9 Engaging Stroke Survivors with Virtual Neurorehabilitation Technology

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INTRODUCTION

For stroke survivors to regain upper limb motor function and recovery, it is important for them to engage in high intensity, functional, and meaningful exercise. Professionally trained physiotherapists and occupational therapists, amongst others, frequently work with patients in one-on-one supervised training sessions to achieve this (French et al., 2016). Research with animal models has demonstrated that high intensity practice of movement can drive neural change. Unfortunately, the amount of practice provided during post-stroke rehabilitation in humans is small compared with that which can be attained in animal-based research. It is possible that current doses of task-specific practice during rehabilitation are not adequate to drive the neural reorganization needed to promote optimal functional recovery post-stroke (Lang et al., 2009). Insufficient intensity of therapy appears to be primarily caused by lack of time and funding (French et al., 2016). Methods where patients can increase the intensity of therapeutic training by themselves or semi-supervised are thus in high demand.

Virtual reality (VR) and augmented reality (AR) technology—computer generated worlds which can be explored in interactive real-time—have potential to support the physical rehabilitation process in a safe and engaging environment. With VR technology, the therapeutic intensity can be adjusted so that patients can practice at a level that is neither too difficult nor too easy, known as the "state of flow" (Csíkszentmihályi, 1990). Patients can be supported to successfully complete tasks beyond their comfort level through the guidance of the VR system or a clinical professional. Working in this way is postulated to be more effective and engaging than traditional therapy thereby enhancing motivation to undertake the training for longer.

Neuroplasticity is the process by which neural circuits in the brain are modified by experience, learning, and/or injury (cf. Nudo, 2003), and this process currently underpins rehabilitation principles of motor-relearning and recovery after stroke. A high number of repetitions of a movement pattern, with feedback, forms the physiological basis of motor learning and is an essential component of motor-relearning (Butefisch et al., 1995).

Neuroplasticity effects can be used in combination with VR techniques to provide many forms of extrinsic feedback (Regenbrecht et al., 2014) to motivate and engage patients in repeated exercise and support their implicit motor learning (Subramanian et al., 2010). Studies have reported increased participant motivation, enjoyment, or perceived improvement in physical ability following the inclusion of VR into stroke rehabilitation (Broeren et al., 2008; Yavuzer et al., 2008; Housman et al., 2009). Importantly, computer games can improve compliance with prescribed rehabilitation exercises (Kwakkel et al., 2008). Combining elements of research and practice in neuroplasticity, physical rehabilitation, VR and AR, and gameplay lead to the new field of virtual neurorehabilitation:

> Virtual neurorehabilitation is the field of practice and research to achieve effective physical rehabilitation by using virtual reality techniques to generate neuroplastic change.

Unfortunately, to date, shortcomings in a systematic approach to progress virtual rehabilitation have included (a) a lack of systematic development and evaluation of virtual neurorehabilitation systems based on sound theoretical and practical principles; (b) combining this technology with tailored therapeutic protocols that can lead to effective gains in motor and cognitive function; and (c) effectively engaging patients in a sustainable way. With our work reported here, we address these shortcomings.

UPPER LIMB STROKE NEUROREHABILITATION

Globally, stroke is the leading cause of complex disability (Adamson et al., 2004). Recovery of upper limb function after stroke is critical to a person's independence and self-care, yet up to 85% of patients never regain upper limb function and remain dependent on caregivers (Harris & Eng, 2007; Alia et al., 2017). Loss of upper limb function accounts for most of the poor subjective well-being after stroke (Wyller et al., 1997; Singam et al., 2015).

Current best practice for the rehabilitation of upper limb function post-stroke suggests the repetitive training of functional upper limb motor tasks, intensity of practice, and the functional relevance of the motor tasks are critical components (Van Peppen et al., 2004; Han et al., 2013; Veerbeek et al., 2014; French et al., 2016). Practice is postulated to advance neuroplastic changes in the damaged neurological pathways augmenting adaptation and enhancing recovery. The functional relevance of the task boosts motivation and cognitive involvement and encourages the neuroplastic changes to be focused on movements that are important for the individual (French et al., 2016). The amount of repetition required to induce these neuroplastic changes is not exactly known (Han et al., 2013; French et al., 2016). Han et al. (2013), however, found that between 30 and 90 hours (1–3 hours/day for 5 days/week over 6 weeks) of repetitive, task-specific training lead to improved arm motor function in stroke survivors.

Upper limb rehabilitation appears to thus require concentrated and intense training which in turn necessitates commitment and motivation from both stroke survivors and highly skilled health professionals providing therapy. Availability of skilled health professionals and the costs of their intense involvement can be prohibitive. Machine-assisted physiotherapy could help in alleviating therapist shortages and costs (Amirabdollahian et al., 2001) and has the potential to improve the outcome of upper limb rehabilitation (Islam et al., 2006). While robot-assisted training is a means of delivering intensive, repeatable, task-specific training, the evidence for its effectiveness to improve upper limb function post-stroke is ambiguous (Alia et al., 2017). In VR-assisted therapy, patients appear to engage in machine-assisted exercise for longer, seemingly motivated by the inclusion into the machine by a mixture of sensory and VR systems (Broeren et al., 2008; Alia et al., 2017).

VR has been defined as the “use of interactive simulations created with computer hardware and software to present users with opportunities to engage in environments that appear and feel similar to real world objects and events” (Weiss et al., 2006). From a technological point of view, VR has been classified on a spectrum between immersive (which is usually delivered via head-mounted displays (HMDs)) and non-immersive VR (usually delivered via personal computer screen and controlled via joystick, mouse, or other form of control device) (Rose et al., 1999).

Low-immersive VR can often be acquired at low cost as it does not require complex hardware; it can be delivered simply via a standard computer and monitor (Holden & Dyar, 2002). The user can simultaneously experience movement in the real world and receive feedback from the system of their movement. Immersive VR requires sophisticated hardware making it expensive and it is often not well tolerated for long durations, with some users reporting nausea, eye-strain, and dizziness or “simulator sickness” (Kennedy et al., 1993).

The potential benefits of VR are seen to arise from: improved patient motivation during rehabilitation (Flores et al., 2008), its ability to be combined with rehabilitation exercise devices (Guberek et al., 2008), and to assist movement, visually capture and assess movement, and provide movement feedback (King et al., 2010). Transcranial magnetic stimulation testing has revealed that this “action-observation” training can enhance the effects of post-stroke motor training by increasing the magnitude of motor memory formation and differential corticomotor excitability change (Celnik et al., 2008). Functional magnetic resonance imaging studies show that VR hand avatars (i.e., the image of a hand in a computer game) can create an “observation condition” that can be mimicked (Adamovich et al., 2009).

Evidence for the use of VR in upper limb stroke rehabiliation is emerging, with positive effects for low-immersive VR systems reported by Holden and Dyar (2002) and a review of VR by Henderson et al. (2007) concluded that the evidence was encouraging and warranted further investigation. Dosage of VR therapy is also emerging, with Laver et al. (2017) reporting that it should be provided for at least 15 hours total therapy time and is most effective when used in the first six months after stroke.

The 2017 Australian Clinical Guidelines for Stroke Management (updated 21/11/2019) (InformMe, n.d.) for upper limb rehabilitation following stroke states that for stroke survivors (a) with at least some voluntary movement of the arm and hand, repetitive task-specific training may be used to improve arm and hand function (French et al., 2016) and (b) with mild to moderate arm impairment, VR and interactive games may be used to improve upper limb function. These guidelines claim that research into upper limb stroke rehabilitation is ongoing, thus the recommendation, albeit weak, for the impact of VR therapy is encouraging.

THE POTENTIAL OF VIRTUAL REALITY TECHNIQUES

VR and related techniques are gaining popularity due to the availability of affordable and robust hardware and software, which makes VR useable in stroke rehabilitation clinics and not only in research environments. Besides its technical characteristics of being a computer-generated, interactive, three-dimensional environment, the distinctive aspect of VR is its ability to stimulate a sense of presence. Regardless of whether the VR environment is experienced on a computer monitor or by way of stereoscopic projection systems, including HMDs, the user should feel they are part of the virtual environment and they should experience the virtual environment in a similar way as a real environment. This experience is the premise of both VR’s potential effectiveness and is potential transferability into the real world.

In a wider sense, VR can be extended, or brought back to the real world by combining real and virtual elements in a coherent way, leading to mixed reality concepts of AR or augmented virtuality. In such scenarios, the same concept of presence applies: the users should experience the environment as plausible, develop a sense of place, and experience the virtual objects present. Both virtual and mixed reality environments exhibit the same potential characteristics, which make them applicable to the virtual neurorehabilitation context:

- Users are able to initiate training in a simplified environment so that they can easily learn the basics
- Complexity of training can be increased at a pace that the user can manage
- Users can challenge themselves to practice complex movements or simulate risky situations within a controlled and safe environment and without risk of damage to self or equipment
- Users can experience accurate and realistic simulations
- Systems can cater for large numbers of users, even over various locations
- Virtual environments provide a highly visual approach to aid learning
- Systems can allow for peer review, feedback, and ongoing assessment
- VR can deconstruct complex data into manageable chunks and visualize complex concepts and theories
- VR systems can be very cost effective
- VR ensures that learning is motivating, fun, and enjoyable where appropriate
- Users can explore virtual scenarios in preparation for real-world scenarios.

VR has shown effective in areas such as training and learning, data analytics, and in particular, psychotherapy. For instance, in the treatment of special phobias, like fear of heights, fear of flying, or fear of spiders, clients are gradually exposed to fear-evoking stimuli and develop coping mechanisms, which then can be transferred to their real-world behavior. Again, central to the effectiveness of the therapy is the concept of presence and with this the ability of the VR system to evoke the same psychological and physiological responses as in real life, for example, exhibited avoidance behavior or an increasing heart rate. VR therapy environments are safe for the client and the therapist is able to control stimuli, measure responses, and systematically repeat exercises (Rizzo & Koenig, 2017).

Of particular interest in rehabilitation is VR's potential to enhance learning. For instance, in studies of serious gaming in women's health care, Knowles (1970) described four elements important to adult learning:

- Adults are autonomic and want independence in their learning. Gaming promotes an active form of learning and allows independence.
- Adults use their past experience. Gaming facilitates this by offering different scenarios according to experience.
- Adults are goal orientated. Gaming is designed around completion of a level or task.
- Adults tend to be problem-based learners and not content-oriented learners. Gaming provides learning experiences that players can relate to realistic clinical problems.

Hence, in combining VR with elements of gamification, we create highly interactive and engaging environments suitable for virtual neurorehabilitation.

VR is possibly the "ultimate neuroplasticity vehicle." Neuroplasticity, the brain's ability to adapt its functions and activities in response to environmental and psychological change, is mediated by sensations, perceptions, emotions, and, finally, beliefs (Regenbrecht et al., 2014). Through its interactive feedback loop of providing meaningful stimuli to be perceived by and responded to by its users, VR changes the emotional state of the users, and eventually, if effective, alters their beliefs. For example, by visually amplifying goal-oriented movements during exercises, the learned nonuse of the impaired limbs can be counteracted (Regenbrecht et al., 2012, 2014; Ballester et al., 2015). While this belief altering can be exploited and abused in certain scenarios, in virtual neurorehabilitation this ability is directed toward neuroplastic change to regain motor function.

The potential for VR to change beliefs solves a problem that occurs when using traditional mirror therapy: the issue of the patient's potential disbelief. In traditional upper limb mirror therapy, the patient's impaired limb is placed behind an optical mirror; the patient knows that the impaired limb is unable to move and so has to develop a suspension of disbelief when observing their unimpaired limb moving in the mirror for the therapy to take effect. They have to believe that what they see in the mirror is their impaired limb moving. VR is less obvious in its inner workings and can be seen more as "magic" by the patient when they observe their impaired limb "moving" and therefore requires much less belief.

In the following, we present three examples of where virtual and AR techniques have been used for upper limb stroke rehabilitation. All three examples use virtual neurorehabilitation as their main principle, applied in different settings. All aim at maximizing patient engagement and promoting the interplay of neuroplasticity, motivation, and repeated exercise and were developed based on sound technological, scientific, and clinical theory, knowledge, and practice.

EXAMPLE 1: AUGMENTED REFLECTION TECHNOLOGY

While the use of fully immersive, HMD-based VR for physical rehabilitation is still in its infancy, the use of semi-immersive VR and variants of augmented realty systems have been studied for close to two decades (Burdea & Thalmann, 2003; Weiss et al., 2004; Cameirao et al., 2008).

Many of these systems visualize patients' movement through the computer system. Systems like the Rehabilitation Gaming System (Cameirão et al., 2009) and YouRehab (Eng et al., 2007) represent patients' hands with computer generated virtual limbs, whereas Weiss et al. (2004) researched a system that used video capture to integrate the video of the patient's actual body into the visualization.

Similar to therapist-led therapeutic interventions, VR systems aim to optimize the frequency and intensity of a given exercise and to provide patients with task-oriented practice and feedback. These systems both stimulate movement execution and provide visual feedback. VR systems have, however, the capability to provide visual feedback beyond what is possible in traditional therapist-led rehabilitation (Schüler et al., 2015): they enable movement visualization, performance feedback, and context information. Movement visualization includes not only the movement pattern of the limb but also a representation of the limb. A wide range of representations are available, from video images of the real hand or limb to computer generated limbs to abstract representations (Schüler, 2012; Schuler et al., 2013).

Presence in virtual rehabilitation interventions is postulated as important (Schüler et al., 2014), but so too is the use of visual feedback beyond just the accurate representation of the physical reality. For example, use of visual illusions of movement to extend the visual feedback beyond the actual capabilities of the patient are thought to further stimulate and enhance rehabilitation outcomes (Ballester et al., 2015, 2016).

Augmented reflection technology (ART) (Figure 9.1) is a computerized system which was developed based on the principles of mirror therapy, a form of therapy shown in a systematic review of 62 studies to be effective for improving upper limb function and motor impairment after stroke (Thieme et al., 2018). These principles include the provision of mirror visual feedback through the ART system while performing systematic and repetitive practice of standardized hand exercises (Morkisch & Dohle, 2015).

The ART has been studied in several empirical evaluations. In these experiments with unimpaired participants, the "fooling" potential of the ART was demonstrated—participants were fooled about their limb ownership and laterality. For example, participants believe that a hand displayed on the left side of a display screen (see Figure 9.1) is their own left hand when in fact it was just a video of their right hand (Regenbrecht et al., 2011, 2012, 2014).

Clinical studies with the ART have also been conducted: application of the ART with six individuals with chronic stroke in a physiotherapy clinic demonstrated that all six were able to use the system with sustained engagement and motivation (Hoermann et al., 2014). Two additional studies showed that the ART was feasible for use in an inpatient setting as an adjunct rehabilitation intervention in the early phase post-stroke (Hoermann et al., 2015, 2017).

Early evidence of the ART's capability to provide autonomous instructions and feedback without the direct involvement of a therapist has also been shown in a nonclinical study with 28 unimpaired

FIGURE 9.1 Augmented reflection technology system (version 4) in action.

volunteers. In this study, participants were able to carry out a subset of a traditional mirror therapy movement protocol via computerized feedback and instructions only. The system instructed participants to execute motor gestures, assessed the accuracy of the execution, and progressed when the gestures were completed adequately. The system provided continuous as well as summative feedback to participants (Pinches & Hoermann, 2016).

EXAMPLE 2: NEUROREHABILITATION INVOLVING SPECIALISED PHYSICAL DEVICES

An integrated rehabilitation system was created to enable upper limb rehabilitation post-stroke comprising of a set of computer games that could be played using three devices: the Able-B (Sampson et al., 2011); the Able-M (Jordan et al., 2014); and the Able-X (Hijmans et al., 2011) (Figure 9.2). The devices were aligned to the degree of impairment, or weakness presented by the patient and encouraged movements appropriate for their recovery. Figure 9.2 shows the relationship of the components of the system to the patient's strength as measured by the Oxford scale of muscle strength (Parkinson, 2000).

The Able-B provides a mechanical linkage between the hemiparetic and the unaffected arm so that the unaffected arm powered a mirrored motion in the affected arm. The Able-M is an "arm-skate" (an arm version of a skateboard) which enables the stroke survivor to interact with the computer while fully supported on a mobile device on a flat surface (e.g., their kitchen table at home), thus eliminating the impact of gravity and friction to movement.

The Able-X comprises an air-mouse, which coupled both arms so that the hemiparetic arm can be guided through space via gravity resistive movement of the unaffected arm, enabling the hand held air mouse to interact with the computer.

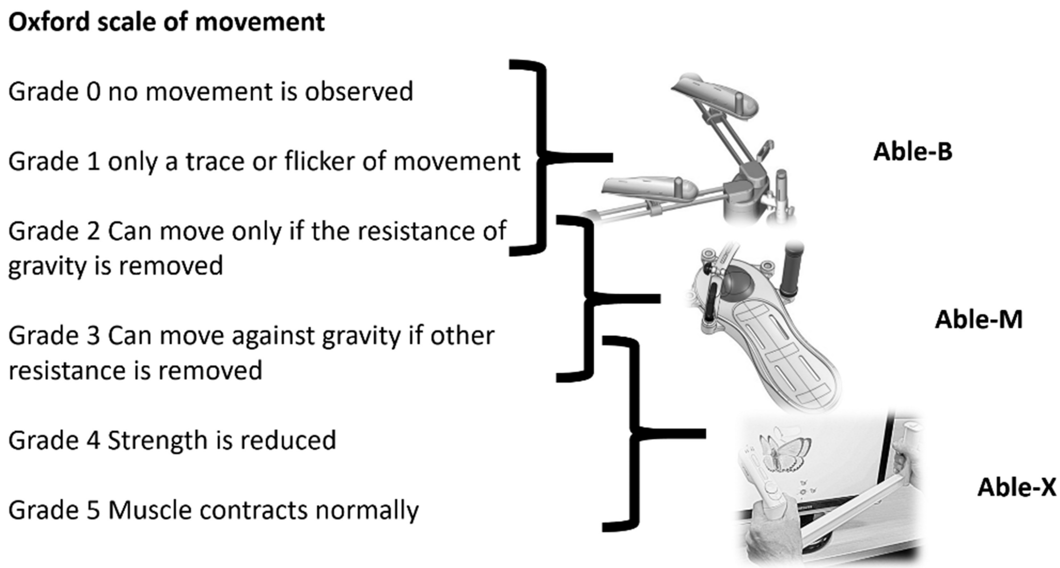

FIGURE 9.2 Able-B, Able-M, and Able-X devices for upper limb rehabilitation and the relationship of the components of the system to the patient's strength.

Computer games were developed using user-centric design principles, as described in King et al. (2010) and Hale et al. (2012), and user perspectives (Lewis et al., 2011). Several factors were identified that motivated stroke survivors to play the games during rehabilitation and these were then included in the game designs:

- Intellectual stimulation during game play
- Feedback (e.g., game scores)
- Physical benefits from the exercise
- Tolerance for disabilities (e.g., game levels suitable for a range of abilities)
- Connecting to the game, i.e., participant understands and relates to the game
- Social interaction during group play.

Furthermore, the games were graded to anticipate the need that some older adults with stroke might require guidance on how to play computer games. Hence, the suite of games started with "easy to achieve" large stationary target reaching games in which random motion of the device would achieve success; graduated to smaller and later, moving targets; then to targets that required manipulation and placement on icons; then to strategic target games; and finally to a choice of sports or mind-challenging games.

As well as the exploratory studies above, the equipment was provided to a small cohort of stroke survivors for unsupervised use in their homes (King et al., 2012). Participants practiced for 4.5–5.5 sessions per week over the 55-day duration of the trial, each averaging 33.5 hours of exercise. This level of exercise was significantly higher than the 16 hours suggested by Kwakkel et al. (2004), or the 15 hours suggested by Laver et al. (2015).

Galea et al. (2016) used the Able-M and Able-B in a 92-participant clinical trial which showed significant improvement in arm function and strength, muscle tone (as assessed by the Modified Ashworth Scale), the Wolf Motor Function Test, the Functional Independence Measure (locomotion, mobility, and psychosocial subscales), quality of life (as measured by the EQ-5D), and overall health. This trial was particularly interesting as it was conducted using a clinical practice improvement approach (Horn & Gassaway, 2007) in a busy clinical practice and it not only improved patient outcomes but it also built capacity in the provision of subacute rehabilitation services. The “Hand Hub,” as the site of the trial was called, typically enabled five patients to be treated at the same time, supervised by one therapist and one allied health assistant. This approach is improving the response of the rehabilitation service to their waiting list by providing a way of streaming patients toward intensive therapy for upper limb dysfunction.

EXAMPLE 3: VIRTUAL REALITY IN HOME-BASED MIRROR THERAPY

VR systems for home rehabilitation have mainly targeted patient motivation and engagement for repetitive exercises by incorporating game elements. These games often consist of tasks that have varying degrees of clinical validity. With the recent emergence of fully immersive VR hardware, it opens the possibilities for new ways to target patients’ home rehabilitation. We present one such immersive VR home rehabilitation system, the ART VR Home (Figure 9.3), which was adapted for home use from the ART system presented earlier.

Immersive VR refers to surrounding a person in virtual content by wearing a HMD as opposed to semi-immersion with a computer monitor. Immersive VR systems have many advantages which include an embodied virtual experience (e.g., mirror therapy illusion), can block out the distractions to exercise presented by the home environment, hardware that is easy to transport and setup. It is also an approach often considered as novel and exciting by patients, and this novelty has the potential to motivate the person to engage in their rehabilitation.

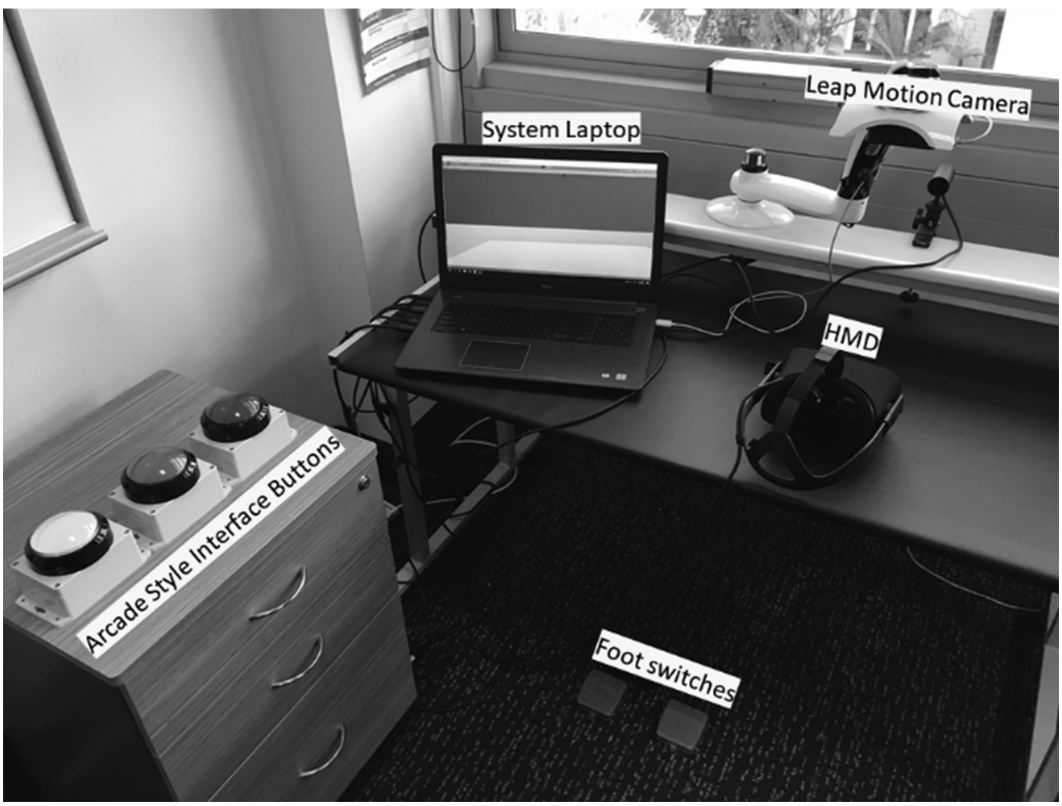

FIGURE 9.3 The ART VR Home system consists of six main components: Laptop to run system, Leap Motion camera for hand tracking, HMD for the patient to experience the virtual environment, arcade style buttons to interact with system outside VR, foot pedals to interact with system inside VR, and a height adjustable desk to place their hands while interacting inside VR.

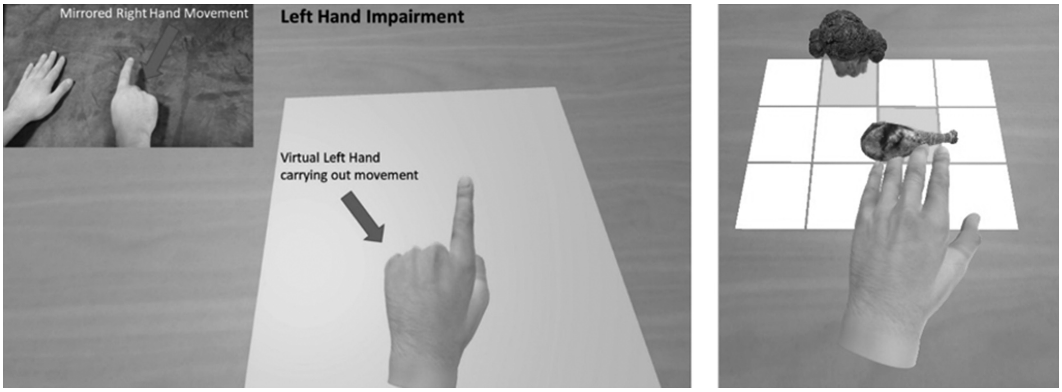

FIGURE 9.4 ART VR home system patient tasks: rehabilitation task (a) and TheraMem memory game (b). This presented scenario is for a patient with a left hand impairment. Our system captures their right (non-affected) hand movement and mirrors this and presents it to the patient in VR such that their left (impaired) virtual hand is performing their mirrored hand movement.

We aimed to provide a home-based VR mirror therapy system suitable for use by stroke survivors with unilateral upper limb impairment that was intuitive and easy to use and that delivered standardized exercises. We worked with the clinicians who had developed a previously used mirror therapy protocol (BeST-ART) and adapted it for use for immersive virtual environments (Figure 9.4). The adapted protocol, the BeST-ART VR protocol, comprised making the numbers 1 through 5 with hand movements, in both the palm down and palm up hand orientations. We also included in the protocol an easy to play memory game (*TheraMem*) that required hand movements to activate virtual tiles (Figure 9.4b). In the rehabilitation task, a virtual computer monitor is placed in the virtual environment and displays an image of the BeST-ART VR hand position. The patient is then asked to copy the position with their hand. In the *TheraMem* task, virtual tiles can be activated to reveal matching pairs of food items.

The clinical ART VR base system comprises four components: a laptop computer to run the VR system, an HMD to experience immersive VR, a hand-tracking camera to bring patients' hand movements into VR, and a height-adjustable table to place their hand on while interacting in the VR environment. As our targeted population are often part of a demographic group that can lack confidence in using computers and technology an easy-to-use, intuitive interface that patients could feel confident operating on their own was necessary. We thus designed an interface that consisted of three arcade style buttons to operate the system outside of VR and two foot pedals to interact with once inside VR (while wearing an HMD). The three arcade buttons corresponded with starting the VR system, changing the VR task to *TheraMem* and changing the VR task back to rehabilitation. The two foot pedals provide patients with the options of moving onto the next hand exercise and showing a virtual training hand (help) performing the assigned hand exercise.

The ART VR Home system runs on a standard (computer gaming) laptop and the hand-tracking camera is a Leap Motion depth sensing camera that is attached to a desk mount arm angled down toward the desk. The desk is a 70 cm × 70 cm height adjustable desk with wheels. The system creates a patient log file every time the system is started which consists of: system time usage, hand exercises completed, how much time spent on each hand exercise/task, and an early prototype of a machine learning classifier to output which BeST ART VR hand exercise the patient was performing.

We conducted a feasibility study with four people with stroke exploring acceptance and usability of the system. The ART VR Home system was placed in participants' homes for four weeks, and they were asked to use the system for a minimum of 15 minutes a day for five days a week (20 days total) and log their use. After a pre-assessment (Upper Limb subsection of Motor Assessment Scale), participants were provided with a 30-minute demonstration of the system and

TABLE 9.1
Participant System Usage over a 4-Week Period

Participant	Days Used	Average Time Used/Day (min:sec)
P1	24	12:00
P2	15	16:37
P3	4	17:22
P4	20	21:56

It was recommended that participants spend at least 15 minutes a day using the system for 5 days a week (20 days in total).

the protocol before having it installed in their home. Participant feedback was gathered through a semi-structured interview at the conclusion of the study. The participant logs were also analyzed to determine how long and often they used the system. Table 9.1 shows that participants were able to use the system for the requested time length; however, the number of days the system was used varied across participants as most reported life events interrupting their schedule (family travel and medical events/procedures).

All four participants were able to complete the study and did not report any adverse events with using the system nor any complaints about having the system in their home. All reported that they were easily able to use the interface (arcade buttons and foot pedals), albeit three classified themselves as not competent with computers. For the rehabilitation task, participants reported they were able to follow the assigned hand exercises shown on the virtual computer monitor within the VR environment; however, they wished there was more variety in the hand positions assigned to them. For the *TheraMem* memory game, all participants found it fun to play but wanted more variety of games to play. Lastly, three participants reported some form of improvement in their impaired limb after using the system (e.g., capable of more fingers movements, able to open fingers more widely, and improvement in shoulder movement).

CONCLUSIONS AND FUTURE WORK

For this chapter, we brought together contributions from clinical and technological virtual neurorehabilitation specialists. VR techniques have been demonstrated to be effective in the rehabilitation of upper limb impairment post-stroke and have potential not only in stroke rehabilitation but also in other therapeutic and rehabilitation areas. Virtual environments are highly controllable and can give immediate and progressive feedback to patients. These environments have the potential for providing unsupervised and semi-supervised rehabilitation and potentially optimizing clinician productivity. We have been able to demonstrate that virtual neurorehabilitation systems are sufficiently motivating for patients to engage in tailored and repetitive movement practice.

In particular, VR can be used to amplify visual simulation and, combined with game elements, potentially enhancing engagement in therapeutic exercises and thus improved outcomes. Tailored applications are preferred over the "black box" applications of commercial games, as individualizing the approach to the patient may result in sustained use after the "wow" effect of the technology wears off.

The biggest challenge is how to implement VR technology into clinical practice. Studies investigating VR have mostly concentrated on chronic stroke populations with marginal results, possibly due to the chronicity of the population with limited recovery potential. More clinical trials are required in acute stroke rehabilitation to demonstrate effectiveness for clinical implementation.

There is significant potential to combine VR techniques with other technical components. Unfortunately, much research in this field is focused on the more complex field of robotics, with associated instrumentation and capital investment. Low-cost and low-complexity systems, such as computer–game interface exercise devices and customized off-the-shelf VR devices tailored to patients' needs will encourage uptake by busy clinical practitioners or by patients in home-based settings. A future focus can be how to integrate rehabilitation technologies with activities of daily living and to make it more meaningful for patients and clinicians.

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