Heading Home – Adapting a Clinical Mixed-Reality Rehabilitation System for Patients' Home Use

Chris Heinrich*
Information Science
University of Otago

Tobias Langlotz†
Information Science
University of Otago

Holger Regenbrecht‡
Information Science
University of Otago

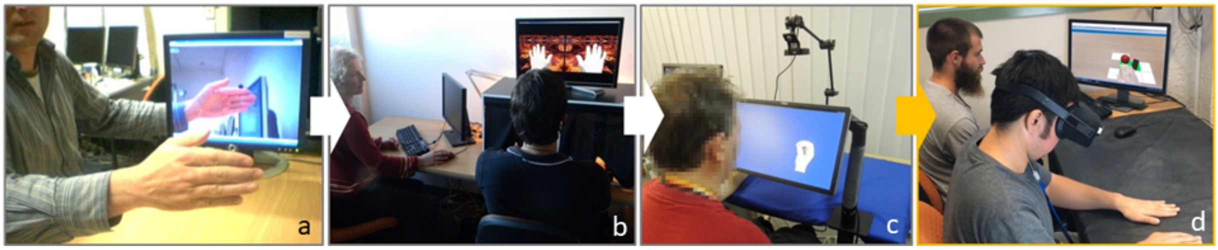

Figure 1: Progression of the different versions of the Augmented Reflection Technology: Traditional Mirror Therapy (a), Dunedin Clinical System (b), Berlin Clinical System (c), and Home Rehabilitation System (d).

ABSTRACT

Over the last decade, there have been countless virtual reality rehabilitation systems make their way from the laboratories into the real world. For one reason or another, this same trend has not occurred for mixed-reality rehabilitation systems. Even less so, are either of these rehabilitation systems making their way to patients' homes for home rehabilitation. As mixed-reality hardware becomes more easily accessible, affordable and accepted; it is becoming more feasible for mixed reality rehabilitation systems to be placed in patients' homes. This brings researchers exciting new possibilities regarding patients' treatments but also new challenges regarding their design/implementation. This paper will discuss adapting one such mixed-reality system, The Augmented Reflection Technology System, in order to allow patients to carry out their clinician recommended rehabilitation at their own home. We present a demonstration system that can be used for immersive home-rehabilitation and discuss future possibilities in the field.

Index Terms: Human-centered computing—Mixed / augmented reality; Human-centered computing—Accessibility system and tools

1 INTRODUCTION

Mirror Therapy was developed by Dr. Ramachandran in 1996 and has been used to help treat many impairments from phantom limb pain to stroke rehabilitation [10]. Mirror Therapy helps the patients' brain re-wire itself by fooling what the brain is seeing, this effect is known as neuroplasticity [4, 5]. Simply speaking, the brain "sees" the impaired limb moving and, therefore, re-wires itself to potentially allow for incremental gain of lost motor function. Previous work has been done to digitalize this illusion and allow it to be carried out in mixed-reality environments. This technology is known as Augmented Reflection Technology (ART) [11, 12, 14].

The ART system has gone through numerous iterations (Figure 1). In the first version of the system, user's placed their hands into two large boxes to decouple their view of their hands [14]. They observed the mirrored illusion on the monitor in front of them (Figure 1-b). Using this system, they firstly evaluated traditional optical mirror boxes against their ART mirror boxes in terms of whether the different setups had any effect on fooling the participants that the mirrored hand was actually their own. They found that participants correctly identified their hands in only 61% of the ART mirror boxes and 71% for traditional optical mirror box meaning they were fooled more often using the ART mirror boxes. They ran a second study which evaluated the effectiveness of the ART mirror boxes and to assess people's confidence in their perceptions and experiences in the system. They found that participant's reported seeing their own limbs in the ART system (97% of time) and that participants were fooled again in the mirroring scenarios (93% of time) [14].

This system was also used to investigate how mirrored/non-mirrored hands are perceived and whether sensations or ownership can be referred [8]. They replicated the original Rubber Hand Illusion (RHI) [2] with the ART system and traditional mirror boxes. They found that participants reported a sense of perceived ownership in both the original RHI and video-mediated RHI, but there was no significant difference between conditions. This showed that the ART system could be a valuable tool to induce ownership perception which is a prerequisite for positive therapeutic outcomes.

Practicing Mirror Therapy Clinicians/Neuroscientists created the Berliner Spiegeltherapieprotokoll (BeST Protocol) [9] which provides clinicians with a standardized, documented procedure for therapists to carry out mirror therapy with their patients. The BeST protocol consists of a number of different clinician-recommended hand exercises patients can perform. This protocol was later validated with the ART system (discussed in Section 2) and eventually the protocol was adapted specifically for the ART system (BeST-ART) [6, 7].

Our mixed-reality rehabilitation system is targeted for stroke patients who are suffering from unilateral, upper limb impairments and, therefore, are suitable candidates for Mirror Therapy. In our virtual neurorehabilitation mirror therapy scenario, patients hands are captured and placed in a virtual environment where they can use a mirrored version of their healthy hand to visually mimic the movements of their impaired hand.

While home rehabilitation has been largely unexplored, there have been a few notable systems that made the journey to patients' homes. Standen et al. [15] carry out mirror therapy in a home setting by attaching infrared markers to the patients' fingertips and these were tracked by a Wii remote (and the illusion was observed on a computer monitor). They were given different games they could

*e-mail: heinrich.chris@gmail.com
†e-mail: tobias.langlotz@otago.ac.nz
‡e-mail: holger.regenbrecht@otago.ac.nz

play and found significant difference between intervention/control groups based on the Wolf-Motor Test. Wittmann et al. [17] provide a system which attaches wireless inertial measurement units to the patients body and patients are able to play two games aimed at aiding recovery. They found that patients used the system quite considerably on their own, despite being told to use it at their discretion. They reported an average training duration of 137min/week (30min per session) and that 8/11 patients would have liked to continue training with the system at their home after the trial was over. Most importantly, they reported a significant improvement in patient Fugl-Meyer assessments after the 6 weeks. Finally, other relevant research has been done on the practical barriers for home-based research [16] and a comprehensive systematic review of home-based technologies for stroke rehabilitation [3].

In this paper, we describe the two ART systems that were used in a clinical setting and the patient results acquired. We describe the changing requirements that happen when moving a MR rehabilitation system from a clinical setting to a home setting. Finally, we present our home-based rehabilitation system and current/future work.

2 Clinical Systems

In this section, we describe the Berlin (Germany) and Dunedin (New Zealand) ART systems which were used in a clinical setting with patients.

Dunedin Clinical Version

The Dunedin Clinical Version of the ART system (Figure 1-b) contains two fiber-board boxes (370mm x 370mm x 370mm) where the front of the box is left open. A curtain is placed over this opening such that when your hand goes into the box, you cannot see it anymore. A wide-angle Logitech Quickcam Pro9000 webcam (80°FOV) is mounted on the roof ceiling of each of the boxes (facing towards the bottom of the box). Lighting was placed in the box and consisted of a grid of 4x4 high power LEDs. The bottom of the box is covered in matte black cloth. This system is ran on a low spec, standard desktop computer consisting of: Windows XP SP3, 4GB RAM, on-board graphics which supports OpenGL 1.1.

Hoermann et al. [7] ran a study at different Dunedin rehabilitation centres which consisted of twelve stroke patients who were after the acute phase, but still inpatients. The purpose of this study was to look at the ART system (in conjunction with BeST protocol) as an adjunct therapy in addition to their regular rehabilitation and hospital commitments. The protocol of the therapy was similar to the one in the Berlin Clinic study [6]. They found that patients were able to attend most of the sessions (average of 9 attended sessions out of 12 assigned). This was enough to meet the minimum number (8) of sessions for a complete cycle of the BeST protocol. Clinical assessments showed that most patients improved with five patients gaining the ability to handle pegs (for the Nine-hole Peg Test), three patients improved their timing in the Nine-Hole Peg Test and seven patients ratings in the Stroke Upper Limb Capacity Scale increased.

Berlin Clinical Version

The Berlin Clinical Version of the ART system (Figure 1-c) consists of a 22 inch computer monitor (Dell UltraSharp 2208WFP, 1650 x 1080 @ 60Hz) placed in front of the patient to decouple their view of their hands. A Creative Senz3D webcam (1280x720 @ 30fps, 72°) is placed behind the monitor (looking down towards the table) to capture the patient's hands. The webcam is attached to a standard camera stand fixed with a universal mount to the table. The computer is a Dell Optiplex 9020 with an Intel Core i5 4670 CPU and 8GB RAM. A blue cloth is placed on the table where the camera is capturing. The software was built in Unity3D (v4.3.5) on a Windows 7 Enterprise 64bit SP1 operating system. To process the camera image, a custom plugin was written that used the Intel

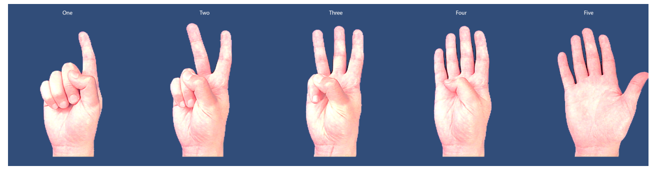

Figure 2: Example subset of the BeST [9] (Clinician-recommended) hand exercises that patients are tasked with carrying out in our Clinical/Home Rehabilitation systems.

Perceptual SDK (v1.8.13842) to interface with the Senz3D webcam and OpenCV(v2.4.9) for video manipulations. The captured image is then split into two images (each sized 640x480) which would represent the left and right hand.

Hoermann et al. [6] ran a clinical feasibility study using this system with five stroke patients (all within 3 months after stroke). They looked to validate the combination of the BeST [9] protocol for mirror therapy with the ART system. They found that all patients were able to perform the required exercises in each session from the BeST protocol with no adverse events reported. Clinicians reported that patients concentrated their attention on the mirrored hand, the vigilance of their patients was high and that the level of difficulty of the exercises were never rated too easy nor too challenging (1.4 average on a scale of 0-3). 3/5 patients showed some improvement on their Fugl-Meyer hand scores. Importantly for this paper, 4/5 patients reported that they could imagine using the system at home.

3 Home Rehabilitation System

3.1 Concept

The goal of our Home System is for patients to be able to carry out their clinician-recommended (BeST) hand exercises at their own home without the clinician being present. The system should be easily transportable, adaptable to be able to be moved to patients homes and can be easily integrated to their existing room layouts. The patient must be able to control and operate the system which means their impairment must be taken into account when designing an interface for such a system.

3.2 Changing Requirements

Adapting the Clinical Systems to fit our conceptual design meant defining what requirements have changed for the new home environment.

- **R1: Limited Space**
  Patients' living arrangement must be taken into account and the system must be robust enough to withstand being potentially bumped into and/or moved around.
- **R2: Clinician not being present**
  The clinician being absent during the patient's rehabilitation leads to numerous potential issues such as:
  - How does the patient know what to do while in the system?
  - How does the clinician know what their patient is doing?
  - How does the clinician know if they were performing their rehabilitation correctly?
- **R3: Clinician not operating system**
  Another side effect of the clinician not being present is that they won't be there to control the rehabilitation system and the patient will have to do it themselves. We need to design an intuitive interface that allows the impaired patient to control the system and what is happening inside without spending lots of time learning how to use the interface.

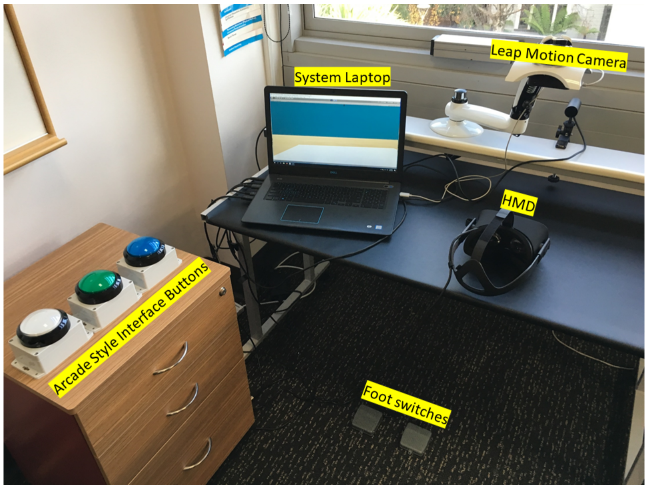

Figure 3: Demonstration of the Home Rehabilitation System setup which includes: three "arcade" style buttons (left) to operate the different system modules, two foot switches (under table) to interact in system while wearing HMD, and a desk with wheels that can easily moved around a patient's home.

3.3 Implementation

We addressed these changing requirements by implementing an immersive mixed-reality rehabilitation system that allows for home-rehabilitation for stroke patients with one-sided impairments.

3.3.1 System

The Home version of the ART system (Figure 3) is run on a 17inch laptop computer (Dell G3 17) which consists of a display screen (1920 x 1080 @ 60Hz), 16GB RAM, NVIDIA GeForce GTX 1060 6GB DDR5, and a Intel Core i7-8750H CPU. A Leap Motion depth sensing camera is attached to an adapted computer monitor desk mount (Digitech Desk Mount Articulating Arm CW-2870) which is angled downwards (towards the desk) and attached to an adjustable height desk with wheels. Black infrared absorbent cloth is placed on the desk for optimal tracking conditions. The patient's interface consists of 3 Arcade style buttons (EG STARTS 100mm) and two foot switches (250V Voltage Rating, 10 AC Current Rating, 80mm x 30mm x 80mm) which are connected via 5pin DIM connectors to a USB Encoder (EG STARTS Zero Delay USB Encoder). The head-mounted display that the patient uses to experience the immersive virtual rehabilitation scene is an Oculus CV1. The Oculus tracking camera is attached to the desk (directly in front of where the patient would sit) and is aimed straight towards them.

Our system was built in Unity3D (v2017.3.0f3) on a Windows 10 Enterprise 64bit (1703) operating system. The Leap Motion uses the Orion SDK (4.0.0+52173). For the machine learning, we use Google's Tensorflow [1] to train and test our model. This was done on the same laptop via a Linux (Ubuntu 16.04 LTS) VirtualBox (5.2.12). The interface (Buttons and foot switches) don't require drivers and are plug and play. The Oculus application (1.38.0.261475) and HMD firmware (709) were kept consistent throughout the implementation.

We have kept a minimalist virtual environment in accordance with the clinician recommendations from the BeST protocol [9]. They stipulate that there should be no distractions inside the patient's rehabilitation space so that the patient can fully focus on the mirrored illusion. Our virtual environment, therefore, consists of simply a table with two computer monitors on it (System Help - 3.3.4) with a neutral (gray) background . There is a white plane defined where the patient is encouraged to keep their hands within at all times (optimal Leap Motion tracking conditions).

Our Home Rehabilitation System currently consists of two modules:

Rehabilitation
In this module, patients are allowed to carry out their prescribed hand exercises at their discretion. They are shown an image of the current hand exercise they are being asked to perform and are able to watch a demonstration of that movement (via Virtual Training Hand - 3.3.3) if they wish. The patient then performs that movement to their satisfaction and moves on to the next prescribed hand exercise. This repeats until they have completed all the prescribed hand exercises.

TheraMem
In this module, patients are allowed to play a memory game called *TheraMem* [13]. This memory game consists of 12 tiles placed in front of the patient . There are 6 pairs of matching food items hidden beneath the tiles and the goal is to find all the matching food pairs. Patients are able to interact with this game using their mirrored hand.

3.3.2 Interface

The interface was kept as simple as possible to allow stroke patients confidence in using the system without the clinician being present. The laptop logins automatically and the VirtualBox/Oculus software launches on start up. The patient presses the green button to start the system, the blue button for the *Rehabilitation* module and the white button for the *TheraMem* module (the patient does have to take the HMD off to switch between modules). The two foot switches are to be used during the *Rehabilitation* module and correspond with "Show Virtual Training Hand" (left foot switch) and "Next Hand Exercise" (right foot switch).

Before the clinician sets up the Home System in the patient's home, the clinician will update a patient configuration file that contains information regarding the patient's impairment (left or right side), task to carry out and the difficulty of the task. With this information, the system will set the mirror therapy condition (based on right side or left side impairment), determine which hand exercises to prescribe and difficulty (random order or incremental).

The tasks patients will be prescribed by their clinician are to carry out different BeST [9] hand exercises. These will start out as making the numbers one through five with the patient's palm face down. If they are able to achieve this, they can move on to making those same numbers with their palm face up. Difficulty can be increased by making the ordering of the numbers random (i.e. not incremental) and also by combining both sets (palm up and palm down exercises).

3.3.3 Virtual Patient Training

To help demonstrate the hand exercise to patients while they are immersed in our virtual environment, we implemented a *Virtual Training Hand* (Figure 4 - slightly transparent hand on right). This training hand is a seven second recording of the hand exercise currently prescribed to the patient. The patient's impairment has been taken into account for this training hand as well (e.g. left hand impairment means they will see a left training hand carrying out the movement and vice versa for right hand impairment). For the patient to view the training hand, they press down on the left foot switch and then the training hand will appear and carry out its recorded movement and then disappear. The training hand is positioned next to patient's mirrored virtual hand depending on the impairment (e.g. In Figure 4 with a left hand impairment, the training hand is left handed as well and positioned to the right of the patient's mirrored left hand and vice versa for a right side impairment). The virtual training hand was made slightly transparent to make it obvious that it is not the patient's mirrored hand. The patient is able to freely

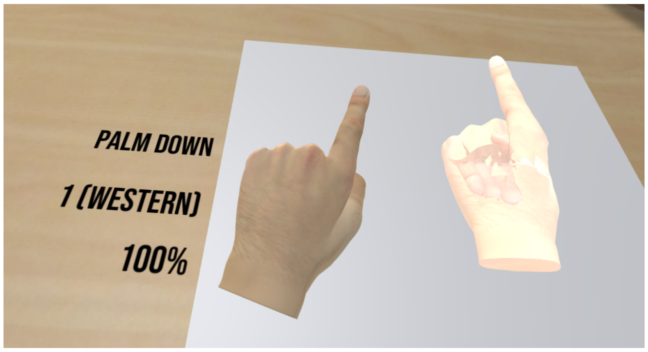

Figure 4: Example scene from our Home Rehabilitation System which shows the machine learning classification (left), patient's mirrored hand (middle) and Virtual Training Hand (right).

use their mirrored virtual hand while the training hand is playing its recorded movement.

3.3.4 System Help

To provide the patient with help while in the immersive virtual environment, we introduced two *Help Monitors* into the virtual environment. These monitors are placed on top of each other just slightly out of the patients gaze (on right side of virtual desk) while they are carrying out their BeST hand exercises. This is following clinician recommendations to not distract the patient while they are carrying out their rehabilitation tasks. The top monitor displays simple interface options for the patient to easily remember if they forget. The bottom monitor displays the current hand exercise they are prescribed to carry out. The concept is that if the patient forgets what the interface options are or what hand exercise they are carrying out, they can quickly gaze up to gain context and then go right back to their (distraction free) rehabilitation exercises.

3.3.5 Machine Learning

We have implemented a machine learning approach as a means for hand gesture recognition inside our system. Using the data available from the Leap Motion SDK, we identified 32 unique features for each hand that are captured in real time. These features consisted of: distance between fingers, distance from fingertips to the palm, and direction of the finger (expressed as 3D vector). Position of the fingers/hand was explicitly excluded as we wanted the model classification to be position invariant (where the patient's hand is on the desk has no effect on the model). We used the Tensorflow estimator class to train a Deep Neural Network (DNN) which consisted of 3 layers (1048, 512, 256). We identified 20 classes per hand to train the model on. These 20 classes are hand exercise positions from the BeST protocol. There are 20 classes to account for numbers 1-5 (palm up and palm down) and for numbers being expressed differently in different cultures (e.g. German number 1 is with the thumb extended compared to with the index finger extended for english cultures). 50 instances of each class (BeST hand exercise) were taken inside our system and used to train the DNN model. This model was exported to a TensorFlow ModelServer which was then used to classify continuous test data (via REST api) from the patient's current hand position while they are using the system. The end result is shown in Figure 4 where the system is able to classify patient's hand positions into BeST hand exercise positions. The percentage shown is the confidence of the trained model regarding the current test data. It should be noted this is how confident the model is in its classification but not feedback for how well the patient is actually performing the movement (discussed in future work).

3.3.6 Clinician Monitoring

To allow for clinicians to monitor what their patients are doing inside the system, we implemented a detailed log file (.csv) that records patient activity while in the system. The log system creates a time stamp at every "event" in the system. These events include: system start/stop, patient information, and prescribed hand exercise order, current hand exercise, and the machine learning classification for the patient's current hand position (if they are currently performing their BeST hand exercises) every 0.5 seconds. The clinician is able to view this .csv file and view what the patient was doing in the system in chronological order (with detailed time stamps for every event).

3.4 Current / Future Work

3.4.1 Clinical Trial

The Home Rehabilitation system is being placed in Dunedin and Berlin rehabilitation clinics with a clinical trial to begin shortly. The aim of this trial is to evaluate the Home Rehabilitation system in a clinical setting before being placed in patient's homes. We will evaluate patient's recovery through clinician assessments (Fugl-Meyer, etc) and the usability of the system.

3.4.2 Patient Assessment

We would like to add an assessment module to our Home Rehabilitation system. The concept for this is that, at clinician determined intervals, patients would perform an assessment (inside our MR system) which can be used to keep track of their rehabilitation progress. We foresee it being similar to the work by Wittmann et al. [17] who, in their home system, validated their own (in system) assessments against the Fugl-Meyer assessment and found that there was significant correlation between them.

3.4.3 Patient In-System Feedback

Implementing in-system feedback for the patient while they are carrying out their BeST hand exercises has been a challenge. Our concept would be for the percentage shown in Figure 4 to correspond with how close the patient's current hand position is to completing the prescribed hand exercise. Currently that percentage represents the DNN model's confidence in it's classification, however, this has no correlation with how well/close the patient is actually performing the hand exercise. We will need to work closely with clinicians regarding this aspect as the feedback provided to the patient during rehab must have clinician validity.

4 Conclusion

In this work, we described two Mixed-Reality rehabilitation systems that use ART to help stroke patients recover by fooling their brain and promoting neuroplastic effects. We presented the clinical results acquired from multiple studies that were ran using those systems. We discuss the changing of requirements when moving a MR rehabilitation system from the clinics to patient's homes. We presented our demonstration system that was adapted from those two systems for home-use. We discuss decisions that went into that system's design/implementation and current/future work with this system.

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