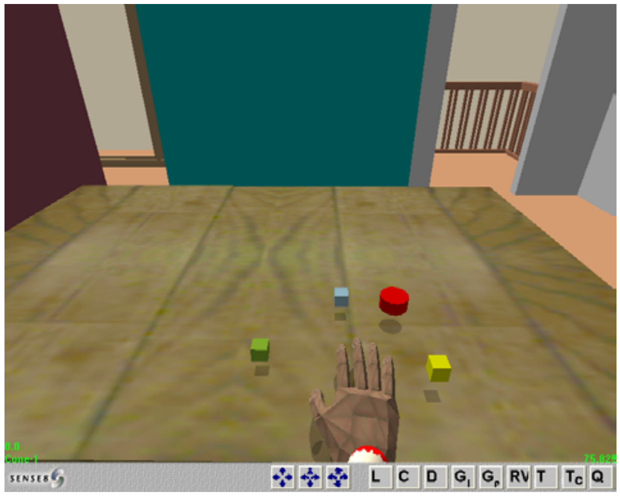

Figure 4. *View of one set up of the reach to target tasks.*

The subjects were divided into healthy and post stroke groups, with 10 and 5 individuals in each group respectively. The composition of the groups in terms of age, sex and details of stroke are displayed in Table 3. The mean age of the healthy group was 42 years and of the stroke group 62 years. Stroke users may have right or left sided weakness and thus the healthy group used a mixture of their right or left hands to operate the VR system to reflect this. The time since stroke of this group ranged from 6 days to 25 years, the mean being 10 years. Again this group comprised more people with chronic stroke as compared to those in the acute phase. The Immersive Tendencies Questionnaire was administered prior to the subject participating in the VR session (see Section 2.4.1). The Task Specific Feedback Questionnaire (see Section 2.4.1) and the Borg Scale of Perceived Exertion (see Section 2.4.2) was administered immediately after the VR session.

2.4.1 Presence. The Immersive Tendencies Questionnaire (ITQ) was developed by Witmer and Singer (1998) and was used in this study to determine differences in the tendencies of individuals to experience presence.

The questionnaire asks the participant to answer 29 questions about issues such as how involved they become in doing tasks, when watching television or movies and also if they are easily distracted from tasks. An example is displayed below:

Do you ever become so involved in doing something that you lose all track of time?

|________|______________|_______________|______________|_______________|____________|

Never   Always

The scale is similar to a visual analogue scale for rating pain perception. From their answers to each question an impression is gained about how susceptible this person might be to being immersed in the VE. The person is scored as having a positive or negative immersive tendency. There is a positive relationship between presence and task performance. Thus a person with a positive immersive tendency might be more likely to be successful in the performance of virtual tasks. It can be seen from the summary of results in Table 4 that in the healthy adults 50% scored positively on the ITQ and 50% scored negatively, indicating that there was an equal balance of those more likely to become immersed as those less likely to become immersed in the VE. A similar pattern was seen on the people with stroke, although data for the outcome has only been measured for 3 subjects to date.

Table 3. *VRR testing participants.*

Healthy group			
Subject number		Age (years)	Right / Left handed use of the VR system
1		70	Right
2		48	Left
3		39	Right
4		44	Right
5		42	Left
6		48	Right
7		37	Left
8		23	Right
9		44	Right
10		28	Left
Post stroke group			
Subject number	Age (years)	Right / left stroke	Time since stroke
1	65	Left	3 years
2	83	Right	6 days
3	78	Right	2 years
4	62	Right	9 years
5	25	Right	25 years

2.4.2 User Experience. The Task Specific Feedback Questionnaire (TSFQ, Kizony et al, 2003) is a modified version of the Witmer and Singer (1998) Presence Questionnaire and queries the users perceived difficulty of the tasks carried out in the VE. This was used to evaluate the experience of using the system. The instrument comprises 6 questions responded to on a scale of 1 – 5, giving a total score of between 1 and 30. For example:

1. Did you experience any feeling of enjoyment?

1 2 3 4 5

1 = strongly agree, 2 = agree, 3 = unsure, 4 = disagree and 5 = strongly disagree

Lower scores indicate that the user had a more favourable experience using the virtual system.

Users of visual simulators may experience simulator sickness symptoms. These can include discomfort, fatigue, headache, nausea and dizziness (Kennedy et al, 1993). Question 7 on the TSFQ asks the participant to indicate if they experienced any discomfort or not. The researcher further asked participants to self-report the nature of the discomfort or the experience of simulator symptoms following the use of our VRR system; this is reported in Section 2.4.3. It can be seen from Table 4 that similar scores on the TSFQ were obtained for individuals in both the healthy and stroke groups, with a mean score of 10.8 and 14.8 for each group respectively. The scores are at the lower end of the 0 – 30-point scale, which as reported above is likely to indicate that the person had a more favourable experience when immersed in the VE. There was one erroneous result from subject 5 in the stroke group with a TSFQ score of 28.

2.4.3 Exertion and Side Effects. The Borg Scale of Perceived Exertion (Borg, 1982) was used to assess the individual's perception of any physical exertion they may have experienced whilst exercising their arm in the VE. Perceived exertion is the overall effort or distress of the body during exercise. The number 0 represents no perceived exertion or discomfort and 10 represents the greatest amount of perceived exertion that the person has ever experienced. Table 4 includes the Borg ratings for each group. It can be seen that in this case there is a difference between the healthy participants and the people with stroke. The subjects in the healthy group rated their perceived level of exertion as being weak, with scores of between 0 and 4. This equates to a range of nothing at all to moderate level of perceived exertion. However, the people in the stroke group rated their experience between 3 and 7 on the Borg scale. This equates to a range of moderate to very strong perceptions of exertion. This is probably to be expected as for individuals with no upper limb motor deficits the VR tasks are quite easy to execute; whereas, for the person with stroke the tasks are likely to require an increase in motor activity and thus effort to complete them.

Table 4 *Results summary of the Immersive Tendencies Questionnaire (ITQ), Task Specific Feedback Questionnaire (TSFQ), and Borg Scale of Perceived Exertion for healthy and stroke groups.*

Healthy group				
Subject number	ITQ (positive / negative)	Borg rating	TSFQ score	Reported side effects (yes / no)
1	Negative	2 - weak	13	No
2	Negative	2 - weak	12	Yes
3	Negative	1 – very weak	9	Yes
4	Positive	1 – very weak	8	Yes
5	Positive	0 - nothing	12	No
6	Negative	0.5 extremely weak	9	No
7	Positive	2 - weak	6	Yes
8	Positive	0.5 extremely weak	11	No
9	Negative	4 – weak/moderate	17	Yes
10	Positive	3 - moderate	11	No
Post stroke group				
Subject number	ITQ (positive / negative)	Borg rating	TSFQ score	Reported side effects (yes / no)
1	Positive	7 – very strong	12	Yes
2	Negative	5 – strong	9	No
3	Positive	3 – moderate	10	No
4	No data	5 – strong	15	No
5	No data	5 - strong	28	No

With respect to side effects experienced having been immersed in a VE, of the healthy group 5 out of 10 experienced transient symptoms, which included headache, dizziness, discomfort and nausea. Only one stroke user experienced symptoms of dizziness, which again was transient.

3. CONCLUSIONS

The VRR system produced by the research team has been tested with respect to the user experience in a small group of healthy individuals and people with stroke. It has been shown that amongst both groups there was an equal balance of subjects more or less likely to become immersed in a VE as tested by the Immersive Tendencies Questionnaire. Participants in both groups indicated a generally favourable experience using the VRR system, as indicated by the lower scores on the Task Specific Feedback Questionnaire. Similarly some healthy users and one stroke user reported transient side effects following their interaction with the system. The main difference between the two groups tested was their level of perceived exertion, as measured by the Borg Scale. The healthy group rated the experience of using the VRR rehabilitation system as none to a weak level of exertion. Whilst the users with stroke perceived the level of exertion demanded to be at a higher level of moderate to strong.

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4. REFERENCES

M L Albert (1973,) A simple test of visual neglect, *Neurology*, **23**, pp. 658-664.

E L Bennett EL (1976), *Neural Mechanisms of Learning and Memory*. MIT Press Ltd: Cambridge, MA.

G V Borg (1982) Psychophysical bases of perceived exertion, *Med Sci in Sport and Exe*, 14, pp. 377-381.

J Broeren, A Bjorkdahl, R Pascher and M Rydmark (2002), Virtual reality and haptics as an assessment device in the post acute phase after stroke, *Cyber Psych Behav*, **5**, pp. 207 – 211.

D A Brown, D L Jaffe and E L Buckley (2002), Use of virtual objects to improve gait velocity in individuals with post stroke hemiplegia, *Neurology Report*, **26**, pp. 105.

G Burdea, S Deshpande, N Langrana, D Gomez and B Liu (1997), A virtual reality-based system for hand diagnosis and rehabilitation, *Presence – Teleoperators and Virtual Environments*, **6**, pp. 229 – 248.

J Chae, F Berthoux and T Bohine (1998), Neuromuscular stimulation for upper extremity motor and functional recovery in acute hemiplegia, *Stroke,* **29**: pp. 975-979.

C Dean and F Mackey (1992), Motor assessment scale scores as a measure of rehabilitation movement control following stroke, *Physio*, **69**, pp. 238-240.

J E Deutsch, A S Merians, S Adamovich, G Burdea and H Poizner (2002), Haptics and virtual reality used to increase strength and improve function in individuals post-stroke, *Neur Report***,** **26**, 2, pp. 79-86.

M Grabowski, J C Sørensen, B Mattson, J Zimmer and B B Johansson (1995), Influence of an enriched environment and cortical grafting on functional outcome in brain infarcts in adult rats, *Experimental Neurology*, **133**, pp. 1-7.

M F Folstein, S E Folstein and P R McHugh (1975), Mini Mental state. A practical method for grading the cognitive state of patients for the clinician, *Journal of Psychiatric* Research, **12**, pp. 189-198.

M A Grealy, D A Johnson and S K Rushton (1999), Improving cognitive function after brain injury: The use of exercise and virtual reality, *Arch Phys Med Rehab,* **80**,pp. 661-667.

M Holden and T Dyar (2002), Virtual environment training – a new tool for neurological rehabilitation, *Neur Report***,** **26**, 2, pp. 62-71.

M Holden, E Todorov, J Callahan and E Bizzi (1999), Virtual environment training improves motor performance in two patients with stroke: case report, *Neur Report*, **23**, pp. 57 – 67.

D Jack, R Boian, A S Merians et al (2001), Virtual reality-enhanced stroke rehabilitation. *IEEE Transactions on Neural Systems and Rehabilitation Engineering,* **9**, pp. 308 – 318.

B B Johansson (2000), Brain plasticity and stroke rehabilitation, *Stroke*, **31**, pp. 223-230.

E R Kandel, J H Schwartz and T M Jessell (1991), *Principles of neural science* (3rd edition), Prentice-Hall International Inc, London.

R S Kennedy, N E Lane, K S Berbaum and M G Lilienthal (1993), Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness, *Intern J Aviation Psycho*, **3**, 3, pp. 203-220.

R Kizony, L Raz, N Katz, H Weingarden and P L Weiss (2003), Using a video projected VR system for patients with spinal cord injury, *Proc 2nd International Workshop on Virtual Rehabilitation*, Piscataway, pp. 82-88.

E M Kolanski (1995), Simulator sickness in virtual environments. *Technology Report 1027:* US Army Research Institute for the Behavioural and Social Sciences Virginia.

J J Kozak, P A Hancock, E J Arthur and S T Chrysler (1993), Transfer of training from virtual reality. *Ergonomics*, **36**, pp. 777 – 784.

G H Kraft, S S Fitts and M C Hammond (1992), Techniques to improve function of the arm and hand in chronic hemiplegia, *Arch Phys Med Rehab,* **73,** 3, pp. 220-227.

G Kwakkel, R C Wagenaar, T W Koelman, G H Lankhorst and J C Koetsier (1997), Effects of intensity of rehabilitation after stroke: a research synthesis, *Stroke*, **28**, pp. 1550-6.

G Kwakkel, R C Wagenaar, J W R Twisk, G H Lankhorst and J C Koetsier (1999), Intensity of leg and arm training after primary middle-cerebral-artery stroke: a randomised trial, *Lancet (North American Edition)*. **354**, pp. 191-6.

P Langhorne, R Wagenaar and C Partridge (1996), Physiotherapy after stroke: more is better? *Phys Res Intern,*. **1,** 2, pp. 75-88.

C H Lewis and M J Griffin (1997), Human factors consideration in clinical applications of virtual reality. *Studies in Health Technology and Informatics,* **44**, pp. 35 – 56.

F Mackey, L Ada and R Heard (1996), Stroke rehabilitation: are highly structured units more conducive to physical activity than less structures units? *Arch Phys Med Rehab*, **77**, pp. 1066-1070.

S M McDonough, J H Crosbie, L Pokluda and M D J McNeill (2003, The use of virtual reality in the rehabilitation of the upper limb following hemiplegic stroke, *Proc 2nd International Workshop on Virtual Rehabilitation*, Piscataway, pp. 98.

A S Merians, D Jack and R Boian et al (2002), Virtual reality-augmented rehabilitation for patients following stroke, *Phys Ther* **82**, pp. 898 – 915.

M A Mon-Wiliams, J P Wann, S K Rushton and R Akerley (1993), Real problems with virtual worlds. *Ophthalmic Physiological Optics,* **13**, pp. 435 – 436.

R L Myers and T Bierig (2000), Virtual reality and left hemineglect: a technology for assessment and therapy, *Cyberpsychology and Behaviour*, **3**, pp. 465 – 468.

A-L Ohlsson and B B Johansson (1995), The environment influences functional outcome of cerebral infarction in rats, *Stroke*, **26**, pp. 644-649.

L Piron, F Cenni, P Tonin and M Dam (2001), Virtual reality as an assessment tool for arm motor deficits after brain lesions, *Stud Health Tech and Inform*, **81**, pp. 386 – 392.

F D Rose, D A Johnson, E A Attree, A G Leadbetter and T K Andrews (1996), Virtual reality in neurological rehabilitation, *Brit J of Ther and Rehab,* **3**, pp. 223 – 228.

M Rosenzweig (1980), Animal models for effects of brain lesions and for rehabilitation, In *Recovery of function: Theoretical considerations for brain injury*. University Park Press. Baltimore, MD.

G V Smith, R F Macko, K H C Silver and A P Goldberg (1998), Treadmill aerobic exercise improves quadriceps strength in patients with chronic hemiparsis following stroke: a preliminary report, *J of Neurologic Rehab*, **12**, 3, pp. 111-8.

G V Smith, K H C Silver, A P Goldberg and R F Macko (1999), “Task-oriented” exercise improves hamstring strength and spastic reflexes in chronic stroke patients, *Stroke,* **30**, pp. 2112-8.

M L Thompson, G W Thickbroom, BA Laing, S A Wilson and F L Mastaglia (1996), Transcranial magnetic stimulation studies of the corticomotor projection to the hand after sub-cortical stroke, *Movement Disorders*, **11**, pp. 25.1.

D J Tinson (1989), How stroke patients spend their days, *Int Disab Studies*, **11**, pp. 45-49.

R Traversa, P Cicinelli, A B Bassi, P M Rossini and G Bernardi (1997), Mapping of motor cortical reorganization after stroke, *Stroke*, **28**, pp. 110-117.

J H van der , R C Wagenaar and G J Lankhorst (1999), Forced use of the upper extremity in chronic stroke patients, *Stroke,*. **30**, pp. 2369-2375.

D T Wade (1992), *Measurement in neurological rehabilitation.* Oxford: Oxford University Press.

D T Wade, V A Wood and R Langton Hewer (1985), Recovery after stroke – the first three months, *J of Neuroy, Neurosurg and Psych*, **48**, pp. 7-13.

B G Witmer and M J Singer (1998), Measuring presence in virtual environments: A presence questionnaire. *Presence,* **7**, pp. 225 – 240.