

A study to evaluate a low cost virtual reality system for home based rehabilitation of the upper limb following stroke

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ABSTRACT

Stroke survivors with continuing impairment in their upper limb find it difficult to access the early intensive, task specific practice that research has shown is necessary for motor recovery. A systematic review of studies that investigate the effects of robot-assisted therapy on motor and functional recovery in patients with stroke found significant improvement in upper limb motor function but the systems reviewed are expensive, require technical support and are hospital or laboratory based. This paper describes the development of a low cost home based system together with a suite of games which would allow patients to practice the movements required for activities of daily living at the frequency required. The ongoing feasibility study is described.

1. INTRODUCTION

Between 55 and 75% of stroke survivors fail to regain functional use of their impaired upper limb (Feys et al., 1998). Upper limb motor impairment limits the individual's functional autonomy and activities of daily living, impacting negatively on participation and quality of life (Nichols-Larsen, 2005).

The evidence for stroke rehabilitation suggests that early intensive (Kwakkel et al., 2004), task specific (van Peppen et al., 2004) practice for a prolonged period of time (van der Lee et al., 2001) facilitates motor recovery. A meta-analysis by Kwakkel et al (2004) concluded that "augmented exercise therapy has a small but favorable effect on ADL, particularly if therapy input is augmented at least 16 hours within the first 6 months after stroke". Reviewing studies where constraints were applied to the less affected arm and thus forcing patients to use the affected arm for "6 hours per day during 2 weeks" (ie, augmentation of 60 hours) led them to conclude that "a high dose of task-specific exercise training should be applied over a shorter period of time. Therefore, research on subjects likely to benefit from higher intensities of stroke rehabilitation should be part of the future research agenda."

In view of the evidence, in the UK the National Clinical Guidelines for Stroke recommend that patients should undergo as much therapy appropriate to their needs as they are willing and able to tolerate (3.13.1). However in practice the intensity and duration of therapy is limited by resources. According to Kwakkel et al (2004) in stroke units the usual direct contact time may be as little as 4% of the total waking time. Patients on the stroke unit in Nottingham were found to spend on average only one hour per day in any type of therapy (Putman et al, 2006) and the median length of stay is now as short as 28 days. In order to prepare the patient for discharge, the focus of rehabilitation while on the unit is on mobility rather than upper limb function (Putman et al, 2006). Following discharge therapy is commonly delivered in patients' homes either by the community stroke teams or under an early supported discharge scheme. However, this support provides on average only six weeks of treatment. A Cochrane review has demonstrated that therapy-based services for stroke patients at home after stroke are effective, however it is not clear what the exact nature and content of

the rehabilitation should be (Outpatient Service Trialists, 2003). Patients with stroke living at home have identified upper limb therapy as an unmet need (Vincent et al, 2007), but the optimal intensity and dose of therapy is unclear.

As yet the definitive number of repetitions of a task required to drive the neural changes for optimal recovery post stroke is not known. A study by Lang et al (2009) found patients carried out an average of 32 functional upper limb movement repetitions during therapy sessions. This falls short of the large doses of practice (in the order of hundreds) that has been found to be effective in animal models. Therefore access to therapy is limited compared to the amount needed to drive neural change and what therapy there is, is not focussed on treatment of the upper limb.

There has been a paradigm shift in rehabilitation with the focus on empowering the patient, self-management and provision of therapy outside of the acute setting. This, combined with the evidence for the intensity of practice required and the limited resources available, has led to interest in the efficacy and efficiency of delivering therapy in novel ways. It has been recognised that face to face contact with a therapist is not the only way to deliver therapy, and may not be the most efficient way. The growing interest in the application of emerging technologies to augment rehabilitation has been endorsed by both the UK national stroke research network and the priority research areas set in the UK National Stroke Strategy. Of these technologies, Virtual Reality (VR) rehabilitation has been heralded as one of the most promising methods for maximizing the intensity and convenience of task specific rehabilitation training (Dobkin, 2004). Long-term participation of stroke survivors in exercise programmes is poor and a further benefit to application of novel technologies to deliver task-specific practice may be improved adherence. The aesthetics and affective properties of rehabilitation are often not considered but are important for sustainability (Rhodes & Fiala, 2009). Thus the use of VR rehabilitation and social interaction may be effective in maintaining motivation and alleviating boredom (Bonk et al, 2001, Sander et al, 2002, Yamashita et al, 2006).

Preliminary research in the area of VR stroke rehabilitation focused primarily on examining the feasibility of complex VR systems that provide the participants with different types of augmented feedback (eg van Dijk et al, 2005) and different VR rehabilitation protocols for acute, sub-acute and chronic stroke patients (eg Merians et al., 2002). Although this work mainly involved small sample sizes it suggested promising trends, triggered the active exploration of telerehabilitation applications (eg Broeren et al., 2004) and finally led to further studies involving bigger sample sizes (Holden et al., 2007) and small controlled clinical trials (eg Piron et al., 2006; Crosbie et al, 2008). This later work established the feasibility, health and safety of VR stroke rehabilitation systems and indicated that previously obtained positive outcomes were not attributed to spontaneous recovery (Holden et al., 2007). Neuroimaging studies also demonstrated that VR training can induce cortical reorganization following stroke (Takahashi et al., 2008). In a systematic review of studies that investigate the effects of robot-assisted therapy on motor and functional recovery in patients with stroke Kwakkel, Kollen & Krebs (2008) found significant improvement in upper limb motor function but not ADL after stroke for upper arm robotics.

Given the fact that most of the above systems employ relatively sophisticated or expensive hardware and software, one question of paramount clinical importance is whether the benefits obtained from these systems can outweigh their cost or if similar results can be obtained with less sophisticated affordable systems. What now needs to be explored is the rehabilitation potential of commonly available VR platforms and games. Although commercially available platforms lack specificity in terms of software, hardware and performance metrics they often provide other equally important advantages such as mass acceptability, easily perceived feedback and most importantly affordability for unrestricted home use. In an earlier study (Chortis et al, 2008) we investigated the use of a commercially available game controller the Novint Falcon http://home.novint.com/products/novint_falcon.php that came with a variety of VR minigames that should motivate users to perform sufficient repetition of tasks. The controller has the advantage of including force feedback which should increase the effectiveness of the participants' actions. Saposnick et al (2010) carried out a feasibility study using Nintendo's Wii together with two of the games suites available with the system. Both of these studies produced promising results however, the interventions employed suffer from two notable drawbacks. First, both controllers require the player to have the ability to grip them for prolonged periods of time. While they allow practice of arm movements, they exclude the practice of grasp and release: a particular challenge to many stroke patients but necessary for many activities of daily living. Second, the games made available with the controllers were not specifically designed with these users in mind and may not actually practice the movements which therapists recommend for recovery of independent functioning.

To overcome these drawbacks, our team have been developing a system that tracks infra-red light emitting diodes (LEDs) positioned on the fingers: a virtual glove (Battersby, 2008; Barker, 2009). This translates the actions of reach, grasp and release into game play but would still be low cost, lightweight, easy to set up in users' homes but would lack the force feedback of the Novint Falcon. This might reduce the

effectiveness of the participants' actions but this would be more than compensated for by the inclusion of grasp and release tasks. In collaboration with user representatives, a suite of three games have been developed that encourages the participant to practice the movements required for activities of daily living. However, unlike commercially available games, this software allows calibration to each user so that even those with limited ability can perform a movement sufficient to achieve a score. For example, initially quite a large gap between thumb and fingers would qualify as a "grasp" but as the user improves, the distance between thumb and fingers necessary to gain a score can be reduced. In order to maintain motivation, the level of challenge can be varied to suit the user in other ways such as increasing the number of tasks that need to be completed or increasing the speed at which stimuli/targets appear on the screen. In addition to calculating and displaying a score so that the user can track their progress, the software collects data on the number of movements made by the user whether they are successful in achieving a score or not.

New gaming devices are frequently appearing so it may soon be possible to identify a low cost commercially available system that overcomes any physical shortcomings in those devices currently available. Given the systems currently available, it is important to investigate whether the hardware and software are practical to use and sufficiently motivating that individuals perform the required number of repetitions of upper limb movements for an improvement in arm function. Nonadherence is common when treatment regimes require prolonged and unsupervised self management (Carter, Taylor, & Levenson, 2003) and between 60% and 80% of people receiving treatment admit to partial or complete nonadherence to home-based exercises (Engström & Öberg, 2005; Sluijs, Kerssens, van der Zee, & Myers, 1998).

It is the future intention of the team to carry out a definitive study to determine the effectiveness of home use of the virtual glove to improve upper limb function in patients recovering from a stroke. Before this can be done, certain crucial information needs to be collected in order to reach the correct design for the main study. The current study is therefore to determine the feasibility of the main study and to pilot whether the components of the main study can all work together. The study will follow the MRC guidelines for feasibility and pilot testing from the framework for evaluating complex interventions (<http://www.hta.ac.uk/funding/troubleshooting/standardcalls.html>).

2. METHODS

2.1 Development methodology

In order to develop the prototype glove and games a user sensitive design methodology was employed that we have previously reported (Brown et al, 2005). This combines established guidelines on User Centred Design, for example USERfit (Poulson et al, 1996) with contemporary HCI and product design research. It is a six stage, iterative, design process in which users are involved at all stages. User input is managed in two ways. First a multidisciplinary Usability Team guide the application of the user sensitive design methodology. This group included occupational and physiotherapists with expertise in stroke rehabilitation as well as researchers with expertise in ergonomics, HCI, manufacturing, experimental design, and product design. Second, a user team contributed to the design process by proposing design requirements and how these could be met in potential design solutions and giving feedback on the prototypes developed. Users were recruited from the Nottingham Stroke Research Consumer Group, Nottingham City Stroke Club and patients and therapists from two local specialist rehabilitation centres.

2.2 Development of the virtual glove

2.2.1 Version 1. The first version of the glove consisted of four light emitting diodes sown into the fingertips of a normal glove (see Figure 1) whose position was tracked with the aid of 2 Nintendo Wiimotes attached to the top of a 24" flat screen monitor. This allows the triangulation of the position of the infrared source and produces a set of 3D coordinates. The decision to use 4 diodes per glove was based on the capacity of the infrared receiver used to pick up the signal from the diodes. As the position of the ring finger is predictable from the position of the fingers either side in most movements, the four diodes were placed on the remaining fingers and the thumb. Testing was carried out with multiple voltages to determine the minimum rating that could be used to run a single diode. A single 1.5V battery (AA) was enough to power the glove of 4 diodes. However, each glove had a battery pack attached that produces 3 volts from 2 AA batteries. This gave the glove a longer life span and a strong signal which improved the responsiveness and accuracy of the system. Including more batteries than this, for example 6V would mean that 4 batteries were required per glove, and this would have seriously impacted on the usability of this device for users recovering from stroke. This version of the glove also included an accelerometer and two linear potentiometers similar to those found inside a Wii Nunchuck controller. The idea behind these additions was that they might be useful to free up analogue inputs to measure strain or hand closure and potentially implement either a fifth finger or more robust information on thumb position. This could also have removed the need for 2 Wiimotes for

triangulating position. Unfortunately, including all these components in the pack on the back of the hand produced too much bulk and weight especially for the target user group.

2.2.2 Version 2. Feedback from therapists indicated that a real glove would not be acceptable to users due to comfort and hygiene issues. This version therefore used hook and loop tape to affix the power pack to the back of the hand and plastic “thimbles” to hold the LEDs (see Figure 2). Users preferred a glove where these thimbles were attached to the power pack with cables to avoid dropping or losing them. This choice led us to reject the proposal to include a wireless transmitter in the power pack. To reduce bulk and weight, the potentiometers were omitted from this version.

2.2.3 Version 3. At this point it was decided to further reduce the bulk and weight of the power pack by omitting the accelerometers and providing the power through two CR2032 batteries. Removal of the accelerometers creates a need to track the horizontal angle of the hand using the diodes alone. This can be achieved by a ‘line-of-best-fit’ regression calculation treating the diode x and y positions as though they were points on a graph. Removing the accelerometers does however increase the difficulty of deciphering which diode is which or ‘point filtering’ and for more complex 3D game interaction, a rugged algorithm and calibration method may need to be developed to achieve this with diodes alone. To cope with varying sizes of finger, LEDs were attached using double sided hook and loop cable ties (see Figure 3). Reducing the weight and bulk of the pack attached to the back of the hand gives the potential to include a usb charging circuit for a 5V rechargeable battery if users prefer this to changing the CR2032 batteries when they are depleted.



Figure 1. *Version 1 of the virtual glove*

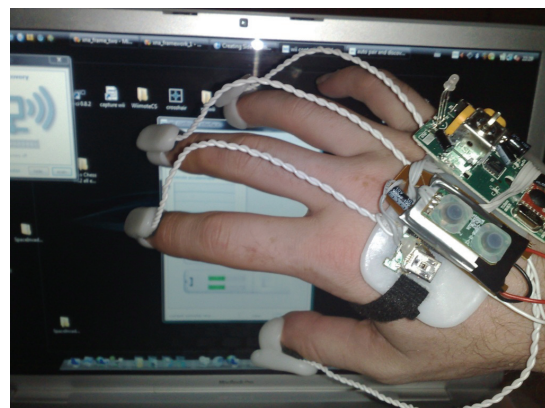


Figure 2. *Version 2 of the virtual glove*

2.3 *Development of the games*

A suite of 3 games was developed based on suggestions received from the Nottingham Stroke Research Consumer group and participants in the pilot study that would involve frequent repetitions of upper limb movements (i.e. pull, push, reach, grasp) that are necessary to effect many activities of daily living. Figures 4 and 5 show a screenshot from one of the games and illustrate how the player has to rotate the wrist to navigate the spaceship through the slot in the approaching wall. Each game has different levels varying in the standard of the movement required to achieve a score, the speed at which events occur and with which responses are required as well as in complexity of challenge in order to keep the participants motivated to continue to use the system but to ensure that they can achieve some success. Participants’ scores are displayed on the screen at the end of a game and there is a permanent visual display of their progress in terms of scores and levels played. Once they have achieved a critical score at one level they are offered the option of progressing to the next level. When a participant returns to a game either at the beginning of a session or after playing another game, they have the opportunity to continue at the level they were at previously or, if the critical performance has been achieved, of moving on to the next level. Offering the participant the option to remain at the lower level ensures they are not presented with too much of a challenge before they refamiliarise themselves with the game’s requirements. A log of when the system is in use is collected by the computer as well as what games are being played and what scores the user obtains. In order to distinguish between use by the participant and use by any other friends or relatives, a user has to enter a code number

before they can play so that only the performance metrics of the participant are logged in the database. The Games were written with Microsoft's XNA Game Development Framework and utilise Brian Peek's WiimoteLib (a .NET managed library for using a Nintendo Wii Remote and extension controllers from a .NET application <http://www.brianpeek.com>) and several accompanying Wiici (Wii Controller Interface) Libraries developed by the third author to enable the device to communicate with the games.

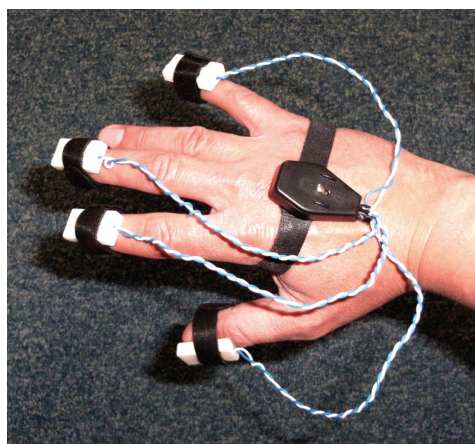


Figure 3. Version 3 of the virtual glove

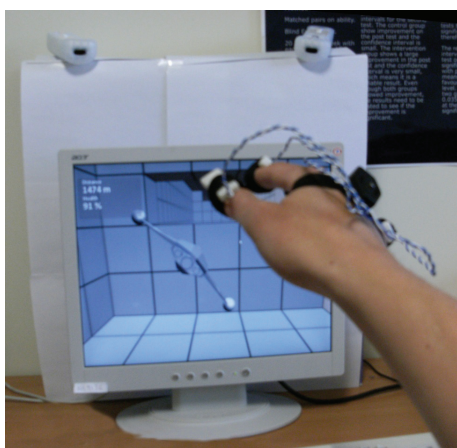


Figure 4. Space race game showing player's hand position

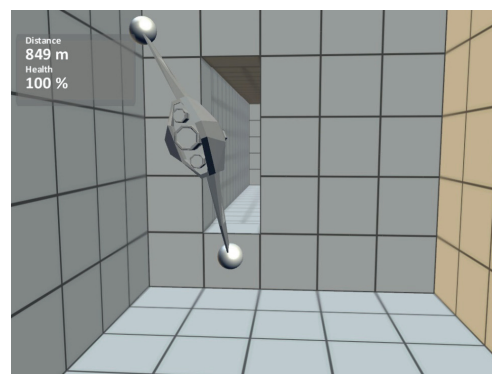


Figure 5. Screenshot of the space racegame

2.4 The study

2.4.1 Design. The glove is being evaluated using a two group randomised control trial to compare the glove with usual care.

2.4.2 Participants. 60 patients aged 18 or over are being recruited, who have a confirmed diagnosis of their first stroke, who are no longer receiving any other rehabilitation therapy and who still have residual upper limb dysfunction.

2.4.3 Intervention. Patients will be randomly allocated to either the intervention group or the control group. Those patients in the intervention groups would have the virtual glove in their homes (see Figure 6) for a period of 10 weeks. In order to achieve the recommended exposure time of 60 hours (Kwakkel et al, 2004) they will be advised to use the system for 20 minutes 3 times a day for 10 weeks to make allowance for missed days or missed sessions.

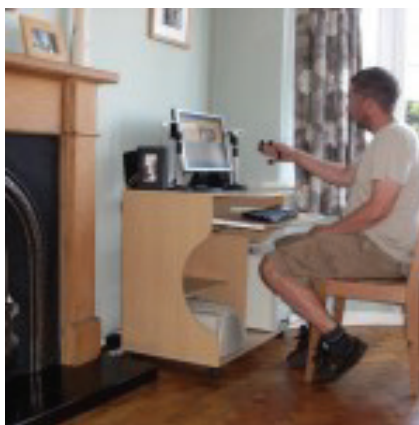


Figure 6. *How the equipment might look set up in a participant's home.*

2.4.4 Outcome measures. Wolf motor functions test (Wolf et al, 1989): a measure of upper limb functioning; Nine-Hole Peg Test (Kellor et al, 1971) a test of fine motor co-ordination and the Nottingham Extended Activities of Daily Living (Nouri & Lincoln, 1987) a measure of functional ability that is commonly used in studies of stroke rehabilitation. It has four subscales: mobility, kitchen tasks, domestic tasks, leisure activities. For the intervention group the frequency of use of the equipment will be collected by the software and the frequency of requests for help and type of queries when using the equipment will be logged by the research team to provide information on feasibility of using the equipment and aspects of the intervention that may influence its adoption.

2.4.5 Provision of support for participants during the trial. One of the biggest challenges to the evaluation is participant failure to adhere to the proposed frequency of use of the system. Several procedures have therefore been planned to encourage participants to use the equipment at the recommended frequency. First, considerable face to face support will be provided. When the equipment is delivered and set up it will be demonstrated to the participant and their carer. A member of the research team will then use the equipment with the participant and observe them using it independently. The researcher will then arrange to return within the next two or three days to repeat this demonstration. If after this visit they feel that the participant has understood how to use the equipment or that there is a carer who understands how to use it, the intervention can commence and the researcher will phone the participant after two days to check that they have been able to use the equipment in its intended manner and offer to visit once more to clarify any outstanding matters. If they still seem unsure of how to use it by the end of the second visit the researcher will arrange to visit again in the next 48 hours. A member of the team will then visit fortnightly to retrieve data and check progress. Second, the participant will be given a phone number on which a member of the research team can be contacted during working hours if they need any advice or if the equipment fails. Third, they will also be provided with an instruction manual which will include Frequently Asked Questions and troubleshooting tips. This will also be available on the project web page for those who have internet access. A record of how many demonstration visits took place and the number and type of requests for help will be recorded as well as the number of extra visits and notes kept of any queries or problems that are raised in each visit or phone call.

3. CONCLUSIONS

A user sensitive design methodology has been successfully employed to develop a virtual glove and a suite of three games that encourage practice of the movements that are essential for activities of daily living for people experiencing problems with their upper limb following a stroke. A randomised control trial to determine the feasibility of a full definitive trial of its evaluation has just commenced.

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