Interactive Haptics for Remote and On-Site Assessment of Arm Function Following a Stroke

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In loving memory of my father, forever missed, never forgotten.

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I also want to thank my mother. Without her, I may never have found this path of study and thus would not be able to contribute valuable research insights to the broader community that may help other stroke survivors in the future. Finally, I would like to thank my father for always believing in me and being proud of me whatever I chose to do. He was an inspiration, and I miss him dearly.

Abstract

There is a great need to improve the rehabilitation and assessment of arm and hand function of stroke survivors in the home due to cost, time and availability of healthcare professionals. Robotics and haptic technologies can be used to improve and facilitate rehabilitation and assessment in the home. The primary goal of this thesis was to explore the feasibility of using lightweight, low-cost haptic devices for remote home-based rehabilitation.

The strategy that this thesis followed was to develop tools, perform unit testing, and finally assess feasibility with target users in a series of case studies. The thesis started by developing an assessment tool, specifically the Nine Hole Peg Test (NHPT), and investigated how haptic devices can be used to enhance the data collection for this task to garner more information regarding the level of manual dexterity a stroke survivor has in their impaired limb. The next study investigated collaboration in haptic environments and how the findings from a collaborative haptic experiment could be used to influence task design for future experiments with haptic environments. The final study assessed the feasibility of a home-based assessment and rehabilitation system with elements of telerehabilitation and remote collaboration and interaction providing four complete case studies from stroke survivors.

In summary, our findings showed that by combining physical apparatus with a virtual world, less variable results are observed than in purely virtual haptic tasks. We also showed that interaction techniques in collaborative haptic environments change depending on the shape of the objects in the virtual task - this information can be used to influence task design to target specific motor deficits when using the device for exercise. Finally, the home-based study showed the feasibility of using the experimental rig at home and provided improvement measures that matched the perceived benefits to arm function that the participants described on completing the trial.

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Introduction

Every two seconds, someone in the world will have a stroke (Stroke Association, 2018), and stroke is the second leading cause of death worldwide (Lawrence et al., 2001; WHO, 2017). Upper-limb impairment is common after stroke, and support for improving gross and fine-motor control skills after discharge from the hospital often varies depending on the treatments that are provided by local health services (Stroke Association, 2018). Many hospitals follow early supported discharge policies to ensure that they are not over capacity (Patel et al., 2017); however, further intervention quickly reduces leaving stroke survivors feeling isolated and still requiring rehabilitation (Broeren et al., 2002; Reinkensmeyer, Lum, & Winters, 2002). Haptic technologies — providing the sense of touch — are being increasingly sought after to promote access to rehabilitation in clinics and at home to assist in the rehabilitation of upper-limb impairment following a stroke (AbdulKareem, Adila, & Husi, 2018; Amirabdollahian et al., 2014; Tobler-Ammann et al., 2016).

Rehabilitation following a stroke is an expensive and complicated task that can involve many carers and therapists and also impact family and informal caregivers (Stroke Association, 2018). Using robotics and VR-based environments to assist in therapy and rehabilitation following stroke is not new (Brewer, McDowell, & Worthen-Chaudhari, 2007; Harwin et al., 2006; Kwakkel, Kollen, & Krebs, 2008; Prange et al., 2006); however, there is still much to be learned about the approaches and tasks that can be simulated and improved upon when using robotic-based treatment and assessment versus a more typical clinical setting. In recent years, there has been a surge in the commercial availability of haptic devices. These devices aim to immerse users in virtual environments by offering an enhanced level of stimulation via force-feedback delivered through an arm or gimbal or a joystick. Many of these devices are aimed at the gaming market (e.g. the Novint Falcon), but they also show great potential for use in a rehabilitation or therapy setting: the devices are low-cost, are of a small form-factor, and are easily portable so can be used comfortably in a person's home. They offer a level of force-feedback that can elicit a muscular response from the person using the device. Point-by-point data can be read and recorded from the device whilst the user is interacting so that outcomes can be measured, and further interactions can be modified or tailored to the user's responses (a dynamic feedback loop).

A significant challenge for continuing treatment, exercise and rehabilitation following discharge from a clinic has been to continue treatment at home (Johnson, Loureiro, & Harwin, 2008). The focus of this PhD thesis is to highlight the use of haptic devices as tools for fine-motor assessment (chapter 3: Embedded NHPT). Also, this thesis demonstrates the utility of haptic devices as comprehensive, home-based assessment and exercise systems for the rehabilitation of fine-motor skill in the hand, wrist and arm (chapters 4 and 5).

The haptic device chosen for investigation in the experiments presented in this PhD thesis is the PHANTOM Omni® (https://www.3dsystems.com). We explore its use as an assessment tool and rehabilitation device for the improvement of arm function following a stroke and other neurological conditions. We conducted three experiments under this path of study: Experiment 1, an embedded reality approach to the Nine Hole Peg Test (NHPT); Experiment 2, collaborative interaction in a haptic environment; and Experiment 3, a 12-week-long home-based rehabilitation study. Figure 1.1 depicts how the research output from the first two experiments contributes to the design of the third and final experiment of the thesis: the home-based rehabilitation study.

Experiment 1 (chapter 3) investigated a novel interaction technique for performing the NHPT: using an embedded reality environment. Our work produced a platform for the design of future embedded reality variations of clinical assessment tools, presented at ICORR 2011: *Using an Embedded Reality Approach to Improve*

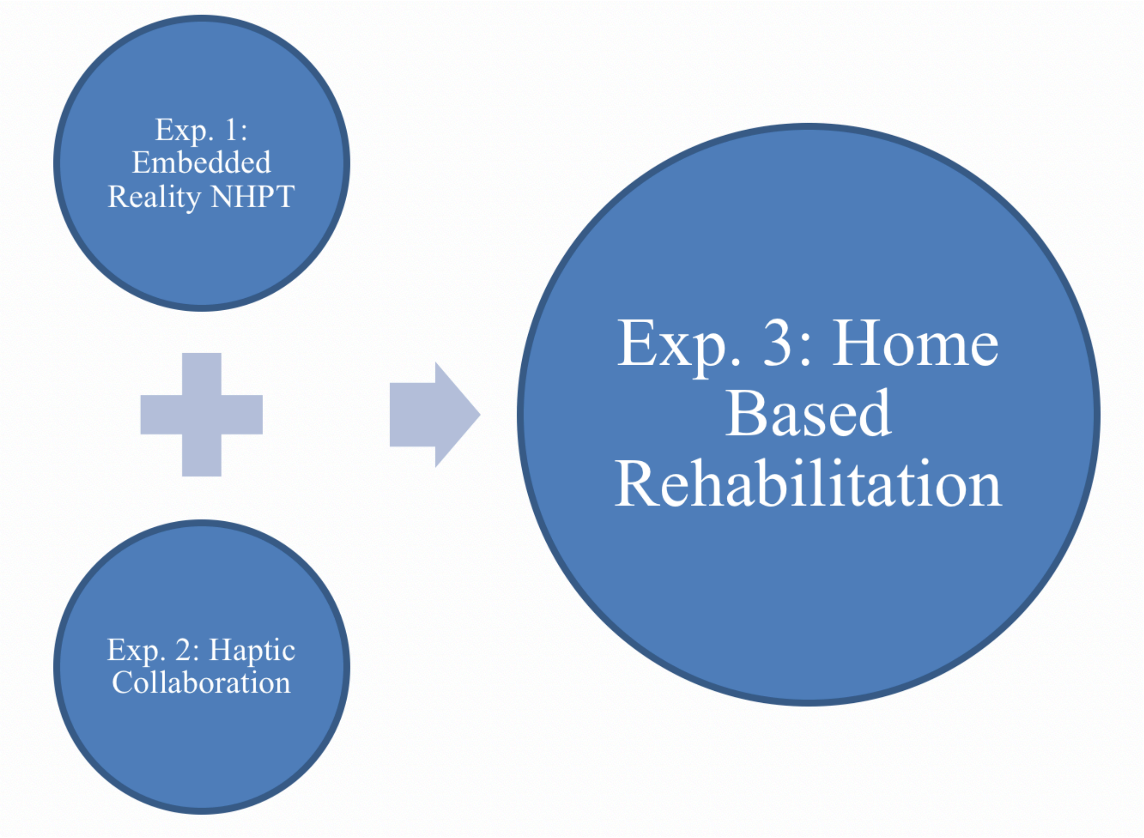

Figure 1.1: **Experiments Conducted.** This diagram shows the experiments that have been conducted for this path of research. The outcomes of the first two experiments were used to drive the design and implementation of the third and final experiment: Home-Based Rehabilitation.

Test Reliability for NHPT Tasks (Bowler, Amirabdollahian, & Dautenhahn, 2011).

Experiment 2 (chapter 4) used a virtual environment modelled on the sorting blocks game designed for children, allowing remote collaboration in a shared haptic environment. This study was part of a three-day experiment at the London Science Museum with over 300 healthy participants.

Experiment 3 (chapter 5) used the haptic assessment tool developed in Experiment 1 (the Embedded Reality NHPT) and combined it with a suite of haptic rehabilitation exercises which included the collaborative environment developed in Experiment 2. This experiment was conducted as a long-term study with four stroke survivors with a research goal of determining the efficacy of haptic assessment tools for rehabilitation at home.

1.1 Motivation

As the prevalence of ICT increases in our everyday lives, we see a rise in efforts to utilise Virtual Environments (VEs) and Robotics for health and rehabilitative purposes (AbdulKareem et al., 2018; Broeren et al., 2010; Butler et al., 2017). Many studies have also shown promising results that robotic interventions can lead to functional gains in motor control and strength (Kwakkel et al., 2008; Mehrholz et al., 2012; Prange et al., 2006). This thesis aims to enhance the value of previous research by showing that, through the use of haptic devices, current rehabilitation and assessment techniques can be improved, and to show that a viable platform for rehabilitation can be integrated into users' homes post-clinical rehabilitation.

Emerging from the field of rehabilitation robotics is the area of 'assessment robotics'. This sub-field aims to define how robotic tools that have been used to rehabilitate patients can be used for assessing specific deficits, such as motor-skill impairment, reduced range of motion, or loss of proprioception (Brewer et al., 2007; Dukelow et al., 2010). There is still a lack of clinically verified technology-based outcome measures for assessing arm function following a stroke (McKenzie et al., 2017); thus it is essential to drive forward progress in complimentary robotic assessment tools that can be validated against their clinical counterparts - as per our Embedded NHPT experiment.

Additionally, the field of telerehabilitation is also gaining popularity for research, due to the ability to reduce costs by performing rehabilitation in the home with a system to feedback information and live-interaction to the clinic (Butler et al., 2017; Johnson et al., 2008; Linder et al., 2013). By coupling improved, measurable, robotic assessment tools with a setup that allows for the assessment and therapy of arm function in the home are crucial at a time where access to care is becoming increasingly limited.

1.2 Research Goals

Following an initial review of current studies and projects researching haptic-based stroke rehabilitation, some fundamental research questions have been identified which will be addressed by this PhD thesis:

Q1: *Can the PHANTOM Omni® be used as a method of assessing fine-motor control skills?*

The first area identified for investigation is the creation of haptic environments for the assessment of arm function. We[1]chose to focus on the NHPT which is a measure of fine-manual dexterity commonly used to assess stroke survivors (Wade, 1992). Previous work has shown that tools such as the NHPT can be recreated using haptic technologies, however with varying results (Amirabdollahian, Gomes, & Johnson, 2005; Emery et al., 2010; Feys et al., 2009; Fluet, Lambercy, & Gassert, 2011; Xydas & Louca, 2007). We aim to enhance previous work by creating a version of the NHPT that uses embedded reality to deliver less variable results than a purely virtual approach. This will be achieved by collecting haptic data, using the PHANTOM Omni® haptic device, from healthy users performing haptic and standard versions of the NHPT.

Our approach to the NHPT differs from that of current investigation in the NHPT problem domain: we chose to pursue an Embedded reality setup rather than relying on virtual reality. As discussed in the *Background* chapter of this thesis, virtual reality systems do not provide the physical anchor to the real world that is required to improve proprioception in virtual environments. As we are creating an assessment tool, it is vital that the user can act as accurately as possible within the environment uninhibited by the loose constraints of a virtual environment. Our embedded setup can be accurately measured and provide an outcome much

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[1] 'We', 'Our', and similar words suggesting a group or team are used out of stylistic choice; all the work presented in this PhD thesis was carried out by the author.

more closely related to the outcome of the physical pegboard than what can be achieved with virtual reality alone.

Q2: *Can we identify key traits and movements of users of haptic environments to design better haptic rehabilitation environments?*

Using the PHANTOM Omni® haptic device, it is a simple task to record and track movements, velocities, forces and positional data within the virtual environment. We want to investigate whether specific patterns or types of actions can be seen in users when interacting with different shapes and when collaborating in pairs, and also to identify specific areas of difficulty for individual users, as would be needed in a remote patient-clinician interaction scenario. To support this, we conducted experiments aimed at exploring these factors to determine variables that could be adapted in real-time to meet the needs of specific users in future systems.

Q3: *Is the PHANTOM Omni® a viable platform for producing home-based rehabilitation systems for hand function following a stroke?*

Following the outcomes of the previous research questions, we created a system that combines assessment tools and haptic rehabilitation exercises in a long-term study (12 weeks) with participants who have upper-limb impairment following a stroke. This experiment will provide four complete case studies to demonstrate outcomes for long-term patient-robot interaction in a home-based exercise-led assessment setting. This study aims to demonstrate the feasibility of our haptic system, including the assessment tools defined in chapter one, for use in a larger scale trial.

The final study aims to build on the work from the first two studies in chapters 3 and 4. The final study utilises the ENHPT assessment tool for measuring arm function throughout the course of the experiment. The interactive haptic techniques built for use by the study in chapter 4, drove forward the development of the system presented in chapter 5. The collaborative haptic environment was used in combination with other tasks to see if similarities could be seen between the way that healthy users interacted with the system versus that of the stroke survivors interactions.

1.3 Platform

The haptic device used for all of the experiments described in this PhD thesis was the PHANTOM Omni®, this is a relatively small haptic device, with a stylus or pen-like grip. The device allows for three active degrees of freedom and three passive degrees of freedom, where an *active* degree of freedom is one where the stylus exerts a force on the axis of movement (x, y, z), and a *passive* degree of freedom is where no force is presented, yet the movement is still translated to the environment $(yaw, pitch, roll)$. The device provides force feedback in all three axes (Cartesian coordinate system), with the added ability to record the orientation of the stylus. The haptic environment was built using the H3DAPI (https://sensegraphics.com/research-and-h3d-api/), which allows for rapid prototyping of 3D environments with the use of an XML SceneGraph and the Python programming language. Haptic force-feedback is generated at the rate of 1000Hz and haptic interactions, shapes, and models can all be customised by writing C++ application code.

Data collection for all of the experiments described in this thesis was performed by collecting log files from the H3DAPI system. By default, logs for the position, orientation, velocity, forces, and button states can all be logged in the form of tab-delimited plain-text files at the rate of 100Hz. We modified the logging code in the H3DAPI to be able to write event strings to the end of each log line whenever a key action had occurred in the haptic environment, such as placing a peg in a hole. Data analysis of the files was conducted using Microsoft Excel, IBM SPSS, and the Anaconda Python package suite that included the Numpy, Scipy and matplotlib libraries.

The experiment protocols and haptic tasks developed were different for each of the experiments that were conducted; thus, this thesis is split into three main chapters.

1.3.1 Chapter 3: Using an Embedded Reality Approach to Improve Test Reliability for NHPT Tasks

The experiment developed for this chapter took an existing assessment tool commonly used for the assessment of arm function following a stroke: the Nine Hole

Peg Test, to address the first research question of this thesis. We created two separate implementations of the task: a virtual NHPT using the PHANTOM Omni® and a laptop, and an embedded reality version of the tasks where, in addition to the PHANTOM Omni® and laptop, there was a physical pegboard present. The premise of the experiment was that the embedded reality approach would improve both task performance and reliability. We developed a new haptic shape for the H3DAPI to simulate the peg-in-hole interactions required for the NHPT task. The peg-hole interaction was implemented following the formulae and methods described by Amirabdollahian et al. (2005). The experiment was conducted with the assistance of 60 healthy volunteers of varying ages at the University of Hertfordshire.

1.3.2 Chapter 4: Interaction Techniques of Stroke Survivors and Healthy Subjects in a Haptic Collaborative Task

For this experiment, we modelled a haptic environment on the children's sorting blocks game: a traditional toy used to help the development of fine-motor skills and shape recognition. We made this a collaborative exercise by networking two laptops together, and each laptop was connected to a PHANTOM Omni®. To achieve this, we wrote a networking layer in the H3DAPI that used UDP to synchronise the haptic environments over the network and allowed participants to interact with each other remotely. There were two experiments conducted with this system: one at the Science Museum (London) with over 300 participants, and the second as part of the home-based rehabilitation trial that we conducted with four stroke survivors. This study was aimed at answering our second research question allowing for the investigation of collaborative movements in a haptic task.

1.3.3 Chapter 5: A Home-Based Haptic System for the Assessment of Arm Function Following a Stroke

The final experiment that was conducted to support this path of study was a 12-week trial with four stroke survivors recruited from a local stroke group. The study consisted of 14 sessions: an initial assessment session, 12 exercise sessions, and a final assessment session. The first exercise session started four weeks after the initial assessment session and continued three-times-per-week for four weeks, with the final assessment session conducted four weeks after the twelfth exercise session. This experiment was developed to investigate our third and final research question providing a set of case studies for assessing the viability of a haptic assessment and rehabilitation system for use in the home.

The tasks developed for the experiment took ideas from many previous studies. The ENHPT and VNHPT tasks were both represented, but also developed was a ‘Clock Targets’ task aimed at assessing participants reactions to perturbation forces influenced by (Patton & Mussa-Ivaldi, 2004) and a haptic guidance task aimed at reducing resistance to movement and muscle stiffness. These tasks were all developed using the H3DAPI with minor customisations.

1.4 Contributions to Knowledge

This PhD thesis focusses on interactive haptics for remote and on-site assessment of arm function following a stroke. To address the first research question of this thesis, one of the objectives was to develop an improved version of the NHPT that would provide the ability to monitor strength, speed/velocity, accuracy and other measures. These recorded metrics could be used to gain valuable insights into arm function and fine-motor skill above what can be determined by the current NHPT. Our approach also aimed to provide the results in a reliable and repeatable way. Our novel approach to this objective was the embedded-reality version of the NHPT task which coupled a real pegboard with a haptic-virtual environment.

Our embedded reality approach to the Nine Hole Peg Test also has further ramifications for other virtual rehabilitation and assessment tasks, where reducing the cognitive load required to perform tasks in the virtual realm by providing physical anchors (e.g. the pegboard) could improve task performance, test-retest reliability, and the accuracy of measurements taken by such systems.

Another objective of this research has been to investigate methodologies for remote collaborative haptics and home-based rehabilitation. The research presented here has explored ways in which shape size and appearance can influence how participants interact in virtual domains and, discusses how this knowledge could be used to design better systems for rehabilitation (research question 2). We also present four case studies of stroke survivor experiences over a 12-week trial with a haptic system for assessment and rehabilitation. The 12-week experiment gave valuable insights into the effectiveness and feasibility of home-based rehabilitation with haptic devices. We believe that the methodology of the trial and the insights discovered could be applied in more formal settings mediated by therapists as a low-cost method of home-based rehabilitation post clinical discharge (research question 3).

The work we presented here can be applied to many research areas including, but not limited to, assessment robotics, rehabilitation robotics, haptic technologies, assistive technologies, human-computer interaction, and remote task collaboration.

1.5 Thesis Overview

This chapter has briefly introduced the subject of Stroke Rehabilitation and the potential for the use of haptic technologies to support rehabilitation and therapy following a Stroke. The primary research goals have also been discussed, along with the methodologies for the experiments that have taken place within this stream of research, and also how answering these research questions contribute to the body of knowledge in the field of Rehabilitation Robotics.

The Background, chapter 2, presents a comprehensive review of the current literature pertinent to this research including current assessment techniques and rehabilitation regimes, statistics on the quality of life and the numbers of people affected each year, and supporting studies promoting the efficacy of including robotic instrumentation for the treatment and rehabilitation following a stroke. Particular attention is given to fine-motor rehabilitation and assessment and how these can be achieved in virtual environments combined with haptic technologies. Furthermore, a discussion is given to the use of such devices at home, and how using commercial off the shelve game controllers can serve as a means to break the barriers of cost and transport, so often seen as a hurdle to giving adequate treatment and contact time.

Chapter 3 presents the use of an Embedded Reality approach to the Nine Hole Peg Test for the assessment of fine-motor skill. This chapter describes, in detail, an experiment with 60 healthy volunteers and compares three different iterations standard, hapto-virtual and embedded reality scenarios along with results and conclusions that feed into the design of the subsequent studies.

Chapter 4 focusses mainly on the second experiment of this PhD thesis: Exploring Human-Robot-Human Interaction in Collaborative Haptic Environments. Here the motives for this path of study will be explained along with the findings and their impact on the design of future systems for this path of research. Particular attention is given to how utilising different shapes within a haptic environment can elicit specific types of movement and how this can feed into an adaptive system for functional improvement of the hand, wrist, and arm.

Chapter 5 presents the design, development and experiment protocol for the long-term study: A Home-Based, Upper-Limb Assessment and Rehabilitation System for Stroke Survivors. The study was conducted over the course of 12 weeks with 4 participants, all having suffered a stroke within ten years prior. Improvements that the participants made throughout the study are discussed, and the results are presented along with discussions of how they contribute to the knowledge gained by this PhD thesis.

Finally, the Conclusion chapter summarises the findings from all the experiments that have been conducted in support of this path of study. The conclusions drawn from the work completed are then used to describe a plan for the future experimentation and how this work could be used to influence the fields of assessment robotics, rehabilitation robotics, and haptic home-based therapy.

1.6 Publications from this Research

The work from Chapter 3 was presented and published in the following:

M. Bowler. "The use of haptic force-feedback devices as assistive technology and assessment tools for the rehabilitation of upper limb impairment" RAEng Young Researchers Meeting, Abstract, Presented September 2010.

M. Bowler, F. Amirabdollahian, and K. Dautenhahn. "Using an Embedded Reality Approach to Improve Test Reliability for NHPT Tasks" ICORR 2011 (Accepted, March 2011)

Chapter 4 was submitted and accepted for the ICDVRAT journal; however, due to complications with a copyright agreement, we were unable to proceed with the publication. This work was presented at the ITAG conference in 2012 and the COST symposium:

- "Comparisons of Interaction Techniques between Stroke Survivors and Healthy Subjects in a Haptic Collaborative Task" ITAG (Interactive Technologies and Games) 2012, Nottingham `https://www.slideshare.net/iTAG_conf/ref25-michaelbowler241012`*

Poster: Enhancing Rehabilitation Robotics through Haptics and Social Mediation, presented as part of COST European Network Conference & Exhibition: 19 March 2012; Southampton, UK.

The work described in Chapter 5 is yet to be published.

2

Background

The focus of this PhD thesis is on designing and implementing haptic-based assessment and rehabilitation tools for stroke survivors suffering upper-limb impairment. The background for this research covers many topics which are introduced here. Specifically, this chapter presents stroke and the impact it can have on a survivor's activities of daily living, stroke rehabilitation and treatment, how impairment is assessed following a stroke, the use of robotics for rehabilitation, and home-based therapy environments for assessing and rehabilitating stroke survivors.

2.1 Stroke

A stroke occurs when the blood supply to the brain is disrupted; this can be caused by either a blockage (Ischemic Stroke, caused by a blood clot or other matter), or a ruptured blood vessel (Haemorrhagic Stroke) which could cause bleeding on the surface of the brain (subarachnoid) or inside the brain (intracerebral). Without a blood supply, the affected brain cells will die; thus the motor functions controlled by those brain cells can be lost or impaired leading to a vast array of problems and disabilities post-stroke.

According to the Stroke Association (Stroke Association, 2018), in Britain, one person every 5 minutes suffers a stroke, and the World Health Organization lists stroke as the most significant single cause of major disability in the United Kingdom (Mackay et al., 2004; WHO, 2017). Stroke is the fourth biggest killer in the UK, and it does not only affect adults, in the UK alone 400 children have a stroke every year (Stroke Association, 2018). The estimated cost of stroke to society worldwide is £26 billion per year (Stroke Association, 2018).

Almost two-thirds of stroke survivors leave the hospital with a disability (Adamson, Beswick, & Ebrahim, 2004). The Stroke Association (2018) lists the following as some of the effects of stroke:

- weakness in arms and legs
- problems with speaking, understanding, reading and writing
- swallowing problems
- vision problems
- losing bowel and bladder control
- pain and headaches
- fatigue
- problems with memory and thinking
- eyesight problems
- numb skin, pins and needles

All of the above-listed issues can be devastating to a person's ability to perform activities of daily living (ADLs) and also to their self-esteem. The result of which can lead to depression and other mental illnesses which can cause further complications in the ability of a person to achieve positive outcomes following a stroke (Intercollegiate Stroke Working Party, 2012).

Hemiparesis is a prevalent condition following a stroke where one side of the body is either paralysed or suffers impaired movement (Gray, Rice, & Garland, 2012). The damage to the brain as a result of the stroke requires neuroplastic changes to occur — whereby new neural pathways are formed — in order for the patient to be able to reuse the impaired limbs, which is encouraged by a regime of physical exercise (Pomeroy & Tallis, 2000, 2002). The efficacy of treatment also depends on the frequency of exercise and the period of time that it is administered following the incident (Tuke, 2008), with early intervention (within the first six months) believed to be more effective (Hendricks et al., 2002; Kahn et al., 2006). Without early intervention, the chances of fully recovering the use of the affected side are severely diminished.

Adequate methods of rehabilitation for impaired upper limbs, following a stroke and other neurological conditions, are lacking compared to rehabilitation efforts for the lower limbs and gait stability (Chortis, Standen, & Walker, 2008). The reason for this is clear: a hospital's most stretched resource is its beds, the sooner patients can walk or be mobile, the sooner they are likely to be able to be discharged from hospital, thus freeing up beds to accommodate new patients.

Upper limb impairment is a major limiting factor in a stroke survivor's ability to perform everyday tasks. Many patients require further rehabilitation following discharge from a clinic (Broeren et al., 2002). Access to rehabilitation following hospital discharge can be complicated due to cost and access to rehabilitative services (Reinkensmeyer et al., 2002). Exercise plays a significant role in stroke rehabilitation; however, there is still no universally accepted standard by which to design exercise programs for stroke following discharge from the hospital (Frontera, Slovik, & Dawson, 2006). There is a strong requirement here to improve access to upper limb therapy once home, not only to improve clinical outcomes for patients but also to alleviate pressure from health care professionals.

In general, the most significant improvements in mobility occur in the first few weeks following stroke (both in and out of the clinic); however, the neuroplastic nature of the brain means that improvements can still be gained in the months and years following stroke as new connections are formed in the brain (Wolf et al., 2008). Neuroplasticity can be encouraged by exercise and diet (Mang et al., 2013); thus exercise should be continued after clinical discharge, and ideally supported by stroke or neurology specialised teams (Bowen, James, & Young, 2016) and by family members if possible. Exercises for fine-motor skill usually include performing ADLs that require fine-motor skill such as writing, picking up coins, buttoning shirts/blouses, tying shoelaces, and putting together puzzles (Stroke Rehab, 2010). These exercise regimes are often referred to as task-specific training (Bayona et al., 2005) and are usually better than general exercise alone.

Accessing rehabilitation services after discharge is often difficult due to cost, distance, and availability (Reinkensmeyer et al., 2002). Studies have shown advantages for Early Supported Discharge (ESD) continuing rehabilitation in the home (Holmqvist, Koch, et al., 1998a; Indredavik et al., 1998); however, this, again, can be compromised by cost, distance and availability. Although patients are often given exercise plans and schedules to perform with them at home, the motivation from the clinician is sometimes not enough for the patient to continue the treatment as frequently, or as well, as it should be (Egglestone et al., 2009). Another issue with ESD is that, approximately, only half of the stroke patients in England, Wales, and Northern Ireland are discharged from the hospital with agreed goals for their rehabilitation and assessment for appropriate therapies (Stroke Association, 2018), this is likely to be similar in other developed countries.

After discharge and early stroke support and rehabilitation, involvement from clinicians and health practitioners starts to wane (Stroke Association, 2018). In the UK, the National Clinical Guideline for Stroke recommends that all stroke survivors should be offered a health and social care review to identify any additional support or treatment they may require. This review should take place at six months, one year, and every year after that (Intercollegiate Stroke Working Party, 2012); however, only 30% of stroke survivors receive an assessment (Stroke Association, 2018).

Recovery from a stroke varies significantly from patient to patient (Timmermans et al., 2010), and predicting expected recovery can be hard to determine (Kwakkel & Kollen, 2013). Kwakkel & Kollen (2013) determined that defining outcomes at activity levels was a better measurement than bodily function; however, due to the range of methods for measuring improvements, results can be inconsistent — we need to improve assessment measures, and activity-led assessment is better than standard bodily function measures.

Assessment is much more reliable when performed soon after a stroke, and this also helps to set expectations for the patient alongside the rehabilitation programme. The earlier that a rehabilitation programme is carried out (within three months for instance), the more optimistic a stroke survivor can be. Kwakkel & Kollen (2013) also determined that the first 8-12 weeks are crucial for the accuracy of predicting outcomes. Deep infarctions perform worse than superficial infarctions and knowing this can help with predictive measures. It is tough to predict outcomes for those with a poor prognosis, i.e. those who show no improvement after six months.

The review conducted by Timmermans et al. (2010) focussed on the influence of task-oriented training and the impact that it has on positive outcomes for recovery following stroke. Some of the key findings were that distributed practice (spread at random intervals over a period) could improve post-intervention performance and has been shown to result in better motor learning than mass practice (a block of continuous practice) sessions (Shea et al., 2000).

As inpatient care and recovery are costly (Saka, Mcguire, & Wolfe, 2009), there is a drive to get patients out of the hospital and back to there own homes. Discharging a patient too soon can have a negative impact on the recovery and progress that the person makes as the frequency of intervention and treatment, in general, is significantly reduced, especially as the person is likely to live some distance away from the treatment centre or clinic. Patients often require more rehabilitation following discharge from a clinic with many patients requiring further rehabilitation following release from a clinic (Broeren et al., 2002).

2.2 Rehabilitation of Upper-Limb Impairment

Rehabilitation is the process of restoring someone to health or normal life through training and therapy (OxfordDictionaries.com, 2018b); whereby, repair occurs via either reorganisation, using the same muscles via different pathways in the brain; or via compensation, activating muscles previously not dedicated to a task (Nudo, 2007). From the perspective of stroke rehabilitation, a rehabilitation programme should focus on improving the stroke survivor's quality of life and the regaining of skills required to perform activities of daily living. Furthermore, rehabilitation should include education and support of family and caregivers for them to assist with a survivor's recovery as much as possible (Kwakkel, Kollen, & Lindeman, 2004).

Upper limb impairment following a stroke can affect many activities of daily living (Stroke Association, 2018; Swaffield, 1996; Wade, 1989). It is essential to rehabilitate motor-function, both gross and fine, as motor-impairment can severely impact a patient's participation in everyday activities which can limit their rehabilitation (Schneider et al., 2007). Assessment and rehabilitation can commence as soon as a patient is in a non-critical condition (Bernhardt, Indredavik, & Langhorne, 2013); but, the focus on mobilising a patient over improving motor-function can lead to upper-limb rehabilitation being neglected (Broeks et al., 1999; Duncan et al., 2003; Malouin & Richards, 2005). Chortis et al. (2008) also suggested that adequate methods of rehabilitation for impaired upper limbs are lacking compared to rehabilitation efforts for the lower limbs.

2.2.1 Typical Treatment Protocols for Upper Limb Impairment

The goal of motor-skill rehabilitation is to improve both fine-motor skills such as tying shoelaces, writing and playing the piano; and gross-motor skills such as carrying a bag, catching a ball or pouring water from a kettle. Krakauer (2006) broadly describes five typical treatment protocols that are used to improve motor skill dependent on the severity of impairment and the impact that the stroke has had on a survivor's ability to perform daily tasks.

2.2.1.1 Arm ability training: impairment-oriented training for mild hemiparesis

This technique is aimed at patients who are less severely affected by hemiparesis (Platz et al., 2001). These patients may score normally when assessed using Fugl-Meyer or other assessment techniques; however, suffer from clumsiness and coordination issues when performing activities of daily living. The tasks are generally practised repetitively, but variation can be introduced by altering the difficulty of each of the tasks.

2.2.1.2 Constraint-induced movement therapy (CIMT)

This technique involves a combination of restraining the less-affected extremity for up to 90% of waking hours while practising tasks using the affected limb for up to six hours per day using a technique known as shaping. Shaping is a type of operant conditioning which rewards good performance; this is to oppose the learned non-use that often occurs with stroke patients who overcompensate for the affected limb by performing most or all of their tasks of daily living with the less-affected limb.

2.2.1.3 Electromyogram-triggered neuromuscular stimulation

Here, the hypothesis is that non-damaged motor areas can be used to perform tasks that were once performed by the damaged motor areas. EMG-triggered stimulation is used to measure EMG signals from paralysed muscles and use the signals to initiate electrical stimulation of the same muscles to produce physical movement in the same muscles.

In addition to the previously covered therapy techniques, two other commonly used rehabilitation programmes are also worth mentioning: Bobath and the Motor Relearning Programme.

2.2.1.4 Bobath

The Bobath method is a popular approach used to rehabilitate patients following a stroke with a focus on improving the quality of movement and regaining normal movement in the affected hemiplegic limbs (Lennon & Ashburn, 2000). The method has evolved from clinical observations and methods are passed on through clinical practice and training. Due to this, there is some controversy about what defines the Bobath method in clinical practice (Olney, 1990). In this technique, the therapist will initially work on the patient's ability to recover balance and then may progress to targetting specific movements to prepare the patient for functional skills (Lynch & Grisogono, 1991). Problems of strength are generally seen as secondary to the quality of movement in the Bobath programme of rehabilitation (Bobath, 1990).

2.2.1.5 Motor Relearning Programme

The Motor Relearning Programme (MRP) is an approach to rehabilitation where patients actively practice context-specific motor tasks to regain lost motor functions (Carr & Shepherd, 1987). The motor relearning approach is built on motor learning theory and requires anticipatory actions and ongoing practice (Chan, Chan, & Au, 2006). Studies have shown that this approach to rehabilitation can shorten hospital stays and improve the functional independence of the patient (Langhammer & Stanghelle, 2000; Lee et al., 1997).

All of the above-described techniques can be augmented by altering the practice method of the tasks in any combination of these three techniques (Krakauer, 2006):

1. Distributed practice — frequent and more extended rest periods
2. Variable practice — varying parameters of a task
3. Contextual interference — random ordering of related tasks

Better retention and generalisation of learning new tasks can be gained by randomisation of training schedules (Krakauer, 2006). Distributed practice improves performance and learning, and variability in therapy sessions can improve performance in the next — retention of skill between sessions, regardless of the performance of the task itself (Shea & Kohl, 1991). Also, repetitive therapy could be more effective (Hendricks et al., 2002; Kahn et al., 2006). Furthermore, rehabilitative training is increasingly moving more to a focus on activity-led or task-led training to improve function, skill, and endurance (Shumway-Cook & Woollacott, 2007)

In addition to direct techniques of therapy involving physical stimulation of the affected limbs via various mediums; therapy outcomes can be vastly improved by ensuring that a patient's quality of life is maintained throughout. Improvements in quality of life can be achieved by including regular outings and social interactions. McCluskey et al. (2013) and her team demonstrated the importance of getting out and about via training and escorted outings and how it can help reduce instances of depression following a stroke and improve therapy outcomes.

2.3 Interactive robotic therapy

All of the above techniques for rehabilitation require the presence of a skilled clinician or therapist in order to conduct and monitor the tasks. Additionally, a team of therapists may be required to support just one patient. This poses a very heavy burden on the staff involved. As the population continues to age (Stroke Association, 2018), more and more skilled therapists will require training in order to support the increasing numbers of stroke survivors requiring rehabilitation. The proposal for robotic-based rehabilitation is that this will alleviate pressure on health care professionals by reducing the number of professionals required to carry out or assist with rehabilitative tasks.

There are now many examples of robotics for providing therapy following stroke (Ates et al., 2013; Balasubramanian, Klein, & Burdet, 2010; Chen et al., 2013; Sivan et al., 2011). At the core, robot therapy can be used to offer assistance to complete tasks that require movement of the affected limb. Assistance can be reduced over the course of the treatment protocol as patients' movement improves. One of the advantages of robot-assisted therapy over EMG-triggered stimulation is that many muscles across all of the joints of the affected limb can be stimulated in coordination as opposed to single muscles at a time. This process of robot-assisted therapy has been shown to be of significantly more benefit than that of conventional therapy regarding measures of impairment and ADLs (Lum et al., 2002).

Although robots offer many advantages in the form of reducing the numbers of clinicians and physicians required to conduct various therapies, they are not without their disadvantages. Many robot systems are large and costly and have to be installed in a room in a hospital or clinic, usually preventing that room being used for anything else thus adding more of a cost to the use and installation of such robots. Many of the robots are also very technical, and although fewer clinical experts are required, technical staff may be required to assist with the setup and application of robot-assisted therapy.

2.3.0.1 Virtual reality-based rehabilitation

Virtual reality attempts to simulate the real world, usually through the medium of computer-generated graphics, via either a monitor or a head-mounted display. A user's actions in the real world are mapped to movements and visual feedback in the virtual world using motion tracking technology. Stimulation and feedback can be augmented by the use of haptic joysticks or gloves that may allow the user to feel interactions within the virtual world, offering various levels of immersion. Some studies have already shown the efficacy of VR environments for stroke therapy (Emery et al., 2010; Laver et al., 2012) with more using VR in combination with robot-assisted therapy (Amirabdollahian et al., 2005; Johnson et al., 2008; Levin et al., 2015; Loureiro et al., 2003).

2.3.1 When can rehabilitation start after stroke?

A question that is often asked when reviewing stroke rehabilitation techniques and protocols is that of when rehabilitation can begin following a stroke. Bernhardt et al. (2013) conducted a review to try to ascertain optimal times for the commencement of rehabilitation protocols; however, this was without a definitive answer, stating that there was no evidence that the exact starting point of therapy would affect outcomes, with the exception that, if required, thrombolysis should be conducted immediately. For other treatments, there is a consensus that they should start early, once all the life-critical issues had been treated and dealt with, but there may be a limited time window that will drive the best possible outcomes for the patient (Bernhardt et al., 2013). Although it is broadly agreed that the sooner that therapy commences, the more positive outcomes are expected, improvements and positive outcomes can still be gained long after the stroke occurred. Continuing treatment and therapy can be of great benefit and is a worthwhile exercise.

2.4 Assessment of Fine-Motor Skill Following Stroke

In order to devise patient-specific rehabilitation regimes, methods for assessing the level of impairment are required (Brewer et al., 2007). Typically a patient will be required to perform numerous tasks that give an indication of the level of functional impairment in areas such as gross-motor control; fine-motor control; manual dexterity; strength; and proprioception. The following section describes three popular, clinically established, assessment tools used for the assessment of upper limb impairment following stroke and other neurological conditions. These tools are not the only measures of assessment for upper limb impairment; however, they are directly relevant to the focus of this PhD thesis.

2.4.1 Nine Hole Peg Test

The original Nine Hole Peg Test (NHPT) apparatus defined by Wade (1992), consists of a board with nine, evenly spaced, holes (10mm wide) arranged in a 3x3 grid and nine pegs (9mm wide). Typically, the patient sits in front of the apparatus and is asked to place each of the pegs, in turn, into each of the nine holes on the board. The time taken to complete the task is recorded. Faster times suggest better fine-manual dexterity (Heller et al., 1987). High inter-subject reliability and test-retest reliability have been demonstrated (Kellor et al., 1971), and clinical norms have been established for adult males and females between 20 to 75+ years of age (Mathiowetz, Weber, et al., 1985) making this a very suitable method of assessment of arm function.

2.4.2 Box and Blocks Test

The Box and Blocks Test (BBT) is a measure of gross-manual dexterity. For this task, the patient is required to move as many blocks as possible, one-by-one, from one compartment of a box to another within one minute (figure 2.1). Studies have shown that this test has good test-retest reliability and correlates well with other measures of manual dexterity (Cromwell, 1960). Generally, the more blocks that the subject can move in the space of one minute suggest better gross-manual dexterity.

Figure 2.1: **The Box and Blocks Test.** This figure shows the box and blocks test being completed by one of the participants in our final study. They are using their left hand to complete the task by moving blocks from one section of the box to the other.

2.4.3 Fugl-Meyer Test

The Fugl-Meyer Test (FMT) (Fugl-Meyer & Jaasko, 1975) aims to assess both the ability to move the arm as a whole and the ability to move individual segments of the arm in isolation. FMT also measures sensation and passive joint mobility. The test is widely used with stroke survivors but is also suitable for the assessment of neurological patients. For each item in the scale, a score of 0, 1, or 2 is given, 2 denoting the ability to respond correctly (Fugl-Meyer & Jaasko, 1975). There are 62 items in the FMT giving a maximum possible score for the test as 124. This test shows good test-retest reliability (Duncan, Propst, & Nelson, 1983; Platz et al., 2005).

Of these assessment techniques, we chose the NHPT and BBT as ideal candidates for use in portable home-based studies and for reproducing within virtual environments given that their dimensions can fit within the dimensions of our chosen haptic device: the PHANTOM Omni®. Furthermore, assessment using the NHPT and BBT requires minimal equipment and time to perform. The Fugl-Meyer requires many items of equipment to conduct the assessment and also a reasonable amount of space, of which we could not guarantee would be available in participants' homes. The outcomes of these measures are essential for both clinical practice and research, and although there is no consensus on the best measures to use (Roberts & Counsell, 1998), these have been widely adopted and validated and are therefore suitable for use in our studies.

2.5 Home-based Rehabilitation

In the UK alone, it is estimated that stroke costs £26 billion a year, with new cases of stroke accounting for roughly £5.3 billion per year (Patel et al., 2017). Around 30% of this sum is expected to be accounted for by the NHS. For each of the 100,000 strokes that occur in the UK every year, the National Institute for Health and Care Excellence (2012) estimate that the NHS could save £1,600 by providing Early Supported Discharge, providing a total saving of roughly £160 million per year. With these costs to society outlined, it becomes clear that there is a need to promote, improve, and facilitate treatment protocols for stroke in the home setting.

Home-based rehabilitation is a method of conducting therapy and treatment following a stroke in the patient's home. Two drivers behind home-based rehabilitation are:

1. To reduce the cost of treatment by discharging patients from the hospital or clinic early, where costs for treating a patient are generally higher.
2. To allow treatment to continue for much longer at home with the support of

clinicians and family to promote and motivate physical therapy and exercise.

Rehabilitation is not just about improving a stroke survivor's physical abilities; it is just as much about regaining confidence and independence following impairment (Kwakkel et al., 2004). Not just for the person affected, but also for the caregivers and family members so that they can assist in the most productive way possible.

Home-based rehabilitation is supported by the stroke organisation (Stroke Association, 2018), especially the concept of Early Supported Discharge (ESD) where patients are helped to get back home quickly following critical care with the assistance of clinicians. Inpatient care and recovery are costly (Saka et al., 2009), so ESD is beneficial for healthcare providers, and some studies have shown no significant difference in the outcomes for home-based versus clinical-based rehabilitation (Anderson et al., 2000; Holmqvist, Koch, et al., 1998b); however; frequency of treatment and exercises usually wane post-discharge from the clinic. Protocols for home-based rehabilitation are being devised to try to improve the uptake of home-based therapy so that similar results can be seen in patients following discharge (Amirabdollahian et al., 2014; Egglestone et al., 2009; Johnson et al., 2008; Sivan et al., 2014).

There may be other, less obvious benefits to a home-based treatment protocol. We previously discussed the benefits of distributed and variable practice; these methods could be advantageous to note when following a home-based rehabilitation protocol where time can be limited, and a strict schedule cannot always be met; varying schedules may be a practical necessity but should potentially also be encouraged.

2.6 Rehabilitation Robotics and Haptic Technologies

With recent advances in technology, virtual reality, and robotics, there is a growing body of research investigating the uses of robotics to support rehabilitation and assessment of function following stroke and other neurological conditions (AbdulKareem et al., 2018; Butler et al., 2017). These systems aim to reduce the current, labour-intensive mechanisms required by standard therapy techniques that generally require one-to-one sessions with therapists, and provide robotic exercises that could be conducted under the guidance of a non-specialist clinician, or in a patient's own home. Robotic devices can be used to provide high-intensity, task-specific, and repetitive therapy just as is used in current rehabilitation techniques. In addition to the potential for long-term reduced costs from the relaxed involvement of a therapist, robotic devices have the potential to provide better rehabilitation treatment by offering the ability to measure minute details of a participant's interactions and then alter the environment in a way that could drive more targetted outcomes in a feedback loop.

There have been many robotic systems developed by different research groups aimed at upper-limb rehabilitation in particular. These systems include, among others, the GENTLE/S (Coote et al., 2003) and GENTLE/A (Chemuturi, Amirabdollahian, & Dautenhahn, 2012), the Bi-Manu-Track (Hesse et al., 2003), the MIT-Manus (Krebs et al., 1999), and the NeReBot (Fanin et al., 2003). These systems take the concept of exercise with the premise (as backed by literature) that exercise and repetitive tasks can help to restore upper-limb function and motor control. Further systems have also been developed that provide hand exoskeletons for the rehabilitation of hand function (Amirabdollahian et al., 2014; Balasubramanian et al., 2010; Maciejasz et al., 2014). It has also been shown that robot-aided therapy can be just as effective as conventional therapy (Kwakkel et al., 2008; Lo et al., 2010; Mehrholz et al., 2012; Prange et al., 2006). More recently, robot-aided therapy has focussed mainly on the proximal, arm and the therapy efforts have not been generalised to rehabilitate the hand and wrist (Prange et al., 2006), there is thus a need to improve efforts to rehabilitate the wrist and hand via robot-mediated therapy.

In addition to the robotic systems described above, there is another important class of robotic device: arm support devices. These devices support the weight of the arm in order to allow the patient to move in a more controlled fashion. This is especially important in the early stages of rehabilitation. In order to achieve this style of movement, the *Swedish Arm Help* (Stienen, 2009)and the *Freebal*(Reinkensmeyer, 2009) systems both use suspension mechanisms to compensate for the action of gravity on the patient's arm. Unfortunately, due to the sling/suspension arrangement, although these devices offer controlled movement, they are very limited in the range of motion that they can provide the user.

In the past 20 years that robotic rehabilitation systems have been investigated and developed evidence of their success in terms of clinical outcomes is still not conclusive and the quality of some evidence of these systems is low (Mazzoleni et al., 2017). In their review, Mazzoleni et al. (2017) suggested that greater functional improvements are seen when robotic therapy is administered in the subacute phase of stroke. They also attest that robot-assisted outcomes can be improved when combining with other treatment therapies such as Functional Electrical Stimulation (FES) or Repetitive Transcranial Magnetic Stimulation (rTMS).

Another smaller class of robotics that are being used for rehabilitation are so-called 'haptic devices'. The word *haptic* means 'relating to the sense of touch' and is derived from the Greek word *haptikos* 'able to touch or grasp' (OxfordDictionaries.com, 2018a). Haptic devices provide the ability for a user to be immersed in a virtual scene (Hannaford et al., 1991) by combining a 3-dimensional visual representation of the task, and a, hopefully, realistic physical interpretation of the virtual world via the use of a haptic force feedback device. Haptic forces must be calculated at a rate of 1000Hz to maintain an accurate level of touch sensation; failing this the kinaesthetic sensation will be unrealistic and may cause instability in the system (Carignan & Cleary, 2000). These technologies present opportunities for rehabilitation in many scenarios: stroke rehabilitation, MS patients, motor-cognitive impairments and HCI for visually impaired users. Many new, relatively low-cost, haptic technologies are now being produced with a small form factor that allows for these devices to be used in subjects' homes, e.g. SensAble's PHANTOM Omni® and the Novint Falcon.

One of the significant benefits of haptic systems lies in the ability to record specific information regarding the subject's movement, such as speed, position in the environment, forces exerted, and orientation of the end effector. The advanced monitoring and logging of a patient's performance can then be analysed at a later date to provide more feedback on the care and requirements of the patient.

In addition to the data collection aspect provided by haptic systems, the virtual environments presented to users of such systems provide the unique ability to create tasks that otherwise would not be feasible to set up in the real world, and improve test-retest reliability by reducing the potential for variation and human error during the setup of the tasks. Robotic and VR based therapies offer a repeatable, testable environment that can be used many times, doesn't tire and reduces in cost over time.

There have already been many research efforts to determine whether haptic devices can be used as rehabilitative robots (Kwakkel et al., 2008; Pareto et al., 2011; Prashun et al., 2010; Volpe, Krebs, & Hogan, 2001) as they allow for a close personal interaction that is not viable in a clinical setting and also removes the need for a patient to be in the clinic to perform all of their rehabilitation. These studies range from investigating lower to upper limb therapy, and from gross to fine-motor control assessment and therapy. In addition to being used for rehabilitation, haptic technologies also lend themselves well to the role of assessment tools. Studies by Tobler-Ammann et al. (2016), Amirabdollahian et al. (2005), and Emery et al. (2010) have displayed promising results regarding the use of haptic peg-in-hole systems and their effectiveness in assessing patients with neurological disorders.

Haptic technologies are generally combined with a virtual environment to enable the user to *see* what they can *feel* with the haptic device. The PHANTOM Omni® and Novint Falcon are *kinaesthetic* haptic devices: they generate forces that guide, manipulate and perturb movements of the user based on forces generated by a computer (Demain et al., 2013), commonly mirrored by events in a virtual scene. Virtual environments also have the potential to motivate and monitor rehabilitation via gamification which can be important when these systems are used in a home-based environment (Chortis et al., 2008). Sallnäs, Rassmus-Gröhn, & Sjöström (2000) showed that these kinaesthetic haptic force-feedback devices could improve performance in a virtual environment. The PHANTOM Omni® haptic device was used for all of the experiments carried out and presented in this thesis.

The PHANTOM Omni® haptic is a six-degrees-of-freedom (DoF) haptic device, providing force-feedback and measurement in 3 axes (x, y, z) and measurement and movement in the pitch, roll and yaw axes. The device transfers force-feedback via the robotic arm to a pen-like stylus. The user is then able to feel the forces through their fingertips as they manipulate and interact with a virtual world using the stylus. Quite complex interactions can be modelled using one of the many APIs available, even though it would appear that interaction would be quite limited with just a single point of contact (the stylus endpoint). Given the limited dimensions of the PHANTOM Omni® (160 W x 120 H x 70 D mm), the tasks that can be performed with the device are restricted to the range of fine- to medium-motor control, presenting excellent opportunities for the assessment and rehabilitation of hand function.

There have been some previous review articles that highlight the efficacy of haptic-robotic approaches to upper-limb rehabilitation that are worth mentioning here to provide added context to the reader:

Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review (Kwakkel et al., 2008): The review conducted here aims to assess the effects of robot-aided therapy on motor and functional recovery of stroke survivors. This review focussed on upper-limb recovery and only investigated RCTs. Due to the difference in the studies reviewed, no overall significant effect was determined in favour of robot-assisted therapy; however, a sensitivity analysis did show significant improvements in upper limb motor function after stroke for upper arm robotics, although these improvements did not translate to improvements in activities of daily living (ADL). The authors offer valuable insights into the future direction that these outcomes present.

Systematic review of outcome measures used in the evaluation of robot-assisted upper limb exercises (Sivan et al., 2011): The reviewers of this study evaluate outcome measures used in robot-assisted exercise trials (RAET) with stroke survivors. The authors found that some of the outcome measures used in recent RAET did seem appropriate for use in future trials and that in outcome measures should be selected based on the severity and chronicity of impairment. The recommendation was that this could be achieved by using the International Classification of Functioning Disability and Health framework.

Effects of robot-assisted therapy on stroke rehabilitation in upper limbs: Systematic review and meta-analysis of the literature (Norouzi-Gheidari, Archambault, & Fung, 2012): This analysis looked at randomised controlled trials that utilised robotic devices for upper-limb rehabilitation. The review pooled scores from outcome measures including Fugl-Meyer, Functional Independence Measure, Motor Power Scale, and the Motor Status Scale. No difference was found between *intensive* conventional therapy and robot-assisted therapy; however, the study did conclude that extra sessions of robot-aided therapy combined with conventional therapy can be more beneficial than conventional therapy alone for motor recovery of the shoulder and elbow.

Virtual Reality for Stroke Rehabilitation (Laver et al., 2012): This review evaluated virtual reality and interactive video games for stroke rehabilitation. Results of studies using video games and virtual reality were compared with alternative and conventional interventions. Upper limb rehabilitation was the most commonly investigated approach for virtual reality-based therapy. Due to the limited number of studies selected there was limited evidence that virtual reality was more beneficial for stroke rehabilitation than conventional therapy.

Immersion of virtual reality for rehabilitation - review (Rose, Nam, & Chen, 2018): This article reviewed 18 previous studies to ascertain human performance and health outcomes following VR-based therapy protocols. This review also investigates the relationship between enjoyment and adherence to the VR rehabilitation routine undertaken. Although no concrete conclusions were drawn, performance measures including postural stability, navigation task performance, and joint mobility showed varying relations to immersion.

Using a low-cost haptic device for rehabilitation and assessment is a crucial enabler for the technology to be used more widely in clinical practice and home-based therapy. Cost is almost always a barrier that limits the practical use of such systems outside of research efforts, and maintenance cannot usually be afforded (Chortis et al., 2008), thus a low-cost commercial offering is imperative for ongoing and future efforts in the domains of assessment and rehabilitation robotics.

2.7 Games for Motivation and Rehabilitation

Games are increasingly being used as a method of motivating patients to perform repetitive tasks as part of an exercise and therapy regime for rehabilitation (Gamito et al., 2017; Shah, Amirabdollahian, & Basteris, 2016). Games used for purposes other than entertainment are often described as *Serious Games* (Zyda, 2005). There are many benefits to combining games with rehabilitation practices. Games provide motivation and, as long as the games are suitably engaging, this will encourage players to play the game again and again (Garris, Ahlers, & Driskell, 2002). Garris et al. (2002) also states that games that provide clear, specific, and challenging goals lead to enhanced performance. Studies have also shown that patients prefer rehabilitation exercises that include diverse and fun games, and that game-based rehabilitation systems can make exercise tasks more appealing to stroke patients (Hung et al., 2016).

Another aspect of motivation is feedback by giving clear, actionable, responses to tasks performed by the player in the virtual world. In the context of rehabilitation, giving feedback to patients on the performance of their therapy can influence the learning process (Vliet & Wulf, 2006). In this regard, games for rehabilitation can be designed to offer targetted feedback to enhance motor relearning.

Commercial games are a relatively low-cost technology in contrast to traditional medical equipment and have already been shown to provide positive outcomes when used as part of a rehabilitation programme (Gamito2011; Deutsch et al., 2008). Many commercially available game systems, such as the Nintendo Wii and Microsoft Kinect, now contain elements of motion-control, allowing for a more immersive gaming experience which has also been shown to improve game performance and rehabilitation outcomes (Gamito et al., 2017). This is positive when combining games with home-based rehabilitation systems where cost can often be a limiting factor on the provisioning of equipment for rehabilitation in the home (Chortis et al., 2008). Very recently, the work of Tannous et al. (2018) studied the feasibility of game-based rehabilitation environments in the home.

2.8 Telerehabilitation

Providing rehabilitation in the home can be difficult for many reasons. The stroke survivor may live far from the therapist, there may not be enough therapists available for home visits (Hoenig et al., 2006), and the cost of providing home-based therapy is high. In order to provide successful rehabilitation, therapists suggest that patient performance should be measured at regular intervals, usually via home visits following clinical discharge (Fisher & Sullivan, 2001; Maclean et al., 2000); however, there is no requirement for these visits to be conducted in person, and they could quite conceivably be conducted via some form of telecommunication.

Another barrier to home-based rehabilitation is motivation. Motivation plays an integral role in rehabilitation (Winters et al., 2001), and the ability for a stroke survivor to self-motivate is crucial to their recovery. It is thought that if robotic tools can be used in conjunction with engaging, motivational virtual environments, and provide a way of remotely involving a therapist with a patient via some form of telecommunication, that patient outcomes could be improved. This process is termed *telerehabilitation* (Carignan & Cleary, 2000; Johnson et al., 2008; Loureiro, Johnson, & Harwin, 2006).

Telerehabilitation is the concept of providing remote therapy to a patient. A typical scenario could be that the therapist is in the clinic, and the patient is at home. A therapist would be able to interact with the patient over a network (e.g. the internet) via the use of haptic and robotic controllers. Telerehabilitation would allow the therapist to monitor the patient as they perform specific tasks and exercises, and also allow the therapist to guide and interact with the patient at the same time. This method of rehabilitation removes the barrier of travel and transport and could also allow for more frequent interactions and therapy sessions for both the patient and the therapist with other patients.

In addition to improving contact time, task frequency, and patient engagement, telerehabilitation also offers the opportunity for remote monitoring and assessment of motor function. Task performance can be recorded and then analysed at a point in the future by the patient's therapist. Remote monitoring could also help to alert therapists to changes (improvements or deterioration) in the patients motor function sooner than would have been realised by conventional means. Recent telerehabilitation studies have demonstrated that robot-assisted therapy combined with home exercise programs can be effective for stroke rehabilitation (Butler et al., 2017; Linder et al., 2013).

2.9 Embedded Reality

In this PhD thesis, we introduce the term *Embedded Reality*. In the context of this work, *Embedded Reality*, means to place physical objects within the virtual world. This definition is opposed to the definition of *Augmented Reality* (AR), where virtual objects are displayed over a view of the real world. *Embedded Reality* allows us to improve tactile feedback and spatial awareness provided to users when using tasks such as the Embedded Nine Hole Peg Test (ENHPT). The interactions with physical objects mirror that which is displayed to the user in the virtual environment. The interactions could be further improved with the use of a VR headset; however, this was not investigated in this research.

2.10 Research Questions

Our research questions were introduced in the Introduction to this PhD thesis. Now, with the context of the background literature presented above, we revisit these questions:

Q1: *Can the PHANTOM Omni® be used as a method of assessing fine-motor control skills?*

The literature suggests that haptic technologies such as the PHANTOM Omni® are good candidates for assessing motor function. Numerous studies have been conducted that show their potential for use in rehabilitative scenarios, and there have also been studies that demonstrate peg-in-hole interactions in haptic environments. The unique approach to this question that we will take is that of *Embedded Reality*, which we hypothesise will improve inter-subject variability and test-retest reliability.

Q2: *Can we identify key traits and movements of users of haptic environments to design better haptic rehabilitation environments?*

Our literature search showed that there is a consensus that virtual environments can be used to improve motivation for rehabilitation and exercise tasks. We also hypothesise that haptic environments can enable us to persuade users to move and interact in different ways depending on the shapes that are presented in the virtual environment due to a tacit inference of how to interact with objects that are similar to their real-world counterparts. Using this knowledge, we hope that future systems can be developed with this in mind to enhance motivation and functional outcomes further.

Q3: *Is the PHANTOM Omni® a viable platform for producing home-based rehabilitation systems for hand function following a stroke?*

The PHANTOM Omni® has been well researched with regards to rehabilitation technologies. Its small footprint and low-cost make it an ideal candidate for research and for the potential to be used in real-world scenarios following studies that prove its efficacy. Our research will take the PHANTOM Omni® out to stroke survivors homes where we hope to show that it is indeed a powerful tool that has the potential to be used as a therapy device in someones home, but also for remote and onsite assessment of arm function following a stroke.

This PhD thesis will incorporate currently established medical assessment techniques and aim to improve upon them in terms of data analysis and acquisition by the use of haptic technologies and haptic tasks specifically designed to assess stroke survivors' performance and recovery while undergoing rehabilitation. Interaction will be further enhanced by establishing a telecommunication protocol to deliver haptic force feedback between remotely located partners.

2.11 Summary

The body of research into haptic and robotic technologies for the rehabilitation and assessment of arm function following a stroke is growing fast. Also, there are now many studies investigating the role that telerehabilitation can play in improving rehabilitation outcomes by allowing stroke survivors to continue their therapy in the home while their performance is fed back to the clinic. The focus of this PhD thesis is to establish assessment techniques, and test protocols that can be used to validate the use of haptic technologies for remote and onsite assessment of arm function following a stroke.

We chose to use the PHANTOM Omni® haptic controller to facilitate the goals of this PhD thesis due to its small footprint and low cost - attributes that we assessed were crucial for a home-based rehabilitation and assessment system. Regarding assessment tools that we have decided to use for this thesis, we have determined that the Nine Hole Peg Test and the Box and Block Test are ideal outcome measures. The NHPT presents a task that fits well within the dimensions of the PHANTOM Omni®, and the BBT can be carried out by a non-clinical expert. Although we considered the Fugl-Meyer as an outcome measure, we ruled it out for the experiments presented in this thesis due to limitations in time and space that we would encounter in participants homes.

Although there is already a vast range of robotic-based therapy, rehabilitation, and assessment systems (as presented in this chapter), where our work stands out is in the application of these tools as a novel assessment system that can be placed in the home that provides accurate levels of measurement approaching the same accuracy as that found in the NHPT. Where other teams have focussed on increasing the level of virtualism in the environments that they create for conducting assessment techniques such as the NHPT, our approach is to merge the two dimensions: physical and virtual in order to get the best from both: haptic tools allowing for accurate measurement and instant results delivered to the therapist, and real world anchors to improve proprioception of the task being conducted.

This chapter has presented the context for the work undertaken by this PhD thesis. We introduced the topics of stroke, rehabilitation, assessment tools, rehabilitation robotics and haptic technologies, telerehabilitation and embedded reality. We also presented further work for the reader to investigate to gain a broader understanding of the concepts involved in stroke rehabilitation. Following this, we presented the research questions in the context of the literature, how they are relevant, and what they can add to the current body of knowledge.

3

Using an Embedded Reality Approach to Improve Test Reliability for NHPT Tasks

Typically, a patient will be required to perform numerous tasks that give an indication of the level of functional impairment in areas such as gross-motor control, fine-motor control, manual dexterity, strength, and proprioception. A patient-specific rehabilitation regime can be prescribed once a stroke survivor's level of impairment has been assessed (Brewer et al., 2007).

Fine-motor control is the ability to make movements using the small muscles in the fingers, hands, and wrists. These movements are essential for performing activities of daily living that require the grasping and manipulation of objects, e.g. picking up a pen, tying a shoelace, or making a cup of tea (Allgöwer & Hermsdörfer, 2017).

A standard method of assessing fine-motor control following stroke is the Nine Hole Peg Test (NHPT) (Wade, 1992). The NHPT is a clinically established and validated tool for the assessment of upper limb motor control (Mathiowetz, Weber, et al., 1985). The test apparatus consists of a board with nine, evenly spaced, holes (10mm in diameter) arranged in a 3-by-3 grid and nine pegs (9mm in diameter).

Typically, the patient is seated in front of the apparatus and is asked to place the pegs, in turn, into the holes on the board (see figure 3.5). The time taken to complete the task is recorded. Faster times suggest better arm function (Heller et al., 1987).

Following the recent development of advanced robotic and haptic systems, several studies into the use of haptic virtual reality for rehabilitation and assessment have been conducted (Amirabdollahian et al., 2005; Crosbie et al., 2008; Emery et al., 2010; Loureiro et al., 2003). The significant benefit of such systems lies in the ability to record specific information regarding the subject's movement, such as speed, position in the environment, forces exerted, and orientation of the end effector; in comparison to the conventional NHPT where only task completion time is available. Furthermore, virtual environments provide the unique ability to create tasks that otherwise would not be feasible to set up in the real world and improve test-retest reliability by reducing the potential for variation and human error during the setup of the task.

Recent studies (Amirabdollahian et al., 2005; Emery et al., 2010) have displayed promising results regarding the use of haptic peg-in-hole systems and their effectiveness in assessing patients with neurological disorders. However, much benefit can be gained by taking a more in-depth look into how variation between tasks and their setup can be reduced to improve the reliability of such 'hapto–virtual' tests before they can be considered in a clinical setting. Furthermore, since this study was conducted, our work has been referenced by studies aiming to achieve the same aims of our study: to improve test reliability in the NHPT whilst improving measurement of the task itself (Johansson & Häger, 2019; Tobler-Ammann et al., 2016), acknowledging the fact that purely virtual approaches to assessment tools do not offer as reliable results as those using physical apparatus.

This chapter highlights the work undertaken to create a platform suitable for use as a haptic assessment tool for fine-motor control, designed to answer the first research question of this PhD thesis: *Can the PHANTOM Omni® be used as a method of assessing fine-motor control skills?* Including the choice of hardware and software and modifications/adaptations of each. Following the development of a virtual and embedded reality NHPT, we completed a study with 60 healthy participants to test the efficacy of our approach.

This study explored three different methods of completing the NHPT: Real (a modified NHPT), Embedded (a mixture of both real-world and virtual environments) and Virtual (NHPT in a virtual workspace). Each task mimics the others in terms of physical workspace dimensions and proportions. It is proposed that, by using an embedded reality approach to the NHPT, we can work towards validating a valuable assessment tool by improving inter-subject variation and limiting human error in task setup, to produce a method of haptic assessment that can enhance the capabilities of non-haptic measures.

3.1 Framework Choice

To create a low-cost system with haptic force-feedback, two critical components needed to be decided: the hardware, and the software. As stated, the device used for haptic force-feedback is the PHANTOM Omni® by 3D Systems (https://www.3dsystems.com). We chose this device due to: relatively low cost (~£1200); small form-factor(168 W x 203 D mm); firewire port; accuracy compared to lower cost devices such as the Novint Falcon gaming controller (www.novint.com); and minimal system requirements. The PHANTOM Omni® has also already been used in many upper-limb rehabilitation research scenarios with promising results, warranting further investigation. Furthermore, the stylus grip is removable, allowing for it to be changed for something that would be more suitable for a stroke patient to hold: a more substantial grip would be better for someone who has impeded dexterity for instance.

The software framework chosen for this PhD work is H3D API. The H3D API is a multi-platform, open-source development framework that uses a combination of OpenGL and X3D with haptics to handle both graphics and haptics (SenseGraphics, 2012). Our choice over other frameworks (OpenHaptics and CHAI 3D) was due to many factors. Firstly, we required an open source development environment to fit the requirements of the funding project. Secondly, we wanted to use a multi-platform environment to produce a system that could be distributed and migrated to other hardware platforms in the future. These factors would also help to reduce cost by allowing the system to be installed on open source operating systems such as Linux.

The H3D API is also multi-platform for haptic controllers, allowing to be used with SensAble haptic devices, the *HapticMaster* from Moog FCS Robotics (www.moog.com), the *Falcon* gaming controller from Novint, and devices from ForceDimension (www.forcedimension.com). Thirdly, at the time, the H3D API had some of the best documentation of any of the haptic APIs and a very active forum, which made troubleshooting software errors much simpler compared to other frameworks (Kadleček, 2011). Finally, the H3D API allowed for rapid development and prototyping of systems due to the 3-layered approach to the platform: C++ and OpenGL for the creation of graphical objects and haptic interactions; an X3D scene graph for creating the scene; and a Python scripting layer to rapidly develop complex interactions between objects in the environment. The C++ layer is well written and modularised, allowing for additional components to be created and distributed relatively easily. This 3-layered approach is beneficial in many ways. The X3D layer is based on XML and allows a complex scene to be built very quickly without having to write complicated code. This setup allows for rapid prototyping of environments using just XML and Python scripting; later, for efficiency, the whole SceneGraph can be written in C++.

The H3D API also includes a plug-in for a Rigid Body Physics simulation, required for creating more realistic virtual environments and haptic interactions. There are also currently several research efforts using this platform in similar contexts, creating a more extensive knowledge base to draw from in the future (Lövquist & Dreifaldt, 2006; Vanackern et al., 2010).

3.2 Additional H3D API Components

When designing the system for home-based rehabilitation, we identified some components that would need to be added to the existing H3D API to allow for: the creation of a haptic NHPT, remote collaboration between two separate users, and special events to be logged at real-time in the Python scripting component of the API.

3.2.1 Multi-Point Collision Detection: PegRenderer

We used a method of multi-point collision to simulate the peg-hole interaction based on the work described by Amirabdollahian et al. (2005). This method detected multiple points of collisions based on the diameter and height of the peg and combined the outcome to simulate the full 3D interaction of the peg with the rest of the environment. The haptic force feedback was calculated for each collision point based on the God-object method for haptic interaction (Zilles & Salisbury, 1995). With this method, a virtual point is created in the scene that must not penetrate any planes, known as the god-object. This virtual position is updated within the haptic loop (1000Hz) and, if the movement of the god-object towards the Haptic Interface Point (HIP) passes through a contact plane, the resulting force is calculated by way of a mass-less spring as per Hooke's law:

$$F_s = -k\Delta x = -k(x_{HIP} - x_{god-object})$$

where Δx is the displacement of the spring and k is the spring constant defining the stiffness of the surface (see Figure 3.1).

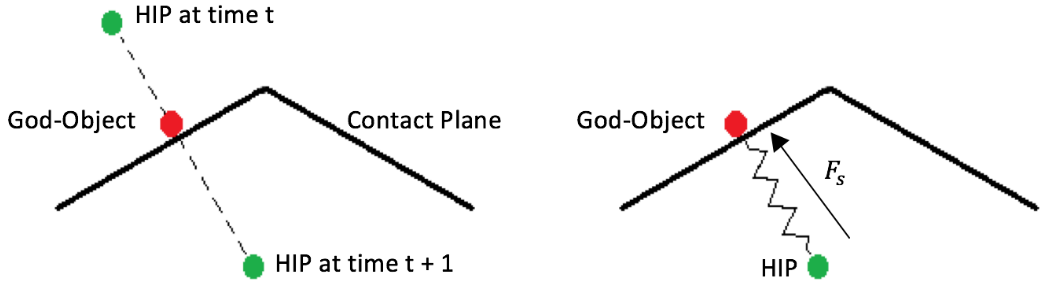


Figure 3.1: **The God-Object model of haptic force feedback.** This figure shows the haptic interface point and how it interacts with the god-object via a mass-less spring according to Hooke's law.

The existing god-object renderer in the H3D API was then modified, and a total of 56 collision points were created: 7 cylinder slice segments with 8 points along the circumference of each slice (see figure 3.2).

The 56 points are centred at the tip of the stylus (the default point of interaction), this reduces the distance between the furthest point of the renderer from the target, making the code more efficient. Further to this, the global variable 'MaxDistance' in the H3D API was increased to accommodate the extra collision points. The peg radius and peg height were variables that could be changed throughout the running of the program through all layers of the H3D API. At each haptic frame (1000Hz) the current positions of the peg points in Euclidean coordinate space are calculated (matrix transformation) based on the position and orientation of the stylus and converting (Axis-Angle convention). As according Euler's theorem, any 3D rotation can be described as a rotation angle, θ, about an axis defined

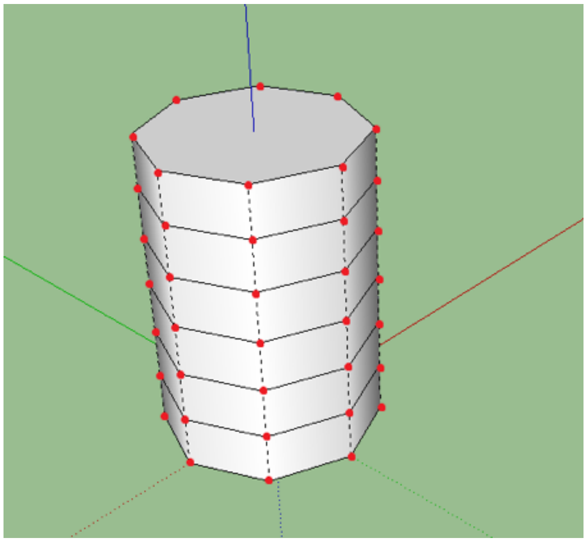


Figure 3.2: **The 56 points created for the PegRenderer.** This image displays the arrangement of the points around the cylinder used for the haptic peg.

as a unit vector $\mathbf{n} = \left[n_1, n_2, n_3\right]^T$ (Trucco and Verri 1998) giving the following Rotation Matrix *R*:

$$R = I\cos\theta + (1-\cos\theta)\begin{bmatrix} n_1^2 & n_1n_2 & n_1n_3 \\ n_2n_1 & n_2^2 & n_2n_3 \\ n_3n_1 & n_3n_2 & n_3^2 \end{bmatrix} + \sin\theta\begin{bmatrix} 0 & -n_3 & n_2 \\ n_3 & 0 & -n_1 \\ -n_2 & n_1 & 0 \end{bmatrix}$$

where *I* is the identity matrix. The sum of the above three matrices produces the matrix:

$$R = \begin{bmatrix} (tn_1^2+c) & (tn_1n_2-n_3s) & (tn_1n_3+n_2s) \\ (tn_1n_2+n_3s) & (tn_2^2+c) & (tn_2n_3-n_1s) \\ (tn_1n_3-n_2s) & (tn_2n_3+n_1s) & (tn_3^2+c) \end{bmatrix}$$

where: $c = \cos\theta$, $s = \sin\theta$, and $t = (1-\cos\theta)$. Combining *R* with a translation component based on the current position of the haptic proxy (x, y, z) we have the final matrix for which to multiply the points of our PegRenderer:

$$R = \begin{bmatrix} (tn_1^2+c) & (tn_1n_2-n_3s) & (tn_1n_3+n_2s) & x \\ (tn_1n_2+n_3s) & (tn_2^2+c) & (tn_2n_3-n_1s) & y \\ (tn_1n_3-n_2s) & (tn_2n_3+n_1s) & (tn_3^2+c) & z \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

The total force variable is then initialised before commencing a loop to calculate the collision forces for each of the 56 transformed points along the surface of the peg. Only shapes that are active in the scene (within the MaxDistance parameter of the H3D API) are tested for intersection with the points to reduce processing time. The force for each point is calculated based on the previously mentioned God-object model of haptic rendering. These forces are then averaged and limited to a value of 9 in the code, corresponding 90% of the maximum 3.3 N of output force as a safety constraint. Furthermore, to reduce oscillations that can occur from force build-up when the peg is between objects with little room either side (Figure 3.3) the output force is reduced by a factor of the velocity (0.05 x dV).

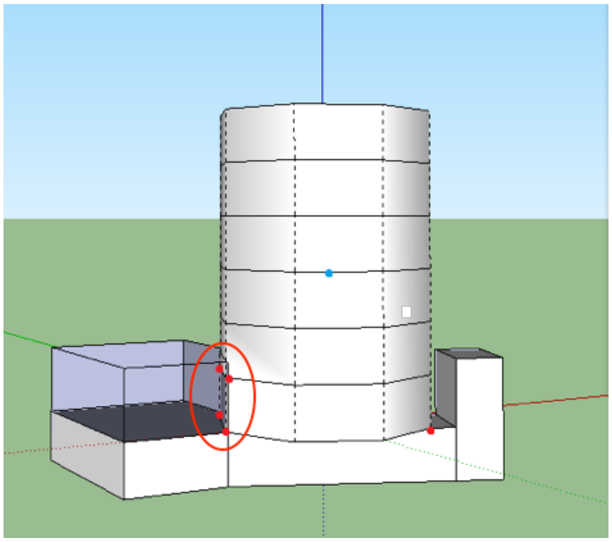


Figure 3.3: **Collision oscillations.** When between a gap with a small amount of distance between the sides of the peg, a collision at one side of the peg causes a force to push back thus causing a collision on the other side of the peg, and this continues causing oscillations.

3.2.2 PegHole Node

Rather than using an X3D model of a peg-hole shape, a peg-hole module was written in C++ for the H3D API that would allow for a peg-hole of any sized bounding box, radius, and hole depth to be added very simply to the environment with the following code in the X3D scene graph:

```
<Shape>
  <Appearance>
    <Material diffuseColor="0.988 0.871 0.404" />
    <SmoothSurface USE="PEG_HOLE_S" />
  </Appearance>
  <PegHole DEF="PEG_HOLE_3" size="0.068 0.05 0.068"
    radius="0.009" hole_depth="0.025" />
</Shape>
```

This parameterisation allowed for different peg hole interactions to be simulated very quickly, in keeping with the rapid development ethic of the rest of the API. The PegHole object was created in OpenGL, based on two H3D API object primitives: Box and Cylinder (see figure 3.4). The normal component on the surface planes of the cylinder was z-flipped to enable the inside curvature of the hole to be felt.

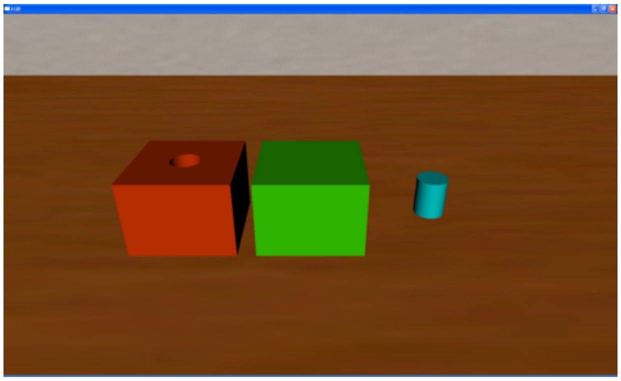


Figure 3.4: **The PegHole shape** (left) was created in OpenGL based on a composite of two H3DAPI primitives: the Box and the Cylinder. The top of the cylinder was removed and positioned in place of the top face of the box. The normal vectors were flipped to produce haptic force feedback on the inside of the hole. Finally, an OpenGL TriangleStrip was used to create the top face between the hole and the edge of the box.

3.2.3 EventLog

Building on the existing *DeviceLog* node in the H3D API a node was created: *EventLog*. The standard *DeviceLog* node allows for the variables: time, position, orientation, velocity, force, torque, and buttons to be recorded in an ASCII text file. Two issues with this approach were identified: there was no way of logging separate events and variables at runtime within the X3D and Python layers of the H3D API; and the default file that the log data was saved to was statically set to ‘log.txt’, which risked losing data from overwrites when recording data from multiple users. A variable ‘eventString’ was created within the EventLog class which was accessible at all levels of the API to solve the issue of logging events. Our event string enabled the quick prototyping of variables to be defined, recorded and analysed after a haptic task was complete; this feature was invaluable when analysing the Science Museum data where a ‘dropped stylus’ event was created which denoted the swapping of interaction partners. The final addition to the log class was to create the filename based on the current date and time in the format: DDMMYY_HHMMSS.txt, this meant that files would no longer be overwritten when running programs one after the other.

3.2.4 Square2D

Finally, a simple node *Square2D* was written to allow a simple, texture-able, square to be created with length and width values in a similar way to the existing *Box* node with positioning performed using the *Transform* node. This improved readability in the scene graph over the standard approach which used a closed line-set where three vertices had to be defined; therefore, amounting to extra lines of XML.

3.3 The Experiment: Embedded Nine Hole Peg Test

We presented these results at ICORR 2011 (Bowler et al., 2011). This chapter provides an overview of the components of the research paper with results, and a conclusion more focused on the goals of this PhD thesis.

To rehabilitate impaired arm function following stroke, one must first assess the level of motor skill that a patient has with their impaired arm. Commonly, clinically established tools such as the Nine Hole Peg Test and the Box and Block Test (BBT) (Mathiowetz, Volland, et al., 1985) are used for this purpose. In keeping with the criteria set for research into a home-based rehabilitation system (small footprint, low cost), we are focussing on recreating the NHPT in a haptic virtual environment to be used as an assessment tool while undergoing robotic therapy. The NHPT was chosen due to its small form factor fitted into the workspace of the PHANTOM Omni® allowing for the virtual task to be created at 1:1 ratio of dimensions between the real. Furthermore, the task used simple apparatus with non-complex objects; again this suited the design of the PHANTOM Omni® and the virtual environment.

The original NHPT apparatus defined by Wade (1992), consists of a board with nine evenly spaced, holes (10mm wide) arranged in a 3x3 grid and nine pegs (9mm wide). Typically, the patient sits in front of the apparatus and is asked to place each of the pegs, in turn, into each of the nine holes on the board. The time taken to complete the task is recorded. Faster times suggest better arm function (Heller et al., 1987).

Recreating the NHPT in a haptic environment is advantageous in many ways. Information regarding a subject's movement, such as speed, position, forces exerted, and orientation of the end effector can be recorded and analysed in addition to the conventional NHPT where only task completion time is available. Furthermore, the task can be broken down into separate components: grasp, transfer and insertion; this can be analysed further to see which component a subject has the most problem with, and then tailor the rehabilitation tasks to their specific needs.

3.3.1 Experiment Design

This study was designed to explore three different methods of completing the NHPT: Real (a modified NHPT), Embedded (a mixture of both real-world and virtual environments) and Virtual (NHPT in a virtual workspace). Each task is designed to mimic the other tasks' physical workspace dimensions and proportions. It is proposed that the embedded task will provide the advantages of the haptic system (real-time data collection) with the advantages of a real-world system, thus reducing cognitive load due to not needing to work in a simulated 3D environment and real tactile sensations from the physical board. The embedded reality approach follows the view of previous work stating that using real objects for rehabilitation is preferential to virtual objects (Mackay et al., 2004).

As with all of the software created to support this PhD thesis, SensAble's PHANTOM Omni® was used as the haptic force-feedback device, and the H3D API was used to create the virtual environment for the NHPT, and also to handle the logging of the haptic data. For the peg interactions, the multi-point renderer(explained earlier) was used. A virtual laser pointer was also added to the virtual environment to assist with depth perception within the virtual environment.

As it was unlikely that many of the participants would have used haptic technologies in the past, a series of four training exercises were also created, increasing in difficulty from first to last. The exercises were designed to be fast-paced and easy to understand. These tasks were mediated using a simulated laser-pointer to help with depth perception – which was particularly useful for participants who rarely used 3D environments.

The first training exercise required the participant to touch five different haptic blocks in turn, placed at various positions within the virtual environment. This exercise helped the participant to realise the depth of the virtual environment.

Once the first exercise had been completed, the participant moved on to the second exercise which required the participant to touch and grasp six numbered blocks in order (one to six). The grasping was performed by holding one of the two stylus buttons. Once all six blocks had been grasped, the blocks were shuffled, and participants were required to repeat the task.

The third exercise required the participant to re-position an object by making contact with the block, grasping the object by pressing the stylus button and then moving it into a specified zone within the environment. The final training exercise required the participant to perform a simple peg-in-hole task, which included picking up a peg by making contact with the peg (felt via force feedback) and then griping either button on the stylus. The 'grip' action would change the peg's orientation to match that of the stylus. The participant then inserted the peg, released the button, and continued in the same way for the remaining two pegs.

As with the NHPT task, all training exercises were explained verbally and also re-explained using onscreen instructions. These training exercises were designed to give participants an understanding of how to control the PHANTOM Omni® to be able to perform the virtual NHPT.

3.3.2 Experiment Setup

Before commencing the study, ethics approval was first obtained from the University according to their regulations and procedures. The experiment then recruited a total of 60 healthy participants aged between 19 and 57 (mean $27.5 \pm 9.2 s.d.$) which included 38 male and 22 female participants. Participants were recruited at the University of Hertfordshire's LRC, and as such, most of the participants were students of the University going between lectures, as such, each session was restricted to 30 minutes. Participants were not paid for the experiment.

In order to determine a base level of participants that we would require to substantiate our findings, we performed a power calculation. We assumed that our data would follow a normal distribution thus used a power calculation to satisfy the students' t-test for comparing two means. We chose a large effect size of 0.8 and a power of 0.9 (the probability that the result will correctly reject a null hypothesis). We also set an alpha component (significance level) 0.05 = 5%. The calculation produced a result of 30.11, meaning that we would need a minimum of 31 participants in order to substantiate any findings in our results.

Of the 60 participants, eight stated that they had used some form of haptic technologies in the past. Each participant was required first to fill out a consent form stating that they permitted us to use their data for this experiment. Once the consent form was signed, participants then completed a demographic questionnaire, collecting relevant information such as age, handedness, or any visual impairment (Appendix A). After the initial paperwork had been completed, participants performed the training exercises in the order previously explained. Each task needed to be completed before moving on to the next; however, due to time constraints, tasks were not re-visited if the participant performed poorly (took a long time).

Following the training exercises, the participants had to complete the NHPT in three different ways: a real NHPT with physical pegs and pegboard; a virtual NHPT, where the pegs and board reside in virtual environment, with all the interaction being delivered haptically; and, finally, an embedded reality approach to the NHPT, where the participant uses the stylus to move a real peg into the pegboard. The position of the apparatus in each task was carefully measured and kept the same in each task to keep the environments as similar as possible. Finally, after participants completed the tasks, they were given a questionnaire to complete to record feedback to be used to influence future experiments (Appendix B).

3.3.2.1 Real NHPT

The real NHPT task was conducted using an apparatus from http://benefitsnowshop.co.uk. This wooden block measures precisely 120mm by 120mm with the peg holes drilled at equally spaced distances (33mm apart). The diameter of each hole is 6mm, and the depth of each hole is 15mm. Each peg measures 5mm in diameter and 30mm in length. These measurements do differ from the original NHPT set out by Wade (1992); however, more recent studies have shown that commercially available pegboards (Grice et al., 2003), also of differing dimensions, work in the clinical setting. As we purchased this equipment from a reputable seller of clinical assessment tools, we assume that this apparatus is made to a high enough standard to be used for this study.

As seen in figure 3.5, the actual setup of the experiment also differs slightly from the original requirements of the test. Usually, the test begins with the pegs scattered in a tray; however, here, the pegs are positioned in a holding box. This setup was chosen to avoid complicating the virtual environments, allowing for a very accurate recreation of size and position of the workspace in each of the three environments. As previous peg-in-hole studies have shown that insertion alone can provide us with useful indicators of performance in a haptic task (Amirabdollahian et al., 2005), it was decided that this setup would still produce valuable results from the insertion and transfer components of the task.

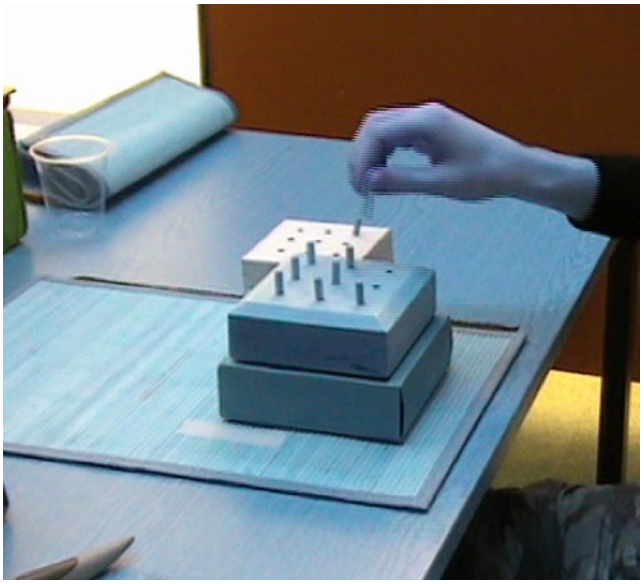


Figure 3.5: **The standard NHPT setup.** The positioning of the apparatus allowed the workspace dimensions to be mimicked across all three of the tasks that the participants performed.

It is also hypothesised that, with this setup, the average time for the real NHPT would be reduced from the times previously stated (Grice et al., 2003; Parker, Wade, & Hewer, 1986; Wade, 1992) due to making the grasping component of the task easier.

Starting with the dominant hand placed in a resting position (by the side of the apparatus, flat, palm facing down), participants were told to place each of the nine pegs into a hole on the board. Participants were told to attempt the task ‘as quickly and as comfortably’ as they could. We recorded the times using a stopwatch, started at the moment that the participant grasped the first peg. We recorded the time participants took to complete the task and used this for the average time taken per peg-placement.

3.3.2.2 Embedded NHPT

The embedded reality task used the same physical pegboard as the real task, located directly in front of the participant, centred at the sagittal plane. Attached to the end of the stylus was a peg (Figure 3.6), clipped on with the use of a small bulldog clip. Complementing this was the virtual environment which displayed all nine pegs and a virtual copy of the pegboard.

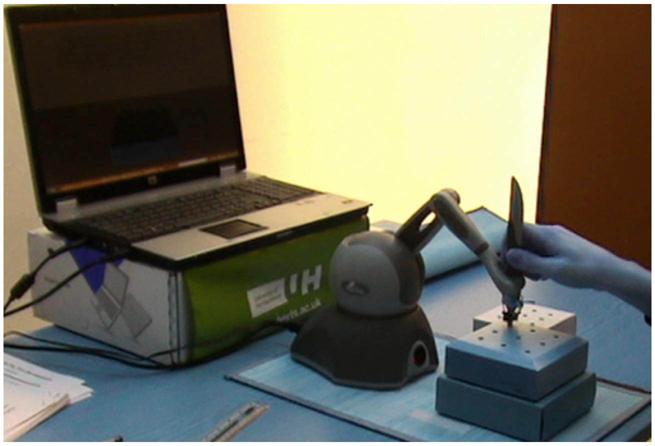


Figure 3.6: **The Embedded reality version of the NHPT.** Attached to the end of the stylus is a peg, that allows the participant to experience real physical interactions, enhanced by haptic interactions that occur when the virtual stylus encounters the pegs and pegboard in the virtual environment.

Participants could grasp virtual pegs by moving the peg attachment of the stylus to a hole in the peg holding box (the white box displayed in Figure 6, also the same as in the real set up) corresponding to a peg in the virtual environment on screen. Once a peg had been picked, the stylus graphic also changed to that of a peg (see Figure 3.7 for explanation). When the peg attachment was fully inserted into a hole on the pegboard, the peg was released, and the visual representation of the stylus was displayed, and the participant could pick the next in the same manner. The setup of the pegs prior to placement matched the layout of the holding box.

Haptic force feedback was given as the stylus touched the virtual peg, even though no physical peg was present, this was to simulate touching the peg to prompt the user to pinch grip the peg - by way of pressing the button on the stylus. The haptic cues also provided the advantage of disallowing the placement of pegs into an already occupied hole. It is also assumed that the attached peg allows for smoother insertion of the pegs into the board due to the increased tactile feedback delivered through the stylus from the peg to pegboard interaction. The physical board was measured, and the position of the holes was calibrated prior to the start of the embedded task by placing the peg in each of the holes first. The calibration process ensured that there was minimum friction between the combination of virtual and physical pegs.

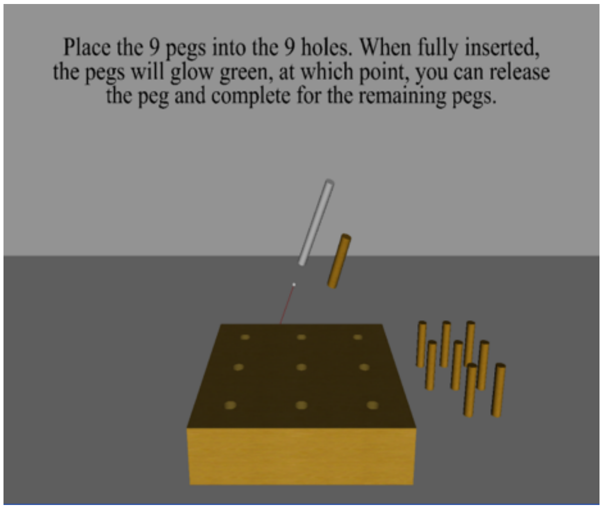

Place the 9 pegs into the 9 holes. When fully inserted, the pegs will glow green, at which point, you can release the peg and complete for the remaining pegs.

Figure 3.7: **The Virtual NHPT.** The pegs start at the right of the pegboard (for a right-handed participant). The stylus is represented by the grey cylinder and grey ball, with the laser pointer shown in red. The stylus image changes to that of the peg when the peg has been picked. All objects including the walls of the environment give an appropriate level of force feedback when contact is made.

As with the other tasks, we instructed participants to complete the task ‘as quickly and as comfortably’ as they could. The task was also timed, with the timer beginning as soon as the first peg was acquired at which point, the log files were also initialised and data recording began. Data regarding the position, orientation, velocity, force, buttons pressed, and events such as PICKED_PEG_X were recorded in the haptic loop.

The force measurement was read from the variables passed in the haptic loop of the H3D API. These measurements are output directly from the driver level and relate to the tension of the motors and actuators inside the PHANTOM Onmi®; thus these are force estimations but can be used comparatively throughout this thesis as this is the only device under investigation.

3.3.2.3 Virtual NHPT

For the virtual task, the position of the PHANTOM Omni® remained in the same position in front of the participant as in the embedded task. This time no physical apparatus were included. All nine pegs and the pegboard resided in the virtual workspace. Participants were instructed to pick up the pegs by using the same method described in the final training exercise (touching the peg and then gripping by pressing either of the two buttons) and then to place each peg, in turn, into the holes of the virtual pegboard. Further visual cues were delivered through the virtual environment: pegs turned bright red when touched, signifying that they were ready to be picked up; and when the participant had correctly inserted the peg into a hole on the pegboard, the peg turned bright green denoting that the peg was correctly inserted and could now be released. Data were recorded as per the embedded setup.

All of the tasks were described to the participants verbally and by demonstration. Tasks involving the virtual environment had onscreen instructions and participants were instructed to read them before commencing the task.

3.4 Data Collection

Data for this experiment was collected in three ways. Firstly, paper questionnaires were used to gather demographic information (age, handedness, any relevant impairment) and also user feedback from the task (difficulty of the task, preference to the type of interaction) to gain insight into participants' attitudes towards the system. Secondly, the log files produced by the haptic tasks were collected; this included files for all of the training exercises as well as the embedded and virtual NHPT tasks. The log files recorded time-stamped data at the rate of 100Hz with the following variables being recorded:

- Position (x, y, z) at the tip of the stylus
- Orientation (a_x, a_y, a_z, θ) of the stylus in axis-angle format (Craig, 1986)
- Velocity (V_x, V_y, V_z) of the movement of the stylus
- Force (F_x, F_y, F_z) of haptic interactions

- Buttons pressed
- Event String (this was updated in the python script at the graphics rate to tag events in the log such as when a peg was picked up (HOLDING_PEG_1) or inserted (INSERTED_HOLE_3).

From these variables, it was possible to split the movement up into three components: grasp, transfer, and release. Correlations between variables can also be analysed to determine any linked variables and the impact that these variables have on the overall task completion time.

In addition to the questionnaires and log files, a video was also recorded. Two cameras were set up: one to record users' facial expressions while performing the tasks, and another directed at the user's hands and to record the interaction and the haptic workspace throughout all of the tasks. The purpose of these recordings was to investigate the cause of any outliers in the results; this would help to improve the system for further trials in the future; however, as this was not required, the analysis of these recordings is outside the scope of this thesis.

3.5 Analysis and Results

The demographic questionnaires were analysed first to determine any factors that may have affected a participant's ability to perform the tasks. The analysis was undertaken using IBM SPSS (www.SPSS.com) and p-values calculated using the Mann-Whitney U test for independent samples. This statistical test was chosen due to the data not being of a normal distribution, most likely due to the factors presented in the demographic questionnaire 3.1. Hand dominance, use of spectacles, and previous use of haptic technologies had no impact on task completion times. However, familiarity with 3D computer games did have a significant (>97% confidence interval) result on task completion times for the haptic tasks: virtual $p = 0.002$; embedded $p = 0.005$; 25 of the 60 participants stated that they were either 'familiar' or 'very familiar' with 3D computer games, spending an average of 8.12 hours per week playing games3.1.

Table 3.1: **Demographic Survey** results. Of note here is that 65% of participants all used computer games on a weekly basis, thus had some familiarity with virtual environments.

Gender	Frequency	Percentage
Male	38	63.33%

Gender	Frequency	Percentage
Female	22	36.67%
Handedness	**Frequency**	**Percentage**
Left	9	15%
Right	51	85%
Use of Games	**Frequency**	**Percentage**
Uses games	39	65%
Does not use games	21	35%
Use of Haptics	**Frequency**	**Percentage**
Used haptics	11	18.33%
Not used haptics	49	81.67%
Age	**Frequency**	**Percentage**
19-24	29	48.33%
25-40	25	41.67%
41+	6	10%

The feedback questionnaire gave an overall impression of participants' attitudes toward the setup of the task, which has provided some recommendations for the design of future tasks; however, no significant conclusions could be found between participants' feelings toward the tasks and their performance in the tasks and therefore were not further investigated.

Figure 3.8 shows a box plot of the completion times of each task compared to its counterparts. The graph describes that times to perform the task increase from the real NHPT test to the embedded NHPT and finally to the virtual NHPT. Of note here is the variation in task completion time for the three tasks which also increases with the time taken for the three tasks. This data was then split into two groups: familiar with computer games and not familiar with computer games; the same trend as seen overall was seen in each of the groups: familiarity with computer games had no impact on this comparison. The reduction in the variation of task completion times seen between the virtual and embedded tasks implies a higher degree of inter-subject consistency for the embedded task. As expected,

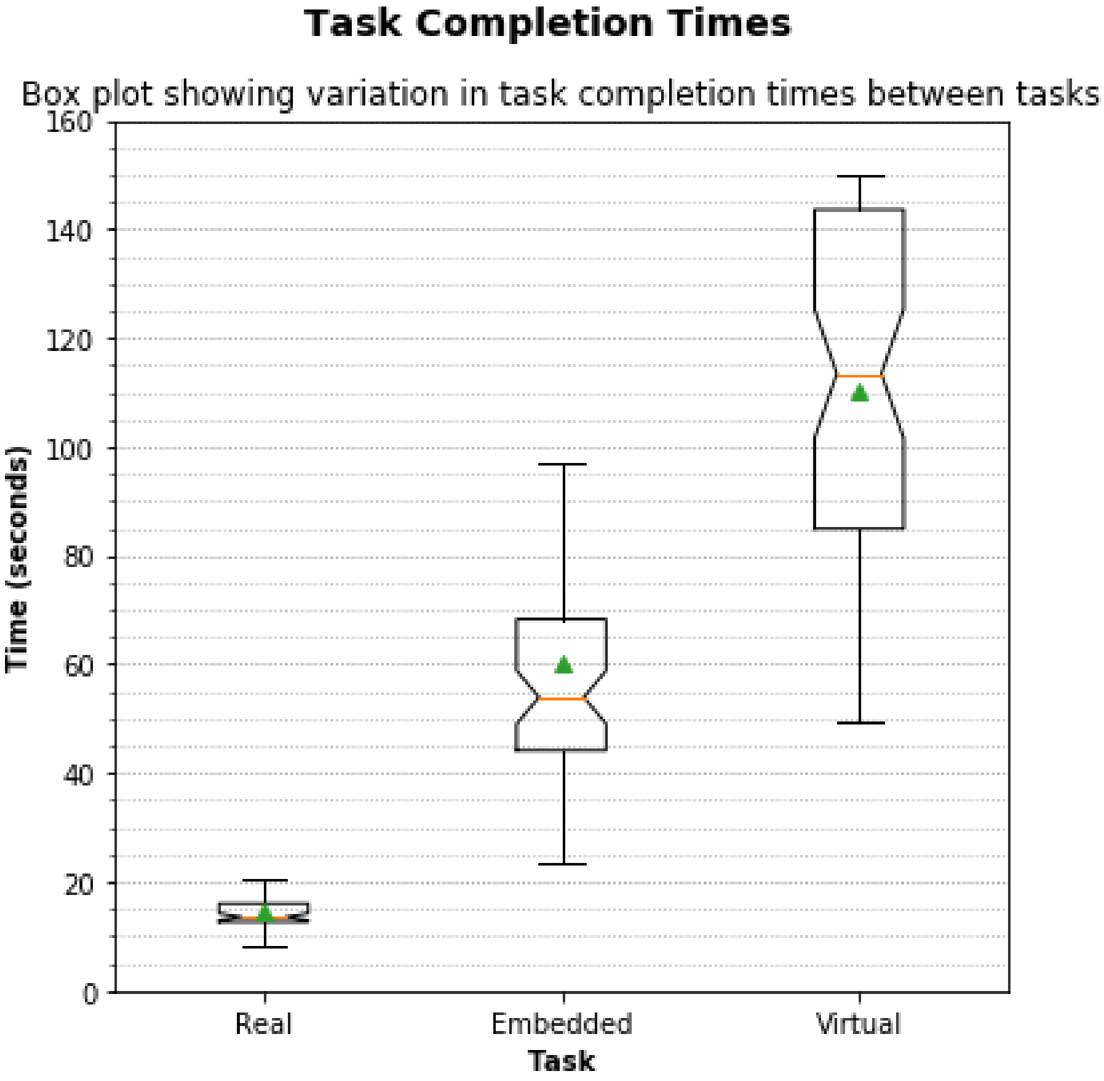


Figure 3.8: **Variations for task completion times** in each of the three tasks: real, embedded and virtual. As elements of reality are removed from the task, the time to complete the task increases, as does the inter-subject variations in completion times.

the embedded reality approach reduces task completion times compared to those seen in the virtual task. The differences in times could be primarily attributed to the limitations of the PHANTOM Omni®, such as low position resolution (which, with other factors, has been shown to impair haptic perception (Sakr et al., 2009)) and the presence of the real-world physical interaction between the peg and the pegboard, felt directly through the stylus. The embedded approach, in this scenario, is closer, concerning speed and variation, to the real task compared to the virtual model, while still providing the freedom to obtain information that would not be possible in the real setup. Further analysis of the video data, specifically determining the time spent looking at the screen in the embedded task, would need to be conducted to see whether the reduced times and variability could be attributed to the reduced cognitive load offered by the embedded setup where there is less need to look at the virtual environment.

We investigated the cause of the differences in times and inter-subject consistency analysing two elements of the NHPT: the transfer time, and the insertion time. The transfer time was determined to be the time taken from the moment a peg was picked up, to the moment that that same peg entered the threshold of a peg hole (point of insertion). The insertion time was then calculated to be the time taken from the point of insertion until the peg was fully and correctly inserted into the hole. Analyses of transfer and insertion times for embedded and virtual tasks were performed using the Wilcoxon Signed Rank test. This test resulted in p-values approaching 0.00; thus it was concluded that there was a significant difference between the transfer times of the two tasks and of the insertion times of the tasks, with the embedded shown to be performed quicker, in both transfer and insertion, than the virtual approach according to the statistical test.

The forces encountered throughout peg insertions of both the embedded and virtual tasks were plotted (Figure 3.9). As can be seen, more interaction and collision forces were encountered when using the virtual setup than those observed in the embedded scenario. In an attempt to explain this phenomenon the angle of insertion was extracted for each peg placement, for each participant, and was tested for correlation against the task time. No correlation was found ($p = 0.408$), and it was discovered that the higher forces were encountered when participants attempted to insert a peg but had misjudged the position of the hole. One likely cause for the angle of insertion not influencing performance is the use of multi-point collision algorithm (Amirabdollahian et al., 2005), which ensured that pegs could only be inserted in an upright position. Further experiments need to be car-

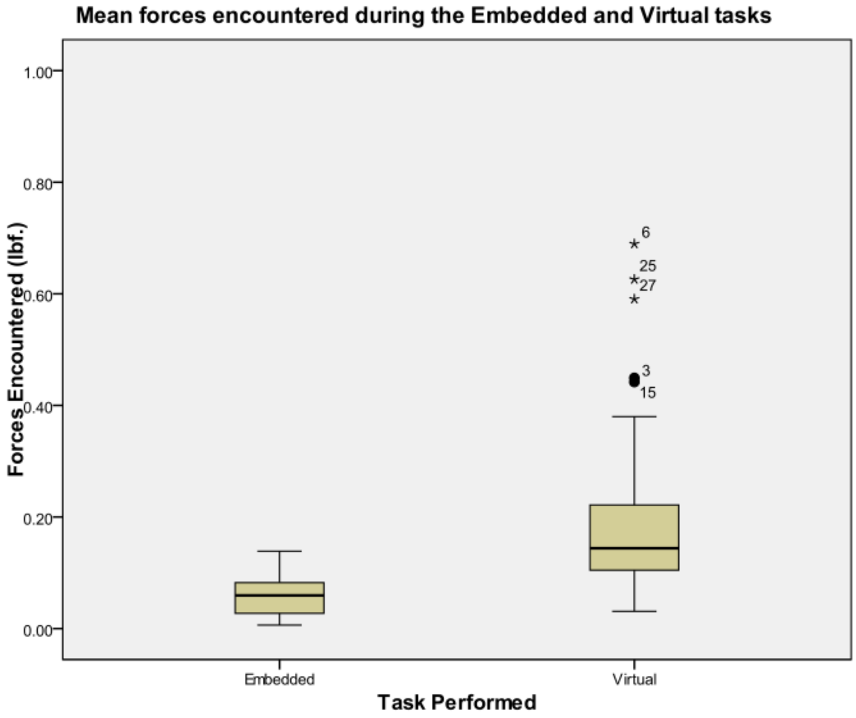


Figure 3.9: **Differences in variation for the mean force encountered whilst performing the embedded and virtual tasks.** Haptic force feedback was much higher in the virtual environment than that seen in the embedded setup.

ried out to present a virtual world with more visual cues allowing participants to perceive the depth of the environment with more accuracy.

The differences between the two components of the tasks (transfer and insertion) were further investigated where placement pairs (peg 1 to hole 1 for instance) were compared between the virtual and embedded tasks. It was found that for 61% of the placements, the transfer times were quicker in the embedded task than the virtual; and for insertion, 82% of placement pairs were quicker in the embedded task. Correlation between the total time and transfer times for each of the tasks using the Pearson Correlation Coefficient to determine whether one of the components had more of an impact on total time: both the transfer and the insertion were found to significantly impact task completion time in the virtual and embedded tasks (Table 3.2).

Table 3.2: **Correlation matrix** describing the relationship between the components of a placement and its total time. This table compares the correlation between the parts of the peg placements (transfer and insertion) and the total time taken to perform the full placement. [a] Significant at the 99% confidence interval.

Task	Pearson Correlation for Transfer Time against Total Time		Pearson Correlation for Insertion Time against Total Time	
	r-value	**p-value**	**r-value**	**p-value**
Embedded	0.833[a]	<0.001	0.645[a]	<0.001
Virtual	0.709[a]	<0.001	0.777[a]	<0.001

When looking at the ratio of time spent on the two elements of the peg placement between the two tasks it was found that, on average, participants performing the embedded tasks spent 86% of the time on the transfer and 14% of the time on the insertion. In the virtual task; however, 70% of the time was spent on the transfer compared to 30% on the insertion; suggesting that the insertion component of the task was more difficult in the virtual task than in the embedded.

3.5.1 Analysis of subgroups

Analysis between subgroups can only be inferential and indicative of requiring further investigation as the sample size for the minority subgroups in each case were not large enough to provide a decent level of significant power (>=80%), see table 3.1; however, it is still interesting to visualise the comparisons between the subgroups that relate to the use of computer games, and the use of haptics. Figure 3.10 plots task completion times for those who were familiar with computer games against those who weren't. The same trend in increased variability of task completion times as more physical components of the test are removed appears in both groups. Although not significantly better, those who were familiar with computer games did perform better than those who weren't.

Similarly to the results for the computer game use, both subgroups relating to haptic technologies (used haptics before and not used haptics before) show the same pattern of increased variability as the tasks progress from NHPT to ENHPT to VNHPT 3.11. This time there is even less of a difference between the two subgroups, with those who have used haptics before performing slightly better at the virtual task but not the embedded.

The fact that the results from all the separate subgroups relating to advance computer use (haptics, games) show that there is no significant advantage for those who had used computer games before of those who had used haptics before. This is a positive outcome, as although computer game use did indicate slightly better performance, this difference was not significant, suggesting that the slight improvement could quickly be gained back with practice.

3.6 Conclusions

It is interesting to note that the average time for the real NHPT task explained here was faster than the original peg-in-hole by approximately 3.5 seconds (14.5 compared to 18 seconds). This could potentially be attributed to two factors: age and modification of the task itself. Firstly, the age range of participants in this study was significantly lower than that of previous studies, following trends established by Grice et al. (2003), that as the ages of the participants increase, so do the times taken to complete the tasks. Furthermore, in this experiment, the pegs were placed upright and separated at a distance of 20mm apart (in a 3x3 grid) in a holding cell. This layout alleviated some of the complexity of the task as the pegs required less manipulation which potentially reduced the average time for the task. However, this configuration also enabled the specific distances between pegs and peg holes to be recorded in all three tasks, something which would otherwise be almost impossible in the real scenario.

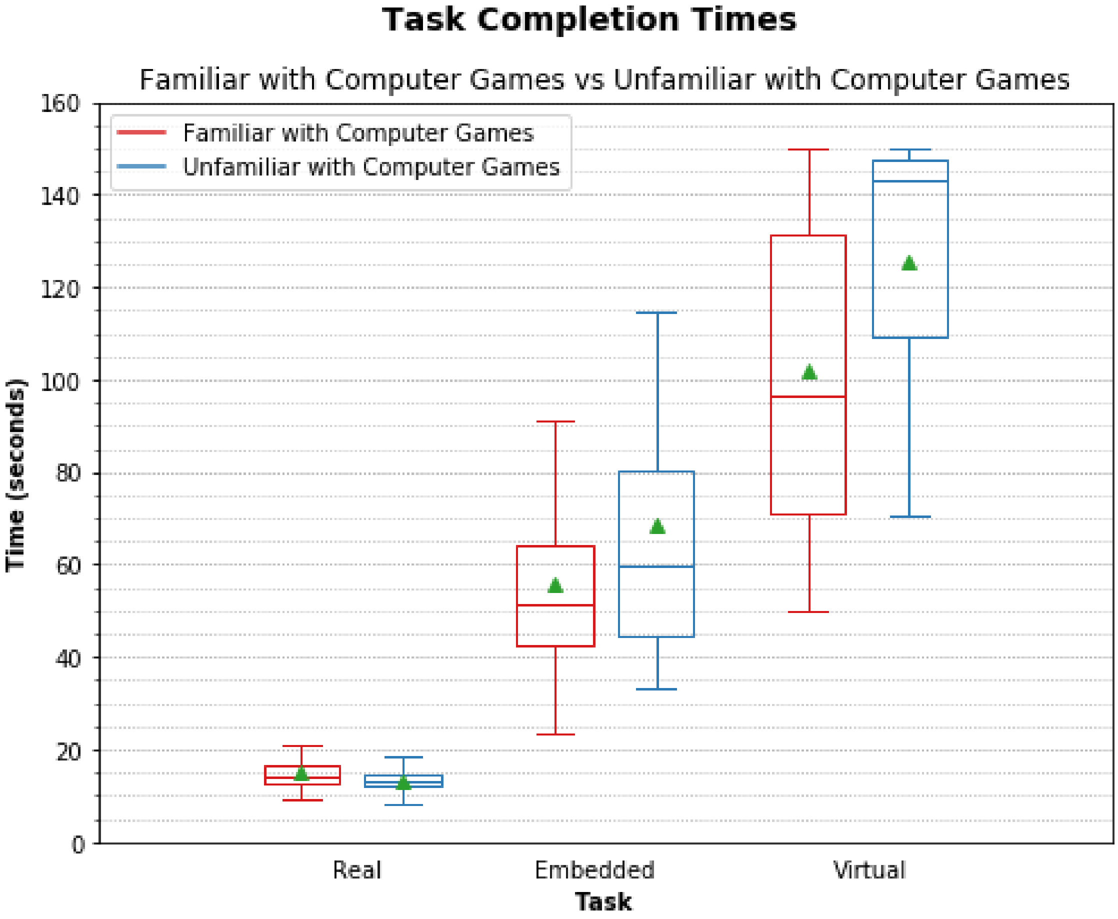


Figure 3.10: **Familiarity with Computer Games.** This figure splits the study cohort by the demographics of those who are familiar with computer games and those who are not. The trend of increased variability of task completion times matches see across the whole cohort is present in both groups.

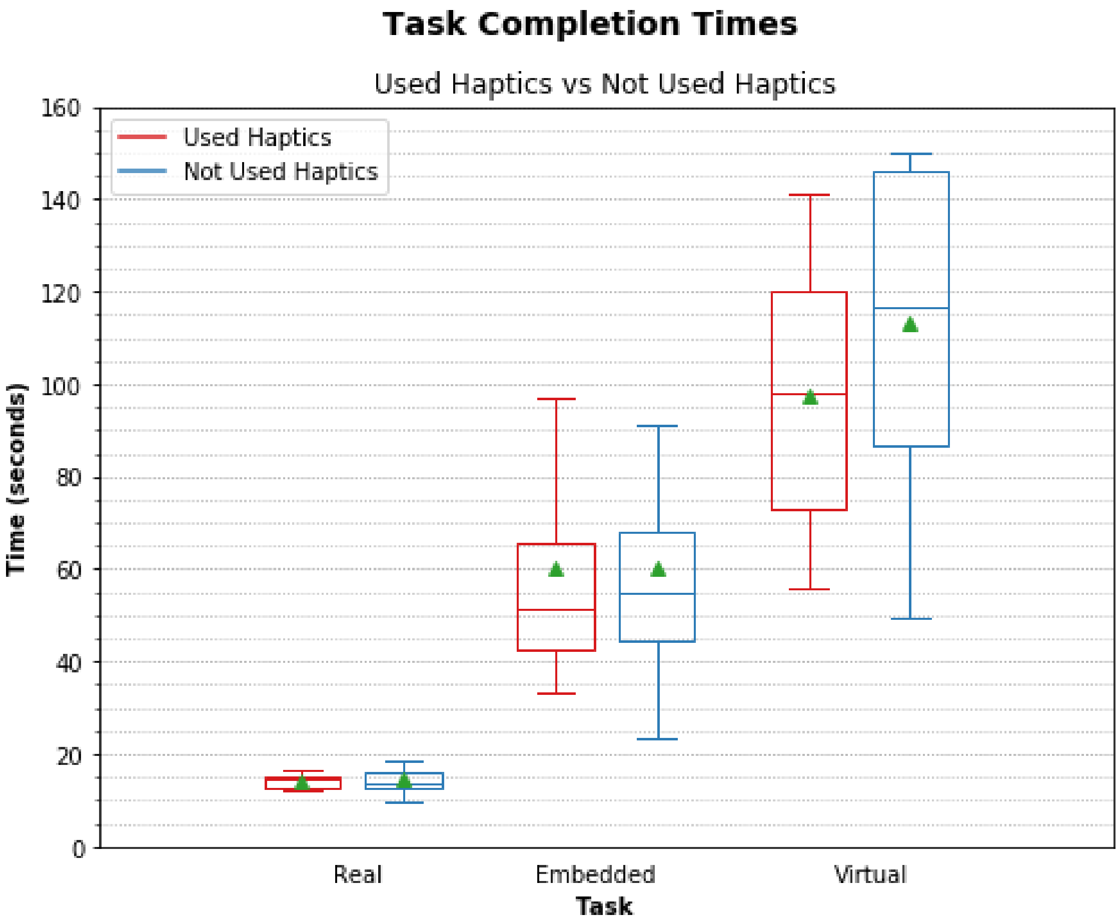


Figure 3.11: **Use of Haptics.** This figure splits the study cohort by the demographics of those who had used haptics before and those who had not. The trend of increased variability of task completion times matches see across the whole cohort is present in both groups.

When designing this set of experiments, initially a stronger relationship between the three tasks was assumed. Very quickly, it was established that these tasks were not only inherently different from the tasks originally described by Wade (1992); they were also different from each other. It was expected that by making a complete replica in terms of dimensions of the virtual scene and position of the workspace in front of the participant, a close correlation between the variations in times would be found; however, we found that this variation increased as more of the element of realism was removed from the task.

We analysed two metrics in an attempt to determine the cause of the variation between the embedded and virtual tasks: task completion times; and the two components of the movement itself: the transfer time and the insertion time. From these comparisons, it was seen that insertion time in the embedded was performed quicker than in the virtual task. Also, the transfer time in the embedded task was, on average, quicker than that seen in the virtual task. It is hypothesised that by utilising the physical properties of the pegboard (solidity and proximity), the embedded task provides better performance; the physical peg attached to the stylus aids the insertion into the peg hole, thus reducing insertion time; whereas the real-world interaction alleviates some of the effects of workspace translation that may be apparent when using computerised 3D graphics.

Using the PHANTOM Omni® allowed for two metrics to be isolated from the task itself: transfer time and insertion time. These measures are key components of the fine motor skills that are being assessed. For insertion time, better times relate to better hand and finger dexterity, improvements in this metric would suggest that the user was better able to manipulate objects with their fingers. Similarly, transfer time relates more to the proximal kinematic chain (arm and shoulder) as the user moves the peg across their body to the pegboard. Again, better transfer times indicate better mobility in the arm and shoulder of the user.

The embedded task has been shown to improve performance over the virtual task; however, it is not without flaws. One of the main limitations of the setup that was noted was the need for the participant to continually refer to the visual display to keep track of the pegs that had been picked up and placed. It is expected that by taking the attention away from the physical apparatus and to the screen and then back again could severely affect the time taken to perform the task.

From the analysis of the insertion trajectories and differences in the orientation of the stylus between the virtual and embedded tasks, it can be assumed that force and insertion angles are not the only contributing factors to the slower times of the virtual tasks. It is also likely that the differences in the physical appearance of the apparatus for the three tasks, i.e. graphical rendering and lack of holding the box in the virtual task, may have also contributed to the differences between task completion time and consistency. Once further differences and their causes are established, experiments will be reformulated to allow for closer matching between the validated NHPT, and the embedded and virtual incarnations. These modifications include making the pick and placement parts of the tasks more consistent with each other to reduce any effect that this may have on the task completion times.

Given our research question: *Can the Phantom Omni be used as a method of assessing fine-motor control skills?* this study has shown that an embedded reality approach to the NHPT has enabled a more accurate and consistent set of data for a large group of participants than that of a purely hapto–virtual reality approach. It has also been demonstrated that, by using the logging and measurement facilities provided by the PHANTOM Omni® we can isolate components of the movements that directly relate to movements in the proximal and distal kinematic chain - arm function and hand function, two key elements of fine motor control skill. These results suggest that further investigation is warranted and improvements based on these results should be made.

Some limitations of this experiment, namely: lack of practice attempts before the actual task, could also have contributed to the high level of inter-subject variation in the virtual task, while it is important to highlight that such differences are less evident in the real NHPT task. Future experiments should include practice runs of the experiment before performing the task under test conditions to improve this. Furthermore, designs of the environment itself will also be adjusted. Changes could include: removing onscreen instructions once the participant has begun the task (which should not be needed if practice runs are included), to reduce any distractions that they may have caused; better visual cues i.e. shadows, in addition to the laser pointer; and less reliance on the visual display for the embedded reality NHPT task.

4

Interaction Techniques of Stroke Survivors and Healthy Subjects in a Haptic Collaborative Task

There is already a wealth of research within the field of haptic technologies, specifically in the area of rehabilitation robotics targetted at the betterment of the rehabilitation of arm function following a stroke (Kwakkel et al., 2008; Mehrholz et al., 2015; Prange et al., 2006). Additionally, the field of telerehabilitation is also gaining popularity for research, due to the ability to reduce costs by performing rehabilitation in the home with a system to feedback information and live interaction to the clinic (Johnson et al., 2008).

A stroke occurs when there is an interruption of blood supply to a part of the brain which could be caused by a blockage (Ischemic Stroke) or a rupture of a blood vessel (Haemorrhagic Stroke) (Stroke Association, 2018). Neuroplastic changes need to occur for the brain to recover from damage. This process creates new neural pathways that allow the patient to be able to reuse the impaired limbs. Recovery is generally encouraged by a regime of physical exercise (Pomeroy & Tallis, 2002), and there is evidence to suggest that this can be most effectively achieved through varied training schedules and tasks that are tailored to patients' specific requirements (Krakauer, 2006; Lum et al., 2002). Previous research also advocates the use of collaborative environments used for therapy to improve the motivation of participants (Groten et al., 2009; Johnson et al., 2008).

Building on the team's previous work, in which an experiment was conducted to show how assessment tools can be adapted to be used in a haptic environment (Bowler et al., 2011), this research focusses on answering our second research question: *'Can we identify key traits and movements of users of haptic environments to design better haptic rehabilitation environments?'* A system was developed that allowed for remote collaboration in a shared haptic environment. Previous research advocates the use of collaboration to improve the motivation of participants (Lum et al., 2002; Schutzer & Graves, 2004), and it is our view that similar systems can be used within a home-based telerehabilitation scenario to overcome the challenges of motivation and frequency of rehabilitation in the home.

To meet the requirements of a system that would allow the type of interactions and collaboration within a haptic environment to be monitored, a system was developed which was modelled on the sorting blocks game designed for children. This system allowed for remote collaboration in a shared haptic environment. Our research aims to develop an understanding of specific patterns or types of movements that can be identified in users when interacting with different shapes and when collaborating in pairs through the use of haptic environments, and also to identify key areas of difficulty for individual users, as would be needed in a patient-clinician interaction scenario. Secondary to the goal of identifying key types and traits of movements, a discussion of how these outcomes can be used to design adaptive rehabilitation environments is presented.

Two experiments have so far been conducted with this virtual environment: a three-day experiment at the London Science Museum with over 300 healthy participants; and a long-term study with four stroke survivors that used this system as part of their haptic rehabilitation therapy. This paper presents the similarities and differences between the types of movements seen in both experimental settings, where participants perform the haptic collaborative sorting blocks game. The chapter will conclude with a discussion into the affordances of different types of shapes (flat-sided and curved-sided) and how the choice of haptic shapes can have an impact on the types of movements performed by participants in a rehabilitation context.

4.1 Experiments

For this comparative study, two experiments were conducted: a short-term, large population (300 participants) experiment with healthy participants; and a long-term study with four stroke survivors conducted in their own homes. The haptic environment that was used for these experiments was modelled on the children's sorting blocks game (Figure 4.1). This section will describe the experiment design, set-up and protocol.

Figure 4.1: **The Sorting Blocks Box**. Here, children must place the blocks into the correct holes to complete the task.

4.2 Experiment Design

This experiment was designed based on the children's sorting blocks game (Figure 4.1). The standard version of the game was designed to develop thinking, physical, and creative play skills in young children through a fun environment. The child must place the shaped blocks into the box; however, the shapes only fit through the matching hole in the box. The tool also encourages problem-solving skills, as well as shape recognition and differentiation. This simple game provided a task that would be easy to replicate within a haptic environment and also an environment that would be familiar and easy to understand for a wide range of participants young and old. Furthermore, this task is similar to the clinically established

Box and Blocks Test (BBT) (Mathiowetz, Volland, et al., 1985), which some stroke survivors would be familiar with, and provides a set up that can be modified in the future to incorporate more features of the BBT to provide a measure of haptic assessment.

A hapto-virtual task was created in the form of a 3D computer game similar to the previously described sorting blocks box game. The environment was created using the H3D API (SenseGraphics, 2012) and used the PHANTOM Omni® haptic controller (Sensable, 2011) for the haptic interactions. In this experiment, the focus was on the observed interaction between participants. To this end, the haptic environment was developed in such a way that the shaped blocks could only be moved if both interaction partners were interacting with (touching) the same shape at the same time (Figure 4.2). Participants were required to collaborate in order to move blocks around the virtual workspace. The scene consisted of four blocks (a cube, a cylinder, a sphere and a star-shaped block), within a wooden platform that also contained four holes that matched the shape of the blocks. Within the scene, only the four blocks gave haptic force-feedback to reduce confusion of the task. Participants could move the blocks by pushing them with the haptic device. The task was completed when all four blocks had been placed into the correct holes (the cube and the star block could only fit into their respective holes; however, the sphere and cylinder objects could fit in either circular shaped hole).

Our definition of collaboration is that of a coordinated and synchronous activity that is a result of a continuous attempt to maintain a shared conception of a problem as described by Roschelle & Teasley (2011). In our task, players will have to give up some of their control to their partner as they are unable to manipulate the shape unless their partner is actively participating. This differs from cooperation where tasks are separated between participants to achieve an end goal. Collaboration is achieved when both participants are actively touching and pushing against the same object at the same time. The object will move in the direction of the sum of forces from the two participants. If either participant loses contact with the shape, then the other participant's force vector is no longer effective, and the shape will continue to move in the direction of movement present at the point where both participants were in contact with the object. Objects moving due to loss of contact appear to slide across the board, eventually slowing to a static position defined by a dampening constant. Participants must, therefore, work together to manipulate the object in a manner that moves it toward the correct hole on the board.

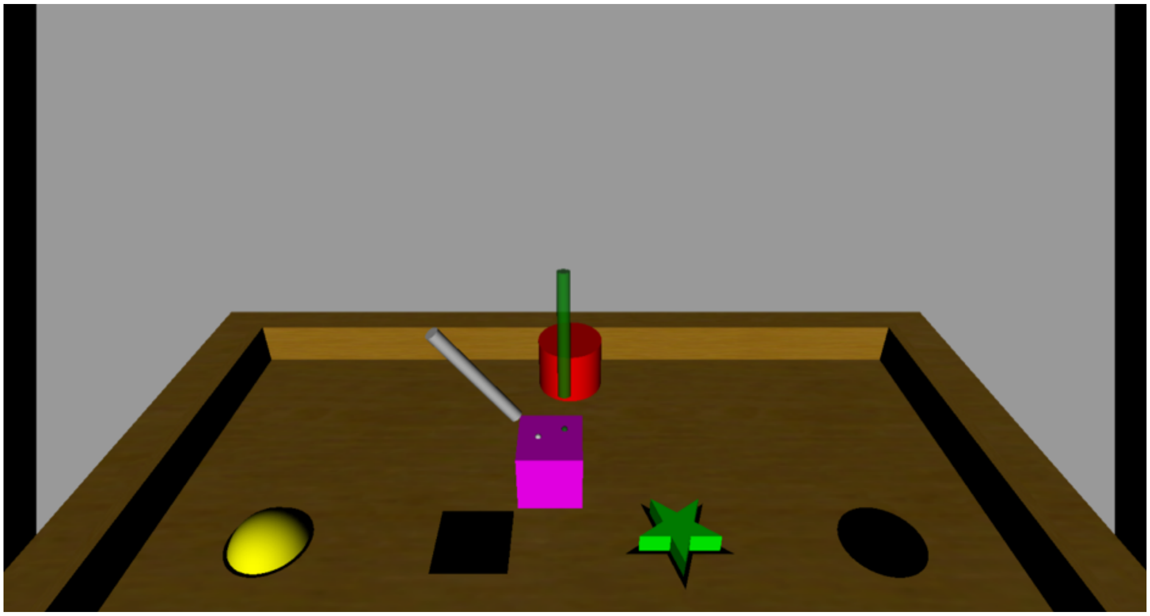


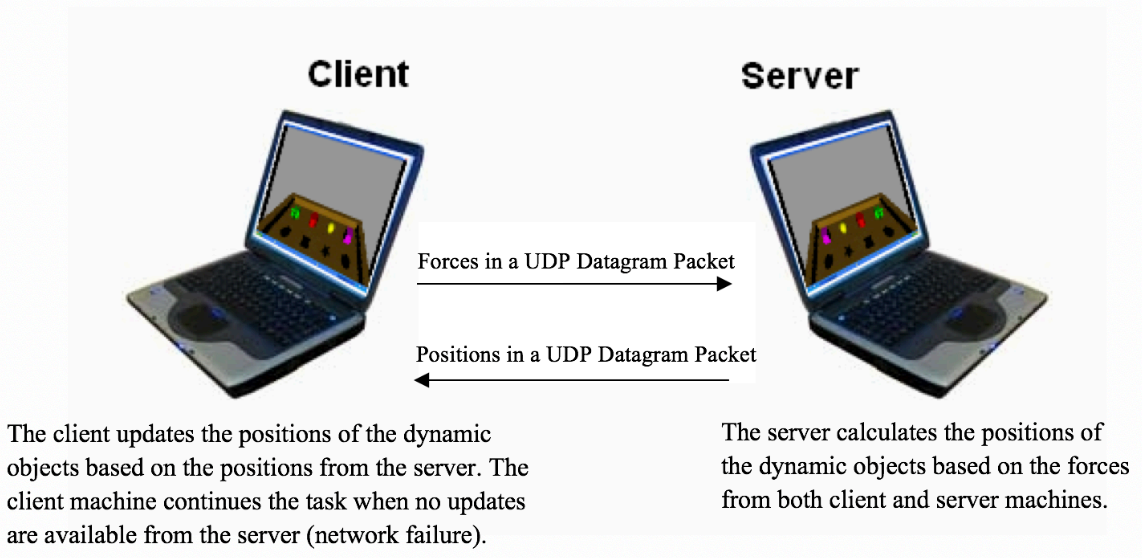
Figure 4.2: **VR environment of the haptic sorting blocks game**. Here two shapes have already been placed into the correct holes. Both participants (grey and green styluses) are currently pushing on the Box in order to place it into the correct hole. All blocks are pushed along the surface of the board and can collide with the edges of the board and the other blocks.

In order to create the virtual simulation described above, simple physics interactions needed to be modelled between shapes and the stylus endpoints within the environment. For this purpose, the H3D API *DynamicTransform* node was employed. This H3D API component provides a shape container that has the basic properties of rigid body motion. First of all, in order for the objects to move when pushed the forces applied by both devices needed to be summed and their output used as the force to set the dynamic object in motion, this should also only occur if both participants are acting on the object. Remote forces were sent over the network and used to provide the input to the *InvertForce* function present on both machines. Further to this, the y-component of the force was fixed to keep the blocks on the board, giving the illusion of the blocks sliding along the surface of the board (Figure 4.2). For the movement of the blocks to come to a halt when not being continuously pushed, a linear damper mechanism needed to be used to reduce the velocity of the blocks over time. This simple algorithm took the defined damping constant for the shape and just reduced the velocity by implementing a simple mechanical damper in the form of:

$$F = -cv$$

Where F is the output force acting on the dynamic object, c is the damping constant, and v is the shape's current velocity. The next interaction to define was the collision between the blocks and the game board, ensuring that all of the blocks stayed within the playable area. The block-board interactions used a simple collision detection algorithm that checked the blocks' positions against the boundaries of the board. When a block hit a block or board boundary, the direction of the spring force acting on the *DynamicTransform* was mirrored along the plane of collision. In addition to reflective forces, an extra damping component was sent to the linear damper for the shape to provide a more visually realistic interaction. Within this same function, the blocks were checked to see whether they had fallen into the correct hole and if so the blocks were removed from the playable area and replaced by an animation of the block dropping into the hole. Finally, the collision between the blocks had to be modelled; this was done in much the same way as the collision between the board and blocks, again extra damping was applied in the event of a collision.

A network communication protocol was employed in order for users to collaborate on the same virtual environment while using separate machines and separate devices. The communication protocol used was the UDP (User Datagram Protocol) transmission model: a simple method of sending datagram packets that require no handshaking or particular data channels to be set up. Data packets were sent in the haptic loop at the rate of 1000Hz. If a network packet was missed (through corruption or network communication error), it was immediately discarded, and the next packet was processed. Occasionally, packets can be received out of order (due to the nature of the UDP transmission model), to overcome this, the timestamps of packets were checked to ensure that the most up-to-date values were used. Fields to be sent over the network were compressed into a byte array and then deserialised to the appropriate variable type by the receiver in C++. The scene was initialised when both virtual environments began transmission of their network packets. The connection between machines was based on a client-server model. The server calculated all the force values based on the forces applied at the HIP of the server and client machines and detected all collisions to send back the updated positions of the dynamic shapes to the client. The client updated its VR environment with the new positions and then sent back the correct forces that were being applied at the HIP to the server for the next frame to be calculated (Figure 4.3). Each machine maintained the state of the virtual environment, which meant that if there were any problems in data transmission, the client would always be presented with a functional virtual environment. In case of packet loss, forces applied from either client would be assumed to be the same until a new packet was sent/received. This kept the positions of the *DynamicTransform* nodes up to date based on the last seen force; however, this never activated in our setup where we used a closed network with the two machines connected directly by a network cable providing a stable rate of transmission.



The client updates the positions of the dynamic objects based on the positions from the server. The client machine continues the task when no updates are available from the server (network failure).

The server calculates the positions of the dynamic objects based on the forces from both client and server machines.

Figure 4.3: **Client-Server communication protocol.** This image describes the network communication between the two machines. Each machine was connected via an Ethernet crossover cable. Client forces were sent as UDP datagram packets to the server machine; the server machine combined the forces present with the remote forces from the client and sent back the updated positions of the objects to the client over UDP.

Each participant was presented with a virtual environment containing a game board with four differently shaped holes, matching the shaped blocks that were also present: a cube, a sphere, a cylinder, and a star-shaped block. For each participant, their collaborator was displayed on the screen as a slightly transparent green stylus, which was explained in the form of on-screen instructions. No time limit was placed on the task; however, the game did not end until all blocks had been placed into the correct holes.

Once the participant pairs completed the task, they were shown a graphical display of their performance against the other participant's performance and a motivational message. Some example messages were: *Most Accurate* - where one player moved more directly from shape to hole than their opponent, and *Most Forceful* - where one player exerted more force consistently throughout the task than the other player. The messages provided a means of gamification to entice players to improve by competition. Measures of accuracy and force could also be used by therapists in the future as measures of improvement, for instance, improvements to accuracy over time would suggest improvements to skilled hand and arm function.

4.3 Experiment Setup – Short-Term, 300 Healthy Participants

This experiment was conducted at the National Science Museum, London, UK, as part of a special event held in the museum's Antenna Gallery entitled 'Therapeutic Robotics'. The event lasted a total of three days, during which time over 1000 visitors viewed and took part in a number of engaging activities involving different kinds of robots.

Ethics approval was sought from both the University of Hertfordshire and from the London Science Museum. Unfortunately, due to the Science Museum's ethical regulations, permission to collect participant information or feedback was not granted; however, permission to anonymously record data with the PHANTOM Omni® by way of log files was granted.

The experiment ran for three days, and in this time data were collected from approximately 300 participants (130 completed games, with some games having multiple interaction partners: where more than one pair took part in a game from start to finish). Two participants at a time took part in the task. Each participant was sat at a desk, in front of a laptop with a PHANTOM Omni® connected. The task was set up in such a way that both participants could see each other if they chose to (sat opposite each other at the desk and could see over the laptop); however, direct communication between participants was not encouraged. Running the experiment at the Science Museum allowed for people of all ages to view and participate in the experiment, participants ages ranged across a broad spectrum from very young children (approx. 4 years) to adults up to approximately 60 years of age, with the participants consisting of roughly 80% children of evenly mixed gender and 20% adults (determined by observation). Interaction pairs consisted of family, friends, and people who had never met before.

4.4 Experiment Setup – Long-Term, 4 Stroke Survivors

The Sorting Blocks Box task used in this experiment was delivered as part of a longitudinal study to evaluate the use of a haptic telerehabilitation system for therapy of a person with an impaired upper limb, where the focus was to assess the viability of the PHANTOM Omni® as a tool for home-based assessment and rehabilitation (see Figure 4.4 for setup). Four members of the St Albans Stroke Club were recruited to participate in this experiment, which ran for 12 weeks. The complete study combined standard assessment tools (Nine Hole Peg Test and Box and Blocks Test) with haptic versions and haptic rehabilitation exercises. The haptic Sorting Blocks Box task was used as a rehabilitation exercise during the 12-week study.

Figure 4.4: **Haptic scenario setup**. This image shows the setup of the PHANTOM Omni® and the laptop which displays the virtual environment. The PHANTOM Omni® is placed in front of the participant, aligned through the median sagittal plane of the participant which provides comfortable positioning of the device as well as limiting left/right-sided bias.

Some ethical concerns must be addressed when working with vulnerable adults, especially when gathering personal data and visiting them in their own homes, this experiment, therefore, had to be approved by the University of Hertfordshire's ethical committee before proceeding. For this experiment to be accepted, written consent from the stroke group coordinator and participating members was required; in addition to this, a valid CRB (Criminal Records Bureau) certificate was also required as the participants are classed as ‘vulnerable adults’ due to their disability.

The study was conducted in patients own homes for their comfort and ease of travel. During the 12 weeks, 14 sessions were conducted: session 1, initial assessment; sessions 2-13, exercise sessions; session 14, final assessment. All sessions were recorded with a video camera for later analysis and also for the safety of the involved parties. All sessions with the PHANTOM Omni® were set up with the device in front of the participant with the screen behind the PHANTOM Omni® (Figure 4.4). In contrast to the experiment conducted at the Science Museum, participants were instructed on how to perform the required tasks, and they were also situated in a more controlled environment with fewer distractions.

4.4.1 Inclusion Criteria

In order to gain the most from this experiment with the limited number of participants that were recruited (four), a number of inclusion criteria had to be set:

- These experiments must be conducted with stroke patients from local stroke groups who have agreed to participate in the study.
- Participants must have suffered some level of upper-limb impairment as a result of their stroke.
- Participants must be more than six-months post-stroke, with no further strokes within the last six months.
- Participants must be able to understand simple instructions given to them.
- Participants must not be receiving any other therapy for hand and wrist function.

4.5 Data Collection

As previously stated there were some restrictions on what could be collected due to the Science Museum’s ethical regulations. Demographic and feedback questionnaire data were not allowed to be collected, and also the use of video recording equipment was prohibited. However, there were no restrictions as to what could be collected through the haptic device as anonymous data, provided that participants be made aware that this was occurring. For this purpose, a notice was displayed on the desk of the exhibition stand and also onscreen before each game started (users had to acknowledge this with a mouse click).

Feedback and demographic questionnaires and video recordings were collected for the Stroke user group; however, these cannot be compared to the findings from the study conducted at the Science Museum.

In addition to the position, orientation and force-feedback variables logged by the system, an accuracy variable, θ, was also calculated based on the angle between the target vector and the direction of the current force of each individual participant. The angle was found using the following calculation (based on the dot product of vectors a and b):

$$\theta = \arccos\left(\frac{a \cdot b}{\|a\|\|b\|}\right)$$

where a represents the force vector, b represents the vector connecting the current position to the target vector, and $\|a\|$ and $\|b\|$ are the magnitudes of vectors a and b.

This angle was then mapped to a percentage value, where an angle of 0° was equal to 100%, and angles of 180°/-180° were equal to 0%.

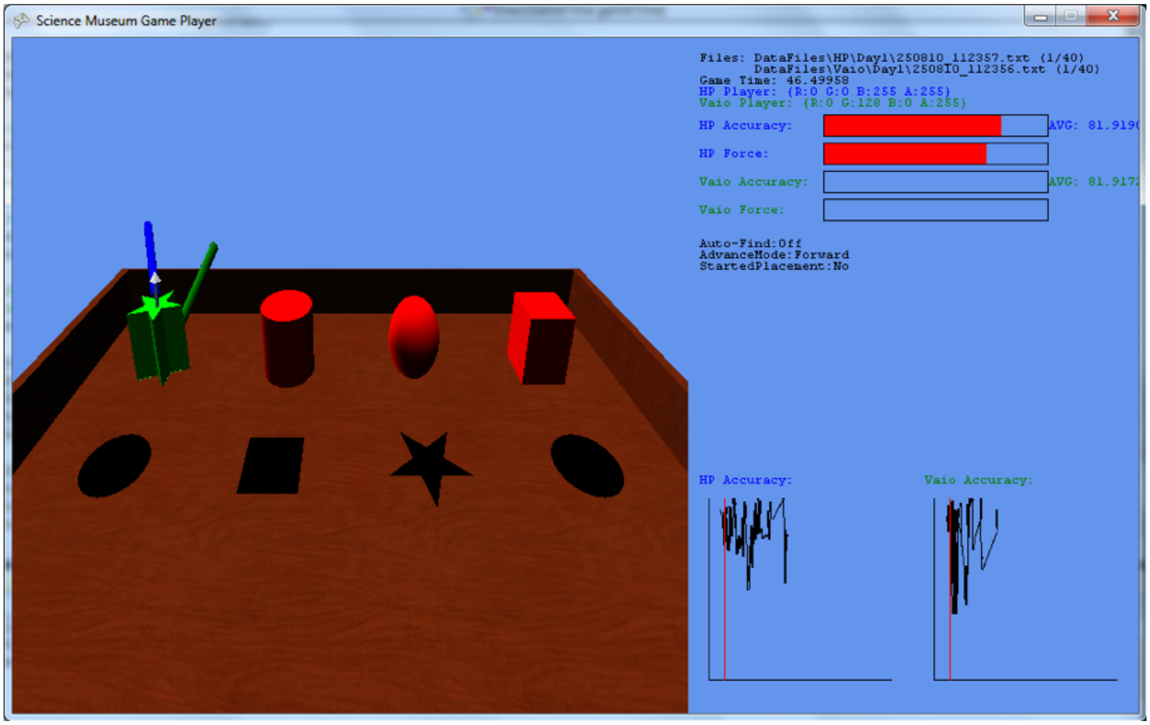
Furthermore, an event string was logged to record special events in order to 'tag' the time-stamped data and also to synchronise events between the data files that were recorded by each separate machine. More specifically the events recorded were: PLACEMENT_X recording the event of a shape being placed into the hole; and DROPPED recording the event of the stylus being placed on the table or back in the inkwell of the PHANTOM Omni® signalling the end of a user's turn before they had completed the task. This data would be used to separate shape placements in the analysis and also to separate games that included multiple interaction pairs which would be detrimental when analysing any learning effects that may be seen throughout each task.

4.6 Analysis and Results

Due to the circumstances for the short term experiment at the Science Museum, there were no video recordings to be compared between the two groups; there was also no questionnaire data to be analysed. As previously mentioned, log files were recorded on each machine at each of the experiments, these log files held information about the environment, such as the position, orientation and forces from the device and the position of objects within the environment, at specific timestamps, recorded at the rate of 100Hz. The setup at the Science Museum also meant that some games were completed by more than two participants; these games were removed as they were not comparable to the setup in the long-term study. We only analysed games that included full interactions for each pair from start to finish were analysed to get a full picture of any learning effects that may have taken place, types of collaboration between two partners (equal effort, or leader-follower), or types of movements performed by the pairs to move the shapes.

In order to further facilitate the analysis of the data, a playback application was created that allowed the tagging of particular points in time with meaningful comments, as would be found in a video coding package. Every time an event occurred, such as placing a block, or dropping a stylus, this could be recorded, and a comment added to the event. The analysis tool itself was developed using Microsoft's XNA framework programmed using C#, which allowed for the creation of a 3D environment that replicated the task environment (Figure 4.5). The models for the virtual environment were created using Google's SketchUp application (http://sketchup.google.com/). Pairs of data files were loaded in turn and then played back using the ScienceMuseum Game Player. Every time an event occurred, such as placing a block, or dropping a stylus, this could be recorded, and a comment added to the event. Finally once a game had been coded; the information was output to .csv and Excel files to enable post-processing in a statistical package.

On loading the file pairs, the files were synchronised by finding the starting packet (first message received from the remote machine), file synchronisation was updated upon the occurrence of each subsequent shape placement to account for any inconsistencies between the timings of the log events on each of the machines. The final function of the Science Museum Game Player was to output data in a formatted manner in the form of .csv and Excel files in which graphs were automatically drawn into the Excel files to be analysed thereafter.



```
Files: DataFiles\HP\Day1\250810_112357.txt (1/40)
       DataFiles\Vaio\Day1\250810_112356.txt (1/40)
Game Time: 46.49958
HP Player: {R:0 G:0 B:255 A:255}
Vaio Player: {R:0 G:128 B:0 A:255}
HP Accuracy:                AVG: 81.919
HP Force:
Vaio Accuracy:              AVG: 81.917
Vaio Force:

Auto-Find:Off
AdvanceMode:Forward
StartedPlacement:No
```

Figure 4.5: **The Sorting Blocks Game Player**. The player was developed using Microsoft's XNA platform in the C# programming language. The game is displayed on the lefthand side of the screen; on the right side are the graphs and relevant information on the running of the player. Objects that were currently being interacted with were highlighted in green, and the direction of the force vectors was also displayed.

The playback application also had an auto-find function for detecting the start and end of placements based on the tagged information from the log files, which would pause at each event so that extra regarding events that occurred whilst performing a placement, such as a user going off task, could be entered about the event.

Within the Sorting Blocks Game Player application, the work done variable was also computed. This variable takes force direction at the HIP (Haptic Interaction Point) of the participant and then computes the dot product with the displacement of the shape in that frame using the following formula:

$$W = F \cdot d$$

where W is the work done, F is the sum of the forces at the HIP of each player, and d is the displacement vector from the previous object position to the resulting position of the object after the combined force was applied. In this way, the work performed by each player could then be compared to see if they were both making an equal contribution to the movement of the object, or if there was another type of interaction occurring, such as a leader-follower scenario. This work variable was also then multiplied by the accuracy variable previously calculated to give the amount of work that was in the direction of the targeted value.

After the initial analysis, 106 complete games (212 participants) from the Science Museum were left for further analysis due to removing games that had multiple interaction partners. A total of 17 games from the long-term study with the Stroke Survivors were used for comparison.

The data collected at the Science Museum were analysed prior to the data from the Stroke Group to identify any preferences that there may have been between the shapes. After viewing the games from the Science Museum study, it was discovered that there were some differences between two specific groups of shapes: flat-sided and curved-sided. It was found that there was a significant difference in the variables: Force, Accuracy, and Work; when comparing these two distinct shape types.

4.7 Shape Preference – Healthy Participants

Of the four shapes (box, sphere, cylinder, and star-block) 2 categories could be defined: curved-sided (sphere and cylinder) and flat-sided (box and star-block). After no significant difference was found between individual shapes, the difference between the two groups was analysed. Again, no significant difference was found between the placement times of the two separate groups. After this, the variables *Force*, *Accuracy*, and *Work* were analysed to see if these were different for the different types of shapes.

4.7.1 Force and Shape Type

The first variable to be compared was *Force*. An independent samples t-test was performed using SPSS as per previous analyses. This test was chosen as the data were found to be normally distributed, and the test best matches the task: Player 1 is independent of Player 2. In each case (player 1 and player 2) it was found that more forces were produced when interacting with flat-sided shapes than with curved-sided shapes (Table 4.1).

Table 4.1: **Differences between Forces Observed for Curved and Flat Sided Shapes**. Higher means were observed for both players for flat-sided shapes, i.e. the participants used more force to get the flat-sided shapes to the hole. The difference between means was significant (^{a}99%).

	t-statistic	p-value	Mean(curved-sided)	Mean(flat-sided)
Player 1	-5.579^a	<0.001	12.76	21.48
Player 2	-7.769^a	<0.001	10.53	16.70

4.7.2 Accuracy and Shape Type

The next variable to be compared was *Accuracy*. This time it was found that greater accuracy was achieved when pushing curved-sided objects towards the goal. The improvement in accuracy indicates that it was easier to push this type of object in a direct route towards the goal than it was to move the flat-sided shapes (Table 4.2).

Table 4.2: **Differences between Accuracy Observed for Curved and Flat Sided Shapes**. Higher means were observed for both players for curved-sided shapes, i.e. the participants were more accurate when moving curved-sided shapes. The difference between means was significant (^{a}99%).

	t-statistic	p-value	Mean(curved-sided)	Mean(flat-sided)
Player 1	2.659^a	0.008	83.95	81.30
Player 2	4.396^a	<0.001	81.70	77.02

4.7.3 Work and Shape Type

The table below (Table 4.3) compares the effect that shape type had on the work done variable. Work done is the mean total work required to place a shape. Following the trend from analysis of the forces and the accuracy, it can be seen that more work was required to push the flat-sided shapes towards the goal; curved-sided shapes tend to require less work to push them towards the goal. However, more analysis is required to determine whether the combined effort is linked to shape preference due to the fact that the forces presented to the objects by participants are based on the force feedback through the object from the remote user.

Table 4.3: **Differences between Work Observed for Curved and Flat Sided Shapes**. Higher means were observed for both players for flat-sided shapes, i.e. more work was required to move flat-sided shapes towards the goal. The difference between means was significant ([a]99%).

	t-statistic	p-value	Mean(curved-sided)	Mean(flat-sided)
Player 1	-4.483[a]	<0.001	10.48	14.79
Player 2	-5.942[a]	<0.001	9.56	14.00

4.7.4 Placement Order

From the order frequency table below (Table 4.4) it can be seen that there was a general preference to place the shapes in order from left to right. This preference could be attributed to the predominantly European audience and may have had an impact on some of the results.

Table 4.4: **Order frequency - healthy participants**. This table describes the general trend to manipulate shapes in order from left to right. Shapes were in left to right order: star, cylinder, sphere, box. The high frequency of the Cylinder for placement 1 is likely because this was to the left of the starting position of the styluses within the workspace (when placed in the inkwell of the PHANTOM Omni®), again, following the left-right pattern.

Placement ID	Star	Cylinder	Sphere	Box
1	39	54	12	1
2	31	26	43	6
3	18	23	50	15
4	18	3	1	84

4.8 Shape Preference – Stroke Group Participants

Unfortunately, a direct comparison between the *force*, *accuracy*, *work*, and *time* variables between the participants at the Science Museum and the participants from the Stroke Group was not possible; as the interaction pairs from the study with the Stroke Group consisted of 1 stroke survivor and the investigator. This pairing gave a bias to any of these variables. The order of the placement was, however, decided by the participant. The frequency table (Table 4.5) shows a similar pattern of objects situated on the right-hand side of the screen being placed last, continuing the trend of preferring left-to-right placement order. More games would need to be analysed to assess the statistical significance of this finding.

Table 4.5: **Order Frequency for Stroke Group Participants.** This table describes the general trend to manipulate shapes in order from left to right.

Placement ID	Star	Cylinder	Sphere	Box
1	3	10	2	2
2	9	3	3	2
3	-	4	12	1
4	5	-	-	12

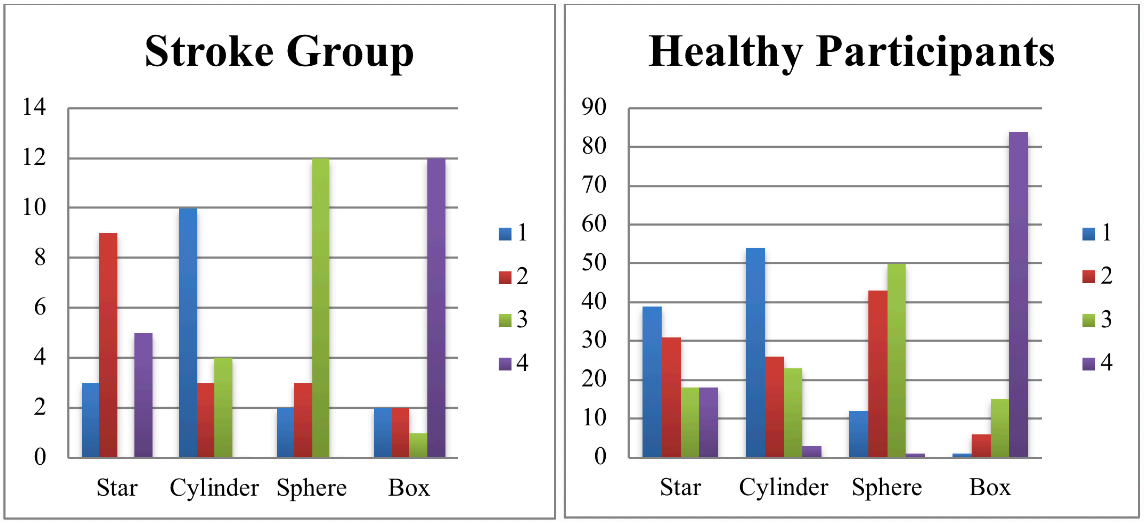


Figure 4.6: **Order frequency**. These graphs depict the preferred order of shape placement described in tables 4.4 and 4.5 above. A general trend in placement order from left to right can be seen.

4.9 Measuring Collaboration

To further investigate the notion of learning within the virtual environment the time spent collaborating was analysed against the total time for each placement (1 through to 4). Time spent collaborating was defined as time spent on the placement phase, where the object was moving closer to the target, calculated as a percentage of the overall time to place the object. When plotting this data as a scatter diagram, it was noted that the data resembled a function on the order of:

$$y = cx^{-a}$$

where c is an arbitrary constant, and x is raised to the ath power. SPSS was then used to provide a curve estimation regression model based on the power equation mentioned earlier (Table 4.6).

The table shows that the amount of variability explained by the model increased from placement 1 through to placement 4 (R^2) and was found to be statistically significant at the 99% confidence interval. The graphs also describe that the model is based on the notion that as more time is spent collaborating, faster times are produced. Time spent collaborating is defined as pushing in the correct direction more of the time should move the object closer to the target, and therefore the placement should be quicker. What is more interesting is the R^2 value, this increases continuously from placement 1 through to 4, suggesting that some learning may have taken place throughout the game.

Table 4.6: **Time Spent Collaborating vs Placement Time – Non-Linear Regression.** Shown in this table are the R^2 values for the regression model described by a power curve. This model shows an increase in explained variability (52.3% to 67.4%) from placement 1 through to placement 4.

Placement ID	R^2	Significance
1	0.523	<0.001
2	0.567	<0.001
3	0.644	<0.001
4	0.674	<0.001

An example of the regression model described above is given in figure 4.7. As more time is spent collaborating, the time to place an object decreases significantly as described by the model (line) plotted on the graph.

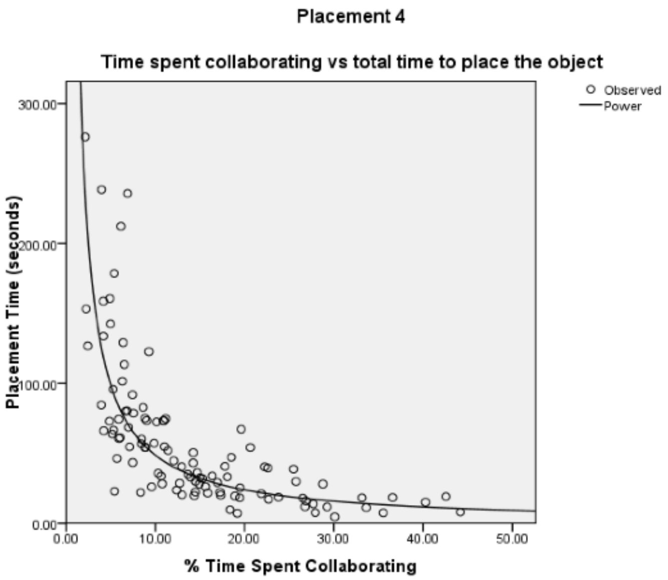


Figure 4.7: **Power curve graph for placement 4.** This plot shows the fit of the data points to the estimated regression model provided by SPSS.

4.9.1 Agreement Times

Agreement times were also analysed to strengthen the case for a learning effect that may have taken place throughout the game. We defined agreement time as the time spent moving around the virtual environment before both coming to an agreement and commencing movement of the shape.

As was seen in the placement times, the first agreement value was significantly slower than the agreement times seen in placement numbers 2 to 4, while the mean agreement times also reduced from placements 1 to 4. Again, we can attribute this to the fact that once the users were acquainted with the task, they were able to perform the placements more efficiently (Tables 4.7 and 4.8).

Table 4.7: **Agreement Times between Placements.** This table compares the agreement times for all for placements for each game played. We can see that after the first agreement time, times are significantly reduced, suggesting a learning effect whereby users have begun to understand the task and come to a decision, on which shape to place next, more quickly. ^{a}The second condition is significantly quicker than the first at the 99% confidence interval.

Test Condition	t**-statistic**	p**-value (significance)**
Agreement 1 and 2	7.675^a	<0.001
Agreement 1 and 3	7.273^a	<0.001
Agreement 1 and 4	7.476^a	<0.001

Test Condition	t**-statistic**	p**-value (significance)**
Agreement 2 and 3	0.440	0.661
Agreement 2 and 4	0.919	0.360
Agreement 3 and 4	0.646	0.519

Table 4.8: **Mean and Standard Deviation of Agreement Times.** There is a decrease in average agreement times from placement 1 through to 4

Placement ID	**Mean**	**Standard Deviation**
1	36.018	2.902
2	13.97	1.078
3	13.432	1.205
4	12.377	1.463

4.10 Observations

From the data collected at the Science Museum, it was observed that forces were higher for manipulating flat-sided shapes, accuracies were higher when manipulating curved-sided shapes, and more work was required to move flat-sided shapes towards the goal. From Figure 4.8, and the following additional observations, it becomes clear that the two shape-types afford different movement styles, whereby curved-sided shapes are likely to be pushed in a more direct route towards the goal (this accounts for the *Accuracy* and *Work* variables). The higher forces seen can also be attributed to the likelihood of competing forces from interaction partners when pushing on different sides of the shape.

As the data collected at the Science Museum was a one-off event, there was no follow up procedure to determine if these interactions would change over time. The participants from the Stroke Group had been training with the haptic device for two weeks before attempting the collaborative task, and each participant repeated the collaborative task many times (Participants 1-4 repeated the task 5, 4, 2 and 6 times respectively).

Analysis of the movements in the games of the Stroke Group participants was conducted using the playback application as described earlier. It was observed that for

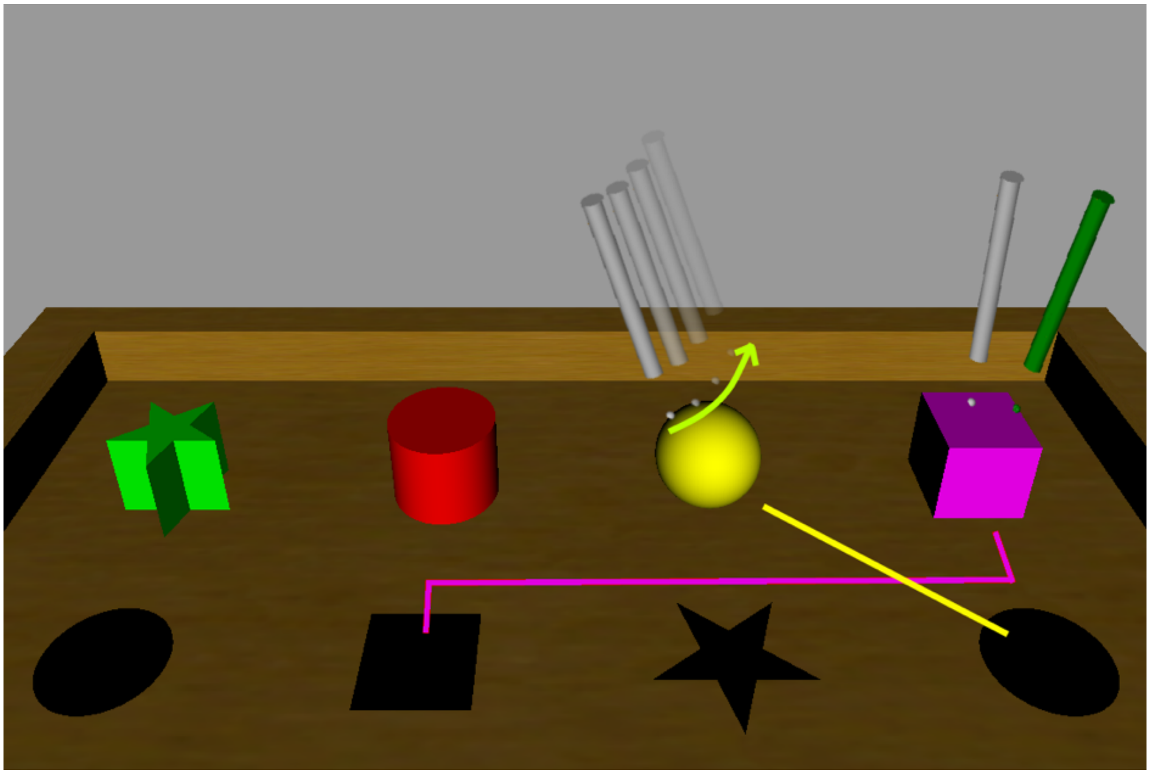


Figure 4.8: **Shape Type Movement Affordances**. This image describes the two types of movements observed that were used to move shapes within this collaborative haptic environment. On the far right participants tended to push the box against the flat sided, in-turn this pushed the box along straight line paths as described by the purple line. In contrast, it was observed that participants pushing the curved sided shapes (sphere and cylinder) were able to take a far more direct path (yellow line), as flat sides did not constrain them. However, a side effect of this movement was the occurrence of brushing/rolling movements (curved arrow above), where participants would try to roll the ball due to the curvature of the shape. It is interesting to see that this natural, real-world motion crossed over into the haptic dimension, even though it was not needed to perform the task efficiently due to the friction present on the surface of the shape.

attempts 1 and 2, participants would likely follow the above pattern of movement for the flat-sided shapes. This interaction was assessed by determining the proportion of the placement (moving the shape to the correct hole) where both participants were touching the same face of the object (Table 4.9). This ratio swayed in favour of spending a higher proportion of time pushing different sides of the same shape as participants repeated the task. This result suggests a pattern of interaction that can be described as leader-follower: initially participants followed the investigators lead as to where to push the object (on which face); however, as they gained confidence and experience they chose where to push, thus creating a more efficient movement trajectory. Although these findings are not statistically significant, it would be interesting to see if the same would hold true if the experiment were to be conducted with a larger pool of participants.

Table 4.9: **Trends in Placement Time.** This table describes the trend to spend more of the placement time (as a percentage) pushing on different faces of the object while moving the object towards the goal.

Repetition	**Participant 1**	**Participant 2**	**Participant 3**	**Participant 4**
1	71.25%	73.66%	94.58%	84.78%
2	77.36%	69.60%	90.19%	73.33%
3	74.76%	75.49%		83.19%
4	76.57%	80.29%		80.04%
5	91.48%	88.31%		88.42%
6				85.32%

In Figure 4.9, two stylus objects can be seen interacting with the star-shaped block. Although neither stylus is pushing in the direction of the target, the object is moving in the correct direction. What happens in this scenario is that users make compensatory movements whereby they forfeit their accuracy for their partner based on the force feedback that they can feel through the shape of the remote user's contribution to the movement of the object. This more collaborative interaction style is much more efficient than the leader-follower style observed in both the Science Museum data and the initial games with the Stroke Group.

Separate to the analysis of the log files from the haptic tasks, some interesting observations were made with the Science Museum data, due to the nature of the experiment setup. First of all, it was seen that although participants were pre-

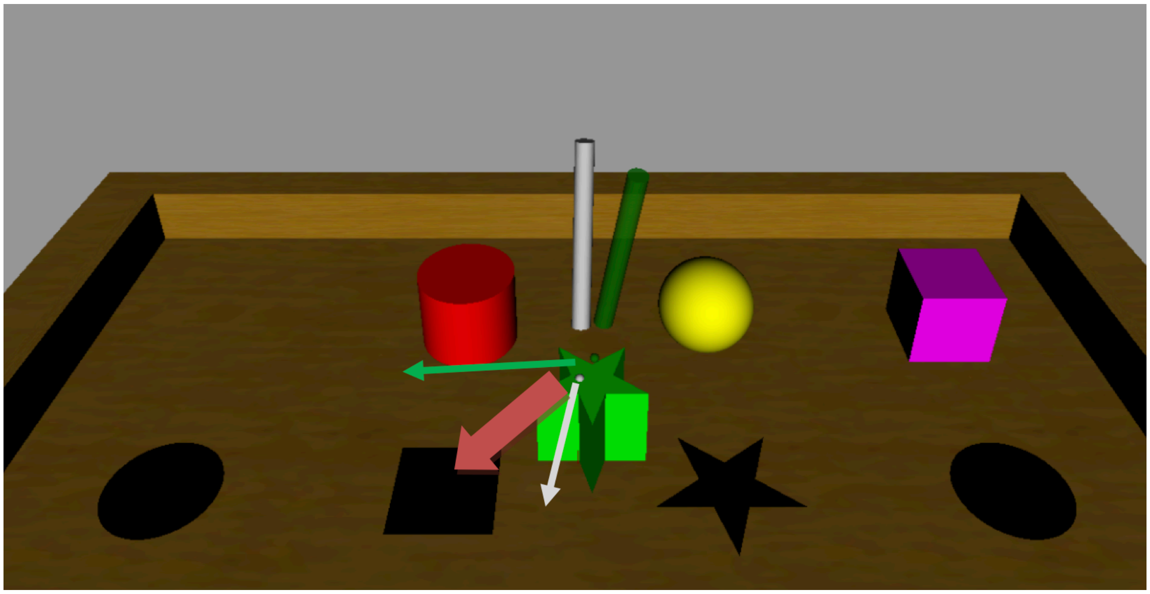


Figure 4.9: **Two participants pushing the star-shaped block.** The grey stylus is the *local* user; the grey arrow here represents the direction of the force being exerted on the shape. The green stylus represents the *remote* user; the green arrow represents the *remote* user's force acting on the star-shaped block.

sented with information on how to perform the task, it was not required: this was observed by the fact that not everyone read the instructions or could read the instructions due to the instructions only being given in English. Participants instinctively knew what to do, showing that the nature of the task presented itself with enough information for the interaction required to be deduced by participants. Secondly, communication between partners was not required for the task to be completed; this was particularly noticeable when interaction partners were utterly unknown to one another. In this setting the task could be tested in the future in two separate scenarios: with communication encouraged; and without communication made possible. In this manner, it could be determined whether the task encouraged communication between two parties (which could be beneficial in a social setting, where stroke patients could use the system to interact with each other whilst performing rehabilitation). Furthermore, the task could also be used in a more controlled/clinical setting, whereby the therapist may want the patient to focus solely on the task at hand, without the cognitive distraction of communication (either via VOIP, video or a combination of the two). However, no distinction was made in the log files between communicating pairs and non-communicating pairs so this is not analysed here.

From the analysis, it was found that (for the Stroke Group participants) there was a tendency to move toward a more cooperative interaction style from that of the initially described leader-follower style observed when moving flat-sided shapes. Establishing a more cooperative style of interaction could be considered as a learning effect where, during repeat performances of the task, players became more effective at collaborating (moved to a more efficient method of collaboration). This type of learning can be described as 'acquisition learning' defined by (Rogers, 2003): *'Acquisition learning is seen as going on all the time. It is 'concrete, immediate and confined to a specific activity; it is not concerned with general principles'.*

The learning effect described isn't without limitations. The main limitation of the results from this study is that there were very few participants from the Stroke Group and this cannot, therefore, be deemed a statistically significant finding. However, future haptic environments can be based on this model of interaction. Cues could be given to participants who are struggling with the task based on their position and interactions within the environment. Flat sided shapes could be used for strength training exercises (due to the higher forces observed when players interacted with these types of shapes), and curved-sided shapes could be used for motor control exercises (due to the small point of contact required to be able to push the object in the correct direction). Motivational cues could also be given in accordance with their level of collaboration (Figure 1.1). This level of collaboration could be described as a function of the direction of movement of the object, the angle between the force vectors of the two players, and whether or not players were pushing the same face of the object.

4.11 Conclusions

When exploring the initial parameters of agreement time, and placement time it could be seen that there was a trend for them to improve from placement to placement. The reduction in placement times suggests that users improved their performance of the task as they continued to play. In this experiment, we found a strong link between modes of collaboration and performance of the task itself. Next, an analysis was performed on the accuracy value in comparison to placement time; however, this showed no significant correlation. It is likely that this is due to the accuracy being tested not being the accuracy of the direction of the object. From the image (Figure 4.9) two stylus objects can be seen interacting with the shape, however, neither stylus is pushing in the direction of the target; however, the object is moving in the correct direction. What happens in this scenario is that users make compensatory movements whereby they forfeit their accuracy for their partner based on the force feedback that they can feel through the shape of the remote user's contribution to the movement of the object. In this case, the accuracy value should be calculated based on the combined force acting on the object and the target vector.

The next stage of the analysis was to identify any preferences between the shapes. After analysing the shapes separately, we discovered that there were some differences between two specific groups of shapes: flat-sided and curved-sided. We found that there was a significant difference in the variables: *Force*, *Accuracy*, and *Work*; when comparing these two distinct shape types. Forces observed were higher for manipulating flat-sided shapes; accuracies observed were higher when manipulating curved-sided shapes, and more work was required to move flat-sided shapes towards the goal. From figure 4.8, and the following additional observations, it becomes clear that the two share-types afford different movement styles, whereby curved-sided shapes are likely to be pushed in a more direct route towards the goal (this accounts for the *Accuracy* and *Work* variables). The higher forces seen can also be attributed to the likelihood of competing forces from interaction partners when pushing on different sides of the shape.

In a follow up to the different types of shapes, trajectory analysis was performed: At each time stamp the absolute distance to the optimum path is taken, this is then averaged for each placement to give an error value for the placement. We found that for placements 1 – 3 more variation was found (higher error) with the flat shapes compared to curved shapes, suggesting that there is a difference in the paths taken towards the goal between the two groups, and that the curved-sided shapes were pushed in a more direct path than the flat-sided shapes (Figure 4.8). Preliminary analysis has shown that there appears to be a brushing technique occurring for curved-sided shapes (viewed subjectively in the Science Museum Game Player), where users try to roll the shape or slip off the side of the shapes as they are presenting their forces (Figure 4.8). This brushing technique can also be seen when isolating the y-component (vertical movement) of the force vector (where x and z are the only components that contribute to force) that there many more peaks throughout the movement of the shapes (Figure 4.10). Further analysis needs to be conducted to isolate the brushing motion from the task to see whether this can be attributed to the properties of the shape. If so it may be possible to design haptic rehabilitation tasks based on the affordances of shapes: where different shapes require the user to perform different types of movement relevant to the rehabilitation.

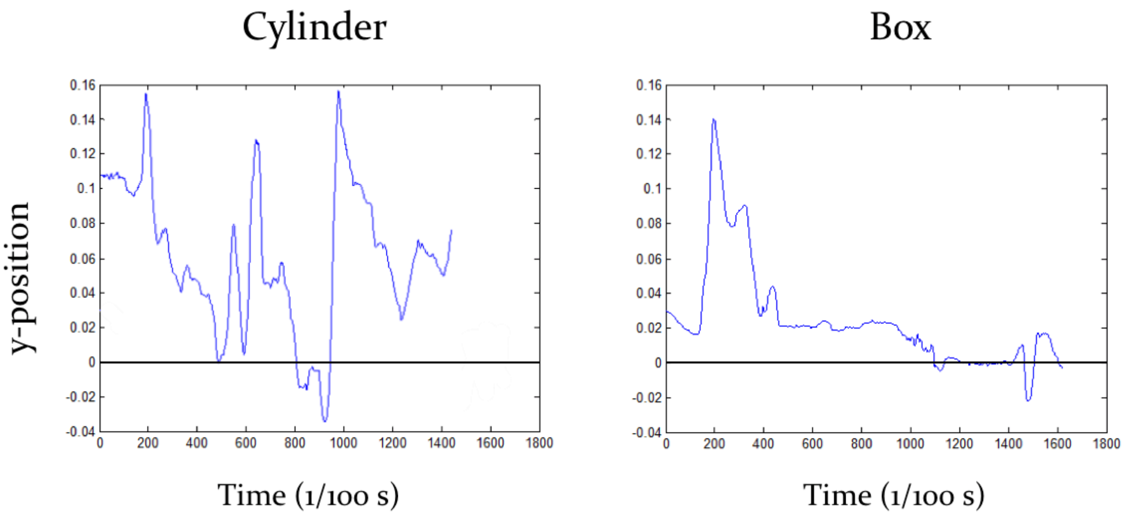


Figure 4.10: **These graphs compare the y-positions of haptic styluses** when pushing shapes over the course of a single shape placement: in this case, the cylinder and the box are being compared. The graphs plot the y-component, relating to vertical movement, against time, where the base of the game board is at $y = 0$. More, and higher, peaks and troughs can be seen for the cylinder (a curved-sided shape) than in the box (a flat-sided shape).

It should also be noted that the ordering of objects could have affected the task performance times, and also, due to learning, of the differences between the shapes that were observed, however, we did not control for this. This task could be improved in the future by repeating the experiment, re-ordering the shapes at random. A full study of the movement of different shapes within a collaborative haptic environment needs to be conducted to support the findings further.

There are a number of limitations to the studies that were conducted with this equipment. The main limitation is that the science museum experiment was not set up in a controlled environment which likely led to quite a number of inconsistencies in the results. As such, no demographic data was collected; neither are we able to compare data between pairs as there is no reason why one pair would perform any differently to another. If this experiment were to be conducted again, improvements would need to be made to the task itself in order to code more events into the log output so that we could track successful moves and better detect movement strategies such as ‘leader/follower’ and ‘collaborator’.

Further to the limitations of the setup at the science museum, the collaborative environment set up in the stroke survivors homes did not give an accurate reflection of real-world performance. In the home-based study, the experimenter acted as the collaborating partner thus adding a large amount of bias to those results. The results presented with respect to the stroke group participants show promise for further investigation in a more controlled setting.

From the results presented in this chapter, it has been shown that there is a distinct difference in the types of interaction performed on different shaped objects within a collaborative haptic setting. Also, a perceived preference for shape movements and placement order was described that was present for both groups of participants. Finally, a learning effect was observed in the stroke group, which would likely be found with healthy participants if the task was repeated in follow up procedures.

Our research question asked *"Can we identify key traits and movements of the users of haptic environments to design better haptic rehabilitation environments?"*. With this system, we have indicated that we can distinguish between brushing/rolling movements, and straightforward pushing movements. We have also shown that the measurement of force and accuracy in the environment can indicate whether or not a game was more collaborative of was played in a more leader/follower style. Due to the limitations of the way in which the data was collected, in an uncontrolled environment, our findings on these factors were not conclusive, but they do show promise for further investigation.

A further study into the movement of different shapes within a collaborative haptic environment needs to be conducted with a larger group of stroke participants to support these findings further. This study would ideally be conducted with a healthy group for control. Learning effects could then be separated from the shape affordances, and a more accurate picture of collaborative haptic interactions could be described.

5

A Home-Based Haptic System for the Assessment of Arm Function Following a Stroke

As the second most significant cause of death in the world (WHO, 2017), stroke poses a significant economic burden on many different sectors of society (Stroke Association, 2018). In the UK alone, it is estimated that stroke costs £26 billion a year, with new cases of stroke accounting for roughly £5.3 billion per year (Patel et al., 2017). Around 30% of this sum is expected to be accounted for by the NHS. For each of the 100,000 strokes that occur in the UK every year, the National Institute for Health and Care Excellence (2012) estimate that the NHS could save £1,600 by providing Early Supported Discharge, providing a total saving of roughly £160 million per year. With these costs to society outlined, it becomes clear that there is a need to promote, improve, and facilitate treatment protocols for stroke in the home setting.

Previous home-based studies for the rehabilitation of arm function following a stroke have shown some promising results. Notably, Holmqvist, Koch, et al. (1998a) ran a study to evaluate rehabilitation at home following early supported discharge. This study found no significant differences in outcome measures between home-based rehabilitation and continued rehabilitation in the clinic, although patient satisfaction was higher in the home-based group. These results suggest that early supported discharge with continuity of rehabilitation in the home could be beneficial as long as outcomes are followed up at regular intervals (3, 6, and 12 months), offering cost savings over clinical rehabilitation.

More recently, other studies have investigated telerehabilitation and robot-mediated therapy with a view to being able to provide these protocols in the home (Chortis et al., 2008; Hoenig et al., 2006; Johnson et al., 2008). Overall, the results show promise that telerehabilitation technology has the potential to improve performance in a rehabilitative context, and that by introducing play and game-based elements (either interactively at home, or remotely via telecommunication) users find the tasks more valuable, engaging, and enjoyable, and are therefore willing to spend more time on the task (Johnson et al., 2008).

Cost can be a limiting factor in providing adequate rehabilitation services in the home (Reinkensmeyer et al., 2002). We have chosen to use a relatively low-cost haptic controller (approximately £1000) for our experiments: the PHANTOM Omni®. There are other benefits to using this device in a home-based scenario, for one, the device is small and can easily be placed on a tabletop alongside a laptop or monitor for the user to complete tasks. The device has 6 degrees of freedom that allow for users to perform natural movements that underpin everyday tasks, and furthermore, the device provides a safe level of force-feedback ($3.3N$ max force) that helps to promoted improvement in strength, speed, stamina and precision of arm function. The minimum requirements for a computer to drive the device are also low so that a relatively cheap laptop or PC could be paired with the device. The software available for programming the PHANTOM Omni® is open source, and there are numerous examples available on the internet that make programming the device much more accessible.

This chapter describes the design, implementation and protocol of the final experiment to support this PhD thesis: a trial to assess the efficacy of a home-based assessment and rehabilitation system using the PHANTOM Omni®. The experiment is a longitudinal study to evaluate the use of a haptic telerehabilitation system for therapy of a person with an impaired upper limb, and is focussed on answering the third research question defined in the introduction to this report:

Q3: Can it be shown that the PHANTOM Omni® is a viable platform for producing home-based rehabilitation systems for hand function following a stroke?

This experiment will, therefore, demonstrate the use of a haptic telerehabilitation system in the therapy of an impaired upper limb. After approaching local stroke groups, four members of the Hertford and Ware stroke group were recruited to participate in this experiment, which ran for 12 weeks. Following the outcomes of our previous studies, this system combines standard assessment tools (NHPT and BBT), haptic assessment (improved embedded and virtual NHPT), and haptic rehabilitation exercises. This study is a single-cohort, pre-peri-post assessment study spanning 12 weeks in participants homes ($N = 4$, mean age = 65.5 ± 13.97). The rationale for this methodology is to provide multiple points of assessment around a period of focussed exercise of the impaired limb, recorded improvements will be used to justify further and future experimentation.

Many ethical concerns have to be addressed when dealing with vulnerable adults, especially when gathering personal data and visiting them in their own homes, this experiment, therefore, had to be approved by the University's ethical committee before proceeding. Written consent from the stroke group coordinator and participating members was required for this experiment to be accepted, in addition to this, a valid CRB certificate was also required as the participants are classed as ‘vulnerable adults’ due to their disability.

5.1 Participants

For this study, we recruited the participation of four members of a local stroke group - the Hertford and Ware Stroke Group. Members of this stroke group came from all areas of Hertfordshire, thus were near the University, so were ideal candidates regarding location. Prior to recruiting participants, we spent time talking to the members in order to gain valuable insights into the daily lives of stroke survivors. We also presented the University's current research in rehabilitation robotics and the research content of this path of study to the stroke group. Members of the group were then given our details so that they could contact us directly if they were willing to participate in the trial.

Four participants volunteered to be a part of this trial following our presentation. These participants had all suffered at least one stroke at some point in the past, some more recently than others. Two of the participants were female, and two of the participants were male. All participants had some level of hemiparesis: for 50% of the participants, this affected their dominant arm, the other 50% of their non-dominant arm.

As part of the presentation to the Hertford and Ware Stroke Group, we informally introduced the PHANTOM Onmi® to the members in attendance. This gave the group the opportunity to try the system and also for them to offer some preliminary feedback on the setup and the tasks that were to be used as part of the experiment. Many of the attendees tried the device and tasks. The four volunteers for the study felt comfortable that they would be able to use the device at this preliminary stage without the use of supports or other compensatory devices.

5.1.1 Inclusion Criteria

We set some inclusion criteria to gain the most from this experiment as we would only be conducting a limited number of case studies:

- These experiments will be conducted with stroke patients from local stroke groups who have agreed to help us with our work.
- Participants will have suffered some level of upper-limb impairment as a result of their stroke.
- Participants must be >6 months post-stroke, with no further strokes within the last six months.
- Participants will have to be able to understand simple instructions given to them.
- Participants will not be receiving any other therapy for hand and wrist function.
- Participants must be able to grasp the PHANTOM Omni® haptic stylus.

As a requirement of this study, it was important that none of the participants was receiving further or continued clinical treatment following their stroke, so as not to impact or influence the findings of this trial.

The selection of participants was dictated by the availability of stroke survivors from the Hertford and Ware Stroke Group. Following a presentation to the group, four participants agreed to be part of the study. As this is a case-study-based qualitative experiment, no formal statistical power calculation was conducted to verify the significance of this sample size (4) to the population.

Participants were given a choice to have the trial conducted either in their own homes or at the University of Hertfordshire. All participants decided that they would participate in the trial in the comfort of their own home. Conducting the study in participants' own homes was beneficial to the study itself, as it would hopefully go some way to validating and testing the concepts of this system in a home-based environment. At the end of the study, participants were given £70 for their time.

Participants will now be described in turn. The names given to the participants here are not their real names; this serves to keep the participants' anonymity.

5.1.2 George

George is a 68-year-old male. He is a retired HGV and Bus driver who could no longer work following six strokes. His strokes left him with acute hemiparesis on the upper left-hand-side (his non-dominant side) and also with a blind spot in his right eye. George suffered his last stroke one year and three months prior to the commencement of the trial; however, he is no longer receiving any form of physical therapy or treatment for his impairments. The only treatment that George received following his strokes was a 6-week course of physiotherapy for his arm and hand function.

George has problems with mobility and upper-limb impairment; however, he manages the general activities of daily living for himself, such as cooking, cleaning, personal hygiene, and making tea.

George knows of computer games and computer devices in general but does not describe that he has any level of competency with such. He does not play computer games and does not use a computer. He has never used a haptic device before this trial.

George is a very happy character, nothing gets in his way, and he is very keen to provide valuable insights into how his impairments affect his daily life.

5.1.3 Linda

Linda is a 75-year-old female. She is now retired. Linda suffered a stroke approximately 3 and a half years before this study. Her stroke left her with upper and lower limb impairment on her right-hand side (her dominant side). She has problems with mobility (her right leg tires easily) and occasionally uses a stick or walking frame to get around, but manages to care for herself. She is very house proud and still enjoys cooking meals for herself and her husband.

Linda does not receive clinical therapy; however, she does attend pilates and keep fit classes on a weekly basis.

Linda has a ‘neutral’ familiarity with 3D computer games: she knows of them but does not use them. She has never used a haptic device and does not own a computer.

5.1.4 Robert

Robert is a 77-year-old male. He is now retired. Following his stroke just ten months before the trial, Robert has to use a wheelchair to get around. He is right-handed, and his stroke has affected both his right and his left-hand side, but his right-hand side (dominant) has been most affected. He is not receiving any therapy for his impairments and relies on his wife to help him with most activities of daily living.

Robert describes himself as very unfamiliar with 3D computer games and has rarely ever used a computer. He had never used any form of haptic technology before and was quite impressed by the PHANTOM Omni® device that we demonstrated to him before the commencement of the trial.

Robert struggles with his loss of independence and sometimes feels like a burden to his wife following his stroke. He gets tired easily and states that he finds it hard to maintain concentration for long periods of time.

5.1.5 Jennifer

Jennifer is a 42-year-old female. She works as an administrator and bookkeeper. It has been 15 years since Jennifer’s stroke, and she is still severely impaired on her dominant left-hand side. Following her stroke, Jennifer is blind in her left eye. She also has hearing difficulties in her left ear.

Jennifer has learnt to perform many activities (writing, cooking, eating and using the computer for example) with her right (non-dominant) hand since her stroke. At the time of her stroke, Jennifer was told that she would be unlikely to make any more improvements after six months following her stroke; however, Jennifer feels that she has made continuous improvements over the last 15 years.

Jennifer describes herself as very unfamiliar with 3D computer games. She does not play any computer games, nor has she ever used a haptic controller or device. Jennifer does, however, use computers on a daily basis for her job.

Jennifer is an enthusiastic and confident lady, she is excited to be a part of this trial and hopes to be able to learn something as well as to give something back to the stroke community through research even though it has been a long time since her stroke.

5.2 Experiment Design

All exercises were fully explained to the participants at the beginning of the trial. Participants were allowed to stop performing a task at any point.

The experiment included limited use of a demographic questionnaire, documented interview-style questions, and a series of on-screen questions that were presented to the participants throughout the trial (Appendices C-F).

Throughout the experiment, we collected video data of the participants' arm movements, and also webcam footage of the participants' facial expressions while they were performing the tasks. The analysis of all of this information is outside of the scope of this chapter, but some video footage was used to confirm anecdotes and sentiment of the notes made on the questionnaires. The recordings were also taken as a safeguard to protect both parties against assessed risk. All of this information was gathered with the expressed consent of the participants of the experiment.

All of the sessions were conducted in the participants own homes. This links well with the literature on home-based studies, where, studies have shown that conducting therapy in the home is often more effective and efficient than elsewhere (Reinkensmeyer et al., 2002; Wade, 1989).

5.3 Experiment Setup

As previously stated, the experiment ran for 12 weeks. During the 12 weeks, 14 sessions were conducted: session 1, initial assessment; sessions 2-13, exercise sessions; session 14, final assessment (figure 5.1). All sessions were recorded with a video camera for later analysis and also for the safety of the involved parties. All sessions with the PHANTOM Omni® were set up with the device in front of the user with the screen behind the device, as in the set up of the original NHPT experiment described in chapter 3.

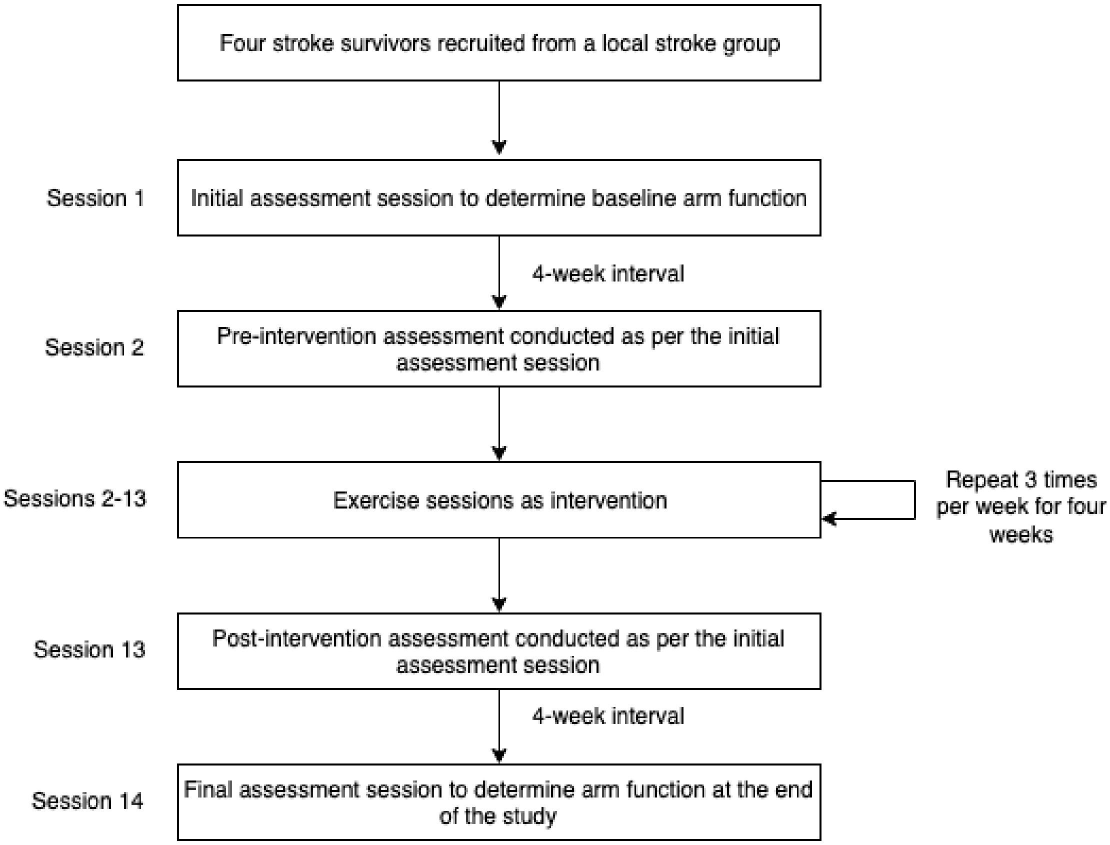


Figure 5.1: **Study Protocol.** This image provides a flowchart of the sessions that were conducted with participants over the course of the 4-week experiment.

Influenced by the work of Timmermans et al. (2010), we scheduled the exercise sessions over four weeks, three times per week, at random intervals and days. Distributed and random practice methodologies have been shown to improve outcomes and retention of learned motor performance over that of bulk, repetitive training (Magill, 2007; Shea et al., 2000). We also varied the tasks that participants performed from session to session. Each session would generally consist of three to five tasks.

None of the participants of this study required arm support to use the system - they were all able to pick up the stylus and move it through both the transversal and sagittal planes of space. None of the participants utilised arm, wrist, or hand supports or any form of compensatory equipment when participating in the study. As this study was not conducted alongside medical professionals, the limitations of the ethics application were also such that we were not able to provide such equipment even if it was thought that it might be necessary. This is a limitation of the study as each of the participants would be prone to differing levels of proximal (shoulder) and distal (hand) fatigue, which could not be reduced by medical apparatus. As is described in the results section - this experiment is a series of case studies; thus the results of each participant should not be directly compared to that of other participants. Figures 5.2, 5.3, 5.4, and 5.5 show how the system was used by participants.

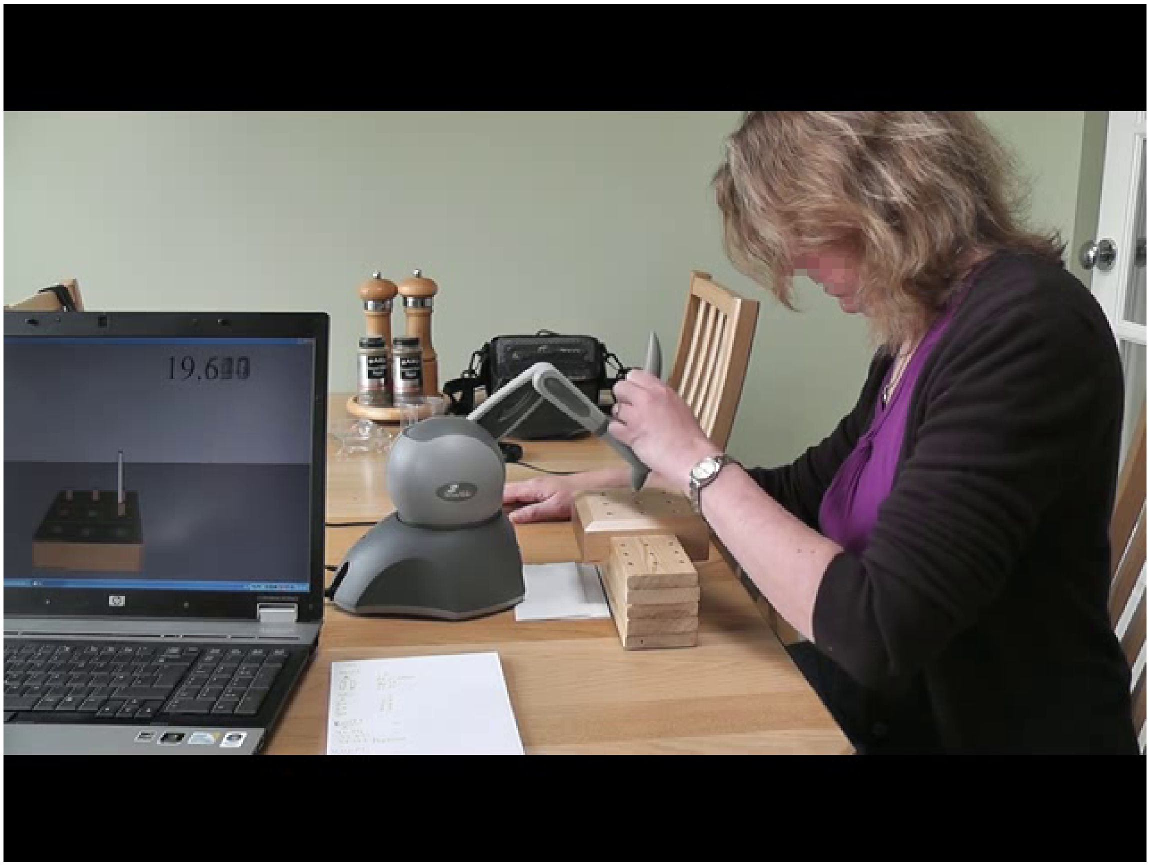


Figure 5.2: **Experiment Setup: ENHPT.** This image shows how the apparatus was set up in one of the participant's homes. The Embedded NHPT apparatus is positioned in front of the participant in a comfortable position

Figure 5.3: **Experiment Setup: ENHPT (2).** This is another example of the Embedded NHPT setup in a participant's home. As can be seen, the PHANTOM Omni takes up very little space behind the pegboard.

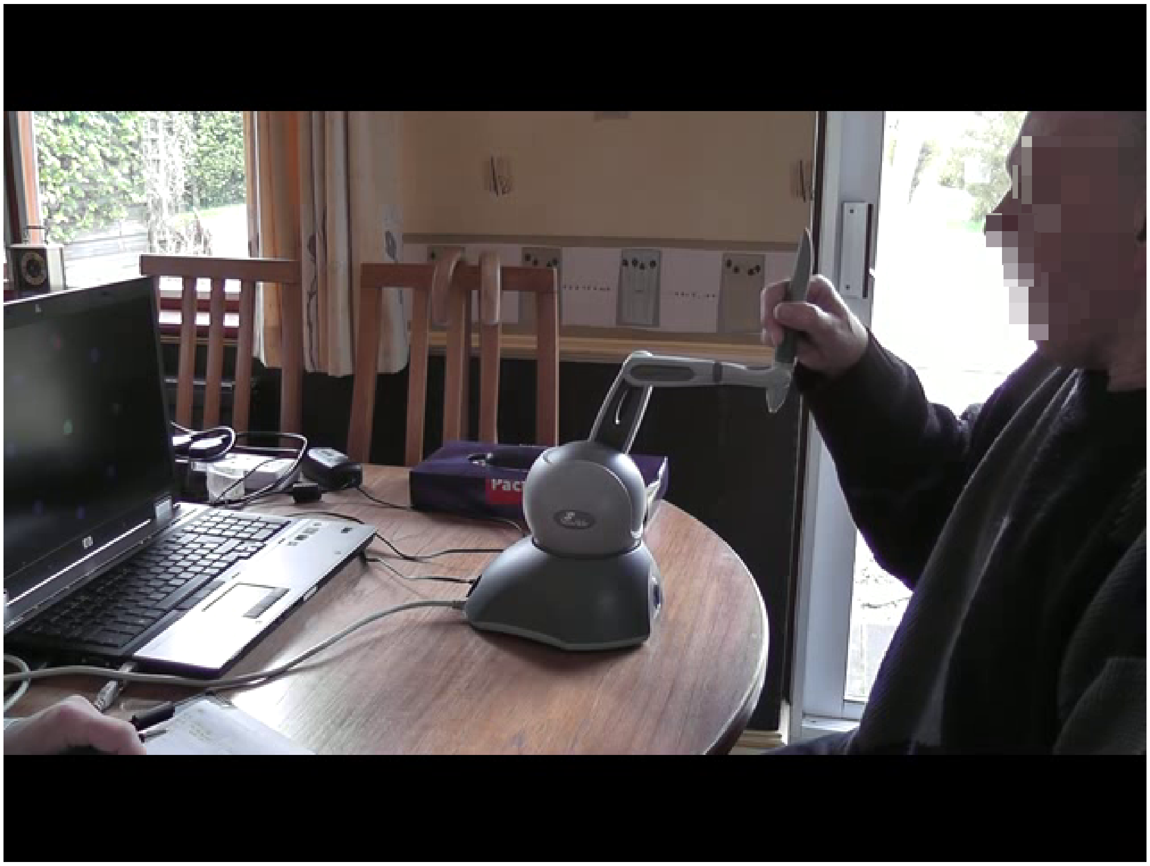


Figure 5.4: **Experiment Setup: Force-field Targets.** This image shows the setup of the Omni and laptop in front of the participant when performing the force-field targets game (described in the *Exercise Sessions* section of this chapter). Again, the PHANTOM Omni does not take up much space and can be easily placed on a table in the home.

Figure 5.5: **Experiment Setup: Force-field Targets.** This is another image of the setup of the Omni and laptop in front of the participant when performing the force-field targets game. The participant chose where in their home that they would like to set up the experiment and they are positioned comfortably in front of the apparatus.

5.3.1 Session 1: Initial Assessment

In the initial session, participants will be required to perform standard tests for assessing fine-motor control, namely: the previously described NHPT and the Box and Blocks Test (BBT) (Mathiowetz, Volland, et al., 1985). The BBT is a test of manual dexterity used by therapists to evaluate the gross manual dexterity of sufferers of upper limb impairment. The test consists of a box with a partition in the centre. On one side of the partition are 150, 1-inch blocks. The subject is then required to use the hand/arm being assessed to grasp one block at a time and transfer it over the partition to be released on the other side. Subjects are given 60 seconds to transfer as many blocks as they can over the partition. The tips of all fingers must pass over the partition in order for the block to be counted. This task is generally completed with each arm in turn.

Once subjects completed the manual tasks, they were formally introduced to the haptic setup with the PHANTOM Omni® this served as a way to present the platform as a test-bed to gain valuable user-feedback prior to commencing the exercise sessions phase of the study. This feedback was used to make slight adjustments to the tasks in order to make the games/tasks as safe and usable as possible for the exercise sessions. During the testing period, the participants were required to complete a short training session based on the exercises from the NHPT experiment, following this, they then performed the virtual and embedded reality versions of the NHPT, updated to include audio cues to improve task performance.

Readers will note that this experiment includes a virtual version of the NHPT alongside the embedded NHPT setup discussed. This is an improved version of the system that was presented in chapter three following further user feedback and research into the use of haptic technologies for assessment. The primary purpose was to gain some feasibility prior to conducting a clinical trial with the system to strengthen our findings in chapter three and also to show that the virtual setup would be suitable for use with a larger study cohort of stroke survivors as the previous system had only ever been used with healthy participants. This trial was proposed, however, was not conducted due to time constraints of the work supporting this PhD.

5.3.2 Sessions 2-13: Exercise Sessions

After the initial assessment and training, the participant began the exercise sessions. These sessions were held tri-weekly over the course of 4 weeks. Data was recorded with camera equipment which focussed on the arm performing the task so that this could be used to analyse movement and performance within the environment. Participants were also assessed in a similar fashion to the initial assessment twice throughout the exercise sessions: once before session 2, and once after session 13. Figure 5.6 outlines the session protocol for session 2.

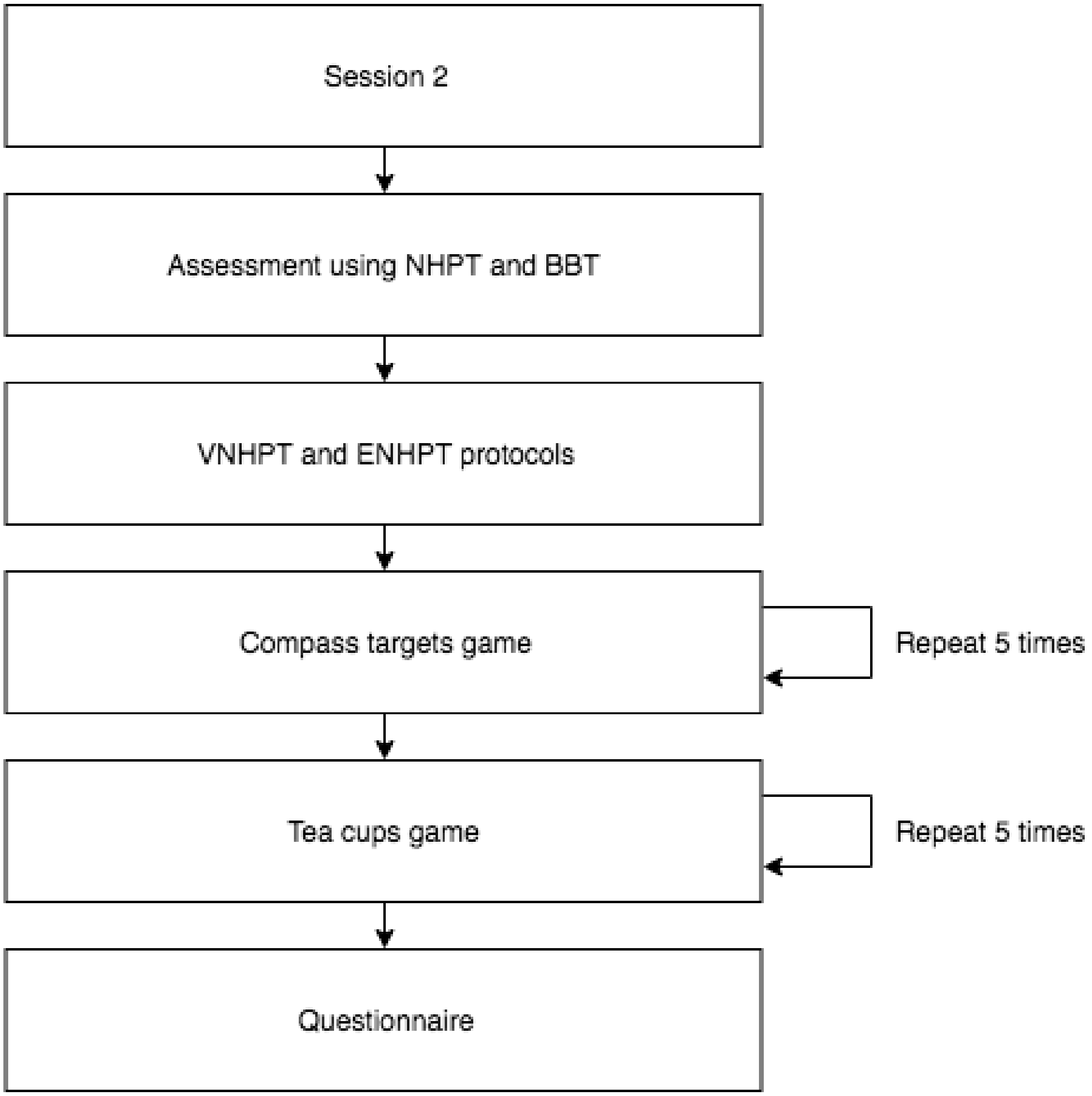


Figure 5.6: **Session 2 Protocol.** The above flowchart outlines the tasks that were carried out as part of session 2 (the first of the exercise sessions). This session also included an element of assessment in order to track participant's progress throughout the trial.

Tasks require the user to move the PHANTOM Omni® stylus which corresponds to a non-screen representation of the stylus. They will perform various ‘pinch and grip’ tasks where they will be able to feel the properties of the shapes displayed on the screen (textures, blocks, and spheres for example). These tasks are designed to exercise specific features of movement: strength, stamina, accuracy, and quality of movement. We varied session content between sessions, each participant carried out the same tasks as each other, but the tasks in the exercise sessions differed throughout the four weeks. Figures 5.7-5.10 show the tasks that were performed as part of the exercise sessions. These tasks all included sound and motivational feedback cues displayed on the screen in an attempt to improve motivation and the playability of the games based on current literature (Zyda, 2005).

Participants were assigned different tasks each at each session, and for each session, all participants would perform the same tasks as the other participants in the study. Table 5.1 summarises the tasks that were performed on each of the exercises sessions (sessions 2-13).

Table 5.1: **Session Content.** This table summarises the tasks that were performed throughout the four weeks of exercise sessions. Sessions were limited to two tasks per session in order to prevent participants from getting too tired while carrying out the tasks. Only one task was performed in session six due to the first participant reaching that session ID only being capable of that task on the day; thus all following participants just completed the same task and no more.

Session ID	Tasks performed	
2	ENHPT	VNHPT
3	Teacups game	Force-field targets
4	Teacups game	Force-field targets
5	ENHPT	VNHPT
6	Haptic guidance	
7	Haptic guidance	Force-field targets
8	Teacups game	Force-field targets
9	Solo	Collaborative haptics
10	Haptic guidance	Force-field targets
11	Solo	Force-field targets
12	Haptic guidance	Force-field targets
13	ENHPT	VNHPT

5.3.2.1 The Teacups Game

The Teacups game is a functional task, based on the daily activity of carrying a hot cup of tea without spilling any, something with which all of the users were familiar (figure 5.7). This task had a subtle difference to the real-world task: the teacup here was set up as a dynamic weight on a spring attached to the stylus interaction point, forcing the users to move slowly and steadily in order not to increase the force and velocity acting on the teacup. Tea would spill if the spring force became greater than a set threshold. This task was designed to improve users' dynamic control and steady movement relating to response to stimuli and reduced tremor respectively.

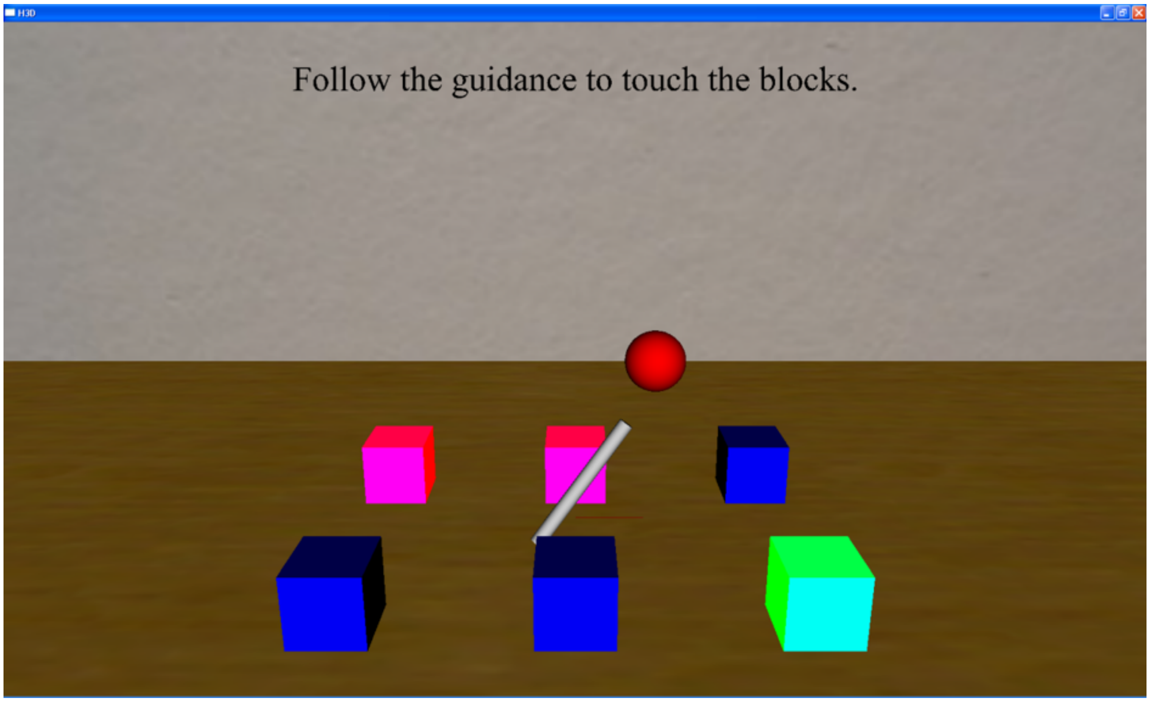
Slow down! Don't spill the tea!

Figure 5.7: **The Teacups Game.** Here the cup is suspended on a spring, and the user has to place the cup on the highlighted mat. The key to this task is to move as steadily as possible so as not to spill the tea.

5.3.2.2 Haptic Guidance

In the haptic guidance task (figure 5.8), users had to follow a magnetic ball that guided them to the different blocks on the screen. The task was performed in two ways: firstly the task was performed without the screen; then with the screen; both for 3-5 iteration search. The rationale for this task was to assess the tactile feedback of the user and their response to forces within the haptic environment.

Preliminary analysis shows that generally, users required greater guidance forces when they could not view the screen; however, when they could see the guiding ball, they were able to perform the task with less guidance (less magnetic force).



Follow the guidance to touch the blocks.

Figure 5.8: **The Haptic Guidance Task.** In this task, the user follows the guidance of a ball as it moves through the virtual environment. This task was used to assess the user's response to tactile stimulation.

5.3.2.3 Force-field Targets

Based on the work of Patton & Mussa-Ivaldi (2004), we used the Force-Field Adaptation paradigm to create a virtual environment that could assess users' responsiveness to movement perturbation stimulation (figure 5.5.1.2.2). Users were given the task first of all without any resistance and repeated five times. After this forces perpendicular to the target direction were introduced, again users repeated the task 5 times before the forces were increased. After the third increase users then performed the task without any forces until they met the average time gained from the initial force-less environment (generally 5-10 attempts). This task was performed in the XZ and XY planes in different sessions. Generally, performance was better in the XY plane (up-down-left-right), this is most likely due to the coordinate mapping from the real to the virtual world where pushing up in the XY plane moves the virtual point up, whereas in the XZ pushing towards the screen moves the virtual point up.

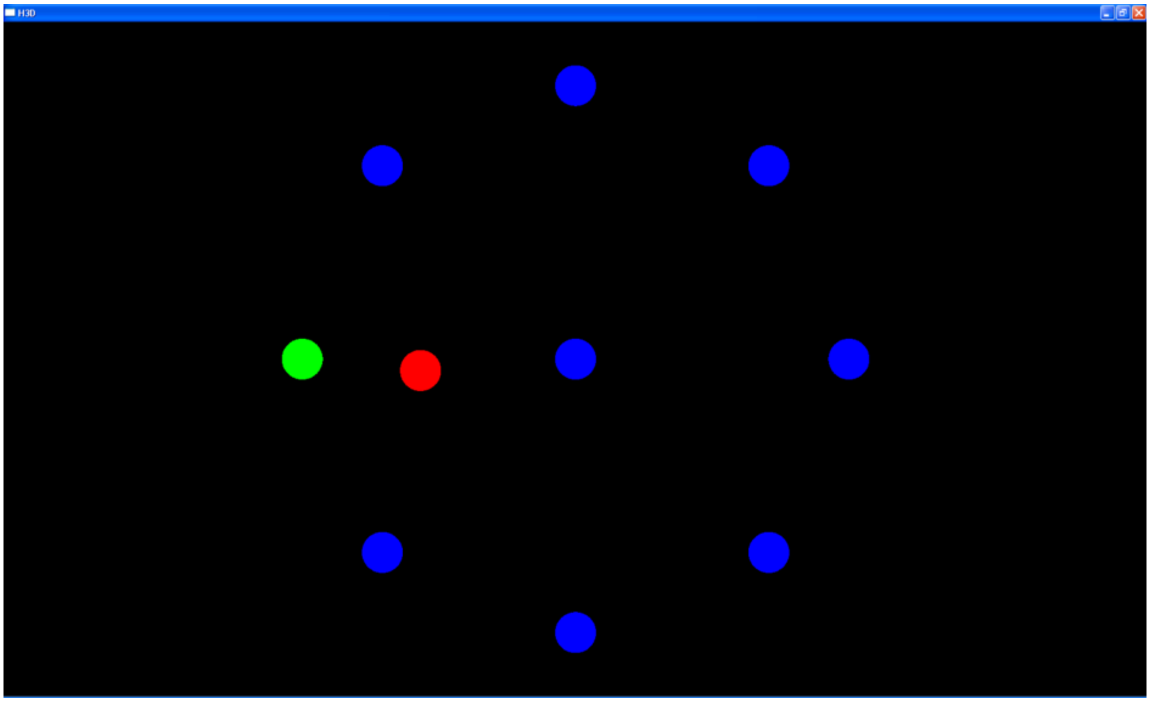


Figure 5.9: **Force-field Targets.** This task used the force-field adaptation paradigm to create a virtual environment that could assess users' responsiveness to movement perturbation stimulation.

5.3.2.4 Solo

A simple game of 'Solo' was written (similar to the popular arcade game 'Pong') (figure 5.10). This task was designed to test and improve users' reflex response. Haptic feedback was presented when the ball hit the bat along with an audio cue (the sound of a ball hitting a bat). To further enhance the exercise element of the task, resistive forces were added in two different ways. Firstly, a drag force based on the velocity component of the users' movement up and down was added to the environment. Secondly (in a separate session), a repellent force based on a function of the difference between the users' bat and the ball was added so that when the user approached the ball, they would be pushed away.

5.3.3 Session 14: Final Assessment

Four weeks after the final exercise session, participants were required to perform the same assessment that they carried out initially to establish their develop-

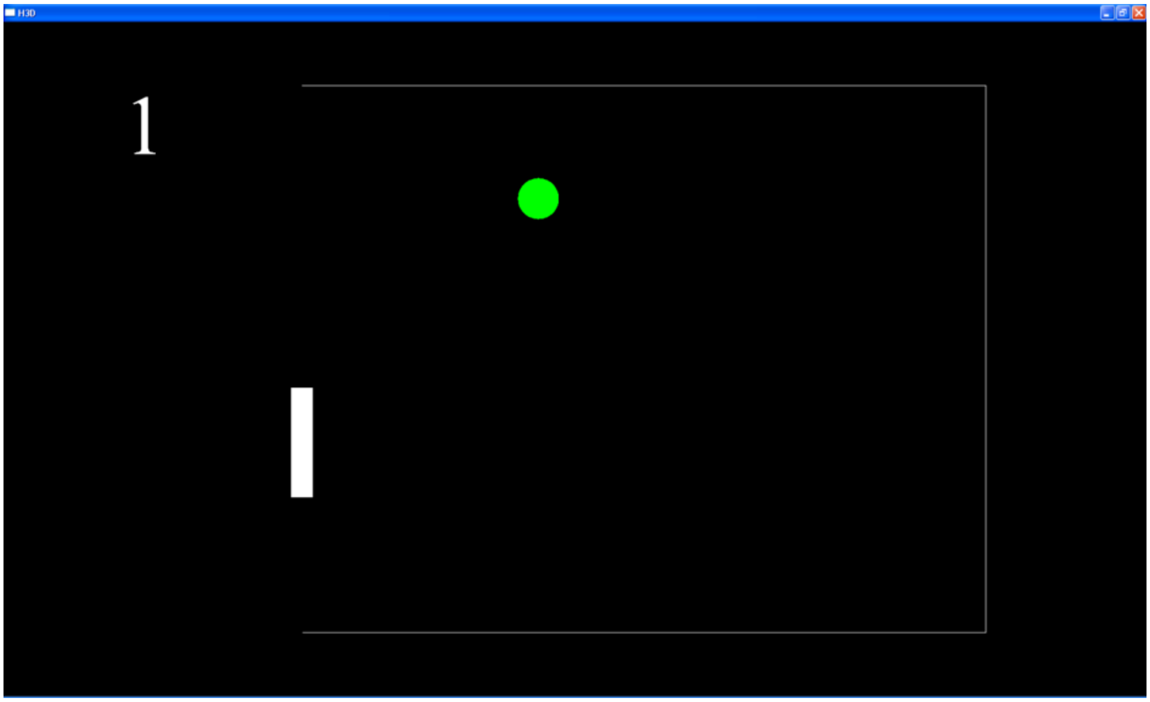


Figure 5.10: **Solo.** A game of Solo, but with resistive forces applied as the user moved closer to the ball. This was used as an exercise and stimulation task for the arm and shoulder of the user.

ment/progress throughout the trial (standard NHPT and BBT along with the haptic assessment tasks).

5.4 Data Collection

Data for this study was collected in three ways: directly from the device in the form of logs, video recordings of the participants' interactions with the system, and thirdly, via questionnaires that were filled out at the end of each session.

The data recorded from the haptic system consisted of a number of timestamped records (recorded at the rate of 100Hz) describing the current state of the haptic end-effector within the context of the virtual environment. As with the VNHPT and ENHPT setups previously described, all tasks collected position (x, y, z), orientation (a_x, a_y, a_z, θ), velocity (V_x, V_y, V_z), force , (F_x, F_y, F_z) and the state of the buttons (*active or inactive*) on the stylus of the PHANTOM Omni®. Each task also had a list of event strings that were written out to the log files to describe a specific action that was currently being performed, such as, reaching a target (*targets* game), or hitting a ball (*solo*). This data allowed for more than just the time of the task to be recorded; we could ascertain which components of actions (grasp, release, placement) took longer to complete, if certain movements were found to be more difficult for the user to perform (due to location for instance), and the potential to track lag (*guidance* task) and smoothness of movement (Daly et al., 2005).

For each session, a video was recorded in order to safeguard participants and the experimenter and also to be used to determine if there were external factors that influenced task performance throughout the study.

Questionnaires, demographic surveys, and an SUS test were all conducted as part of this study. In the initial assessment, participants were required to fill in a 'Consent and Demographic' questionnaire (Appendix C) in order for them to participate. The main purpose of the demographic form was to ascertain the length of time since the participant's stroke, their handedness and, the arm of which has been most affected by their stroke.

After each of the exercise sessions, the participants filled out a more general questionnaire relating to the tasks that they had performed, requiring them to rate their performance and also to rate the quality of engagement that the task provided. This questionnaire allowed for us to be able to compare participants' actual performance to their perceived performance, and also to understand whether or not the tasks could be considered 'engaging' which would be positive for the use of these tasks in future studies.

After the final exercise session, where the participants had been using the system for four weeks, the participants filled out a Systems Usability Scale (SUS) (Brooke, 1996) survey which is a ten-question Likert scale designed to give a subjected assessment of a system's usability. The result of this survey would be used to broadly describe whether this system was considered usable, and thus suitable to be used again in future work.

5.5 Results

This experiment is a qualitative study, and, due to the limited number of participants (four), no direct comparisons will be made between the participants themselves. We will attempt to draw some generalisations about the efficacy of this particular setup (the PHANTOM Omni® with the interactive tasks developed) and its suitability for use as both an assessment tool, and a remote or on-site therapy and assessment system.

The following sections will describe the results for each of the participants in turn. This analysis includes results from the record logs of the interactive session as well as anecdotal evidence collected from the surveys and questionnaires given at the end of each of the sessions. A final section will then conclude the results found for the participation group.

5.5.1 George

George was a very enthusiastic and positive participant throughout the trial. His left arm (non-dominant) was most affected by his stroke which makes it difficult for him to carry out tasks of daily living such as cooking, washing, and cleaning. George was not receiving any physical therapy at the time of this study.

In the initial assessment session, George performed the NHPT (Nine Hole Peg Test) and BBT (Box and Blocks) tests. These results serve as a baseline measurement for George's fine and gross motor arm function for the length of this study (table 5.2 and 5.3). George is right handed and impaired by his left arm.

Table 5.2: **George's task times for the NHPT.** George performed better with his dominant, non-impaired arm (right) than with his impaired arm.

Attempt Number	Right	Left
1	14.8s	44.69s
2	14.72s	43.65s
3	14.22s	36.31s

Table 5.3: **Number of blocks that George managed to move** from one side of the box to the other. As with the NHPT test, George performed better with his right arm.

Attempt Number	Right	Left
1	40	16
2	40	16
3	44	14

George performed better with his right-non-impaired arm in both the NHPT and

BBT tests. His performance with his left arm was significantly different from his right arm's, up to a factor of 3 times slower (NHPT) or fewer blocks (BBT). He was able to complete both tasks fully with each arm, which meant that we could continue the study with him as a participant.

Throughout the course of the study, George described the sessions and tasks positively, rating them 'Quite Helpful', and quite or very easy to complete (Appendix F, questionnaire results). Throughout the trial, George described himself as quite/very motivated and confident and enjoyed all of the sessions. George occasionally felt discomfort in his impaired arm (left) when using the PHANTOM Omni® and interactive tasks, however, not pain that would cause him to stop performing any of the tasks.

George liked audio cues in the tasks and liked the 'clapping' sound at the end of the tasks when he completed them, he felt that this gave him something to aim for, and he found other audio cues helpful to completing the tasks. In one session out of the 12 (week 4, session 1), George rated his performance of the tasks poorly and stated that his arm felt 'a little stiffer than usual', other than that, George rated his performance positively throughout the trial.

In the final questionnaire (Appendix E) participants were asked to rate their arm function during the experiment, in the week immediately after completing the experiment and, in the final assessment session (4 weeks after completing the exercise sessions). George's results are given in table 5.4. From the results of the questionnaire, we also took the median score from the answers to the questions, grouped by the number of weeks since the experiment. Figure 5.11 shows a radar chart of the scores taken from the questionnaire.

Table 5.4: **George's responses to the statements given in the final assessment** session of the study. The statements are all in the context of the impaired arm; 'arm' in these statements mean 'impaired arm'.

Statement	Response
In the weeks of the experiment, I felt more capable with my arm	Strongly Agree
In the weeks of the experiment, I felt more discomfort with my arm	Strongly Disagree
In the weeks of the experiment, I could move my arm more	Strongly Agree
In the weeks of the experiment, my arm felt stiff	Strongly Disagree

Statement	Response
In the weeks of the experiment, I could move my hand more	Strongly Agree
In the weeks of the experiment, my arm felt tired	Strongly Disagree
In the week after the experiment, I felt more capable with my arm	Agree
In the week after the experiment, I felt more discomfort with my arm	Strongly Disagree
In the week after the experiment, I could move my arm more	Strongly Agree
In the week after the experiment, my arm felt stiff	Strongly Disagree
In the week after the experiment, I could move my hand more	Agree
In the week after the experiment, my arm felt tired	Strongly Disagree
Since completing the experiment, I felt more capable with my arm	Disagree
Since completing the experiment, I felt more discomfort with my arm	Agree
Since completing the experiment, I could move my arm more	Disagree
Since completing the experiment, my arm felt stiff	Agree
Since completing the experiment, I could move my hand more	Disagree
Since completing the experiment, my arm felt tired	Agree

From the graph (figure 5.11), it can be seen that George reacted very positively to the sessions throughout the trial. He perceived highly positive benefits immediately following and one week after the exercise sessions; however, after four weeks his perceived benefit of the trial had regressed to a score of 2.

In the weeks of the experiment, George strongly disagreed with the negative statements of feeling more discomfort, tiredness, and stiffness. In the week following the exercise sessions, George still agreed ('Agree') with the positive statements,

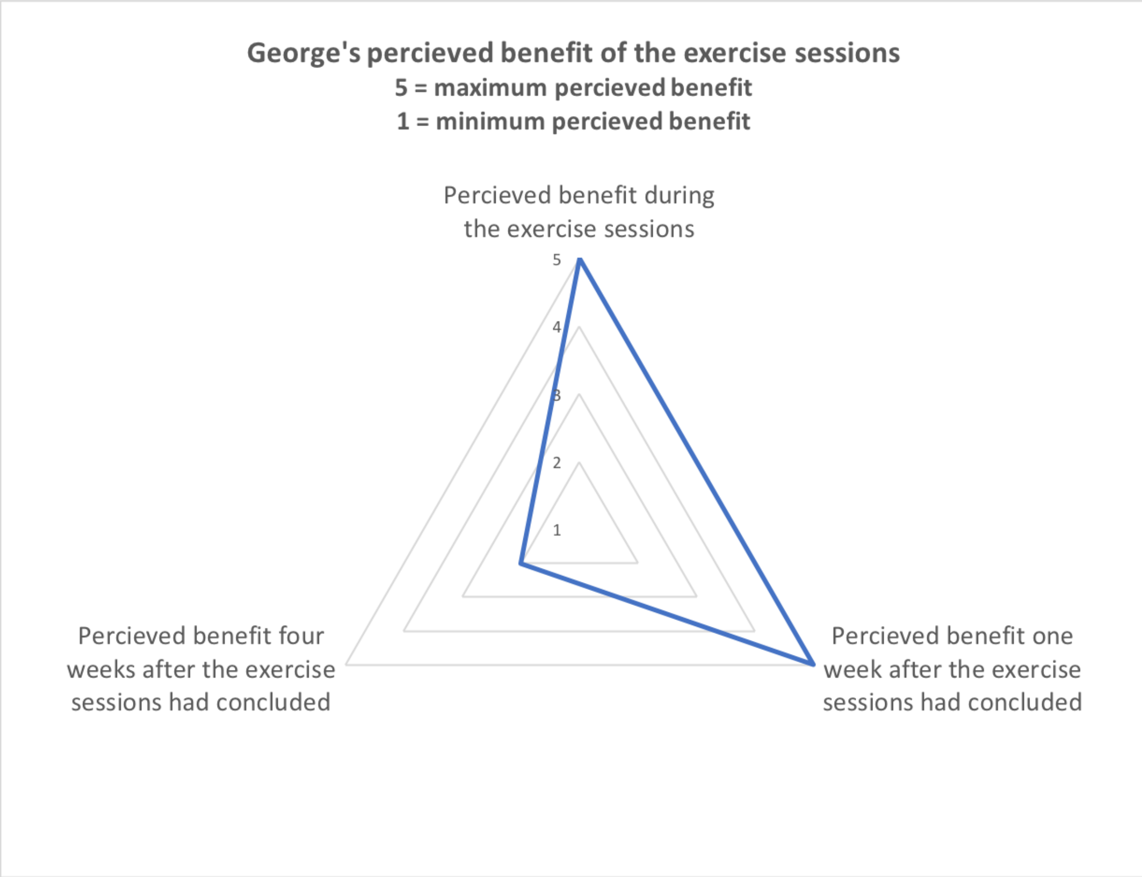


Figure 5.11: **George's perceived benefit from the experiment.** The three axes describe the scores that George gave for each of the periods following the conclusion of the exercise sessions: immediately after, one week after, and four weeks after. The axes run from 1 to 5, where 5 is the maximum perceived benefit that could be scored. The statements from the questionnaire are all in the context of the impaired arm.

and was still in strong agreement with the statement that he could move his impaired arm more. George still strongly disagreed with all the negative statements.

Since completing the experiment (this was asked at the end of the final session, four weeks after the exercise sessions), George no longer felt more capable with his impaired arm (responded with 'Disagree', he also disagreed with the statements that he could move his impaired arm and hand more. Conversely, he was now in agreement with all three of the negative statements. From George's perspective, any improvements that he had made throughout the exercise sessions had now diminished back to levels of function that he had prior to this experiment.

Throughout the weeks of the experiment, the participants were assessed with the NHPT and BBT protocols every four weeks in an attempt to measure changes in arm function over the course of the study. Figure 5.12 shows George's NHPT protocol times throughout the study. By the 13th session (end of week eight) of the experiment (after four weeks of interactive exercise sessions using the PHANTOM Omni®), George had improved his NHPT time using his impaired left arm by approximately 6 seconds (taking the best times from each session). This improvement then increased slightly in the four-week gap between the last exercise session and the final assessment session. As to be expected, George performed the NHPT better with his unimpaired right arm.

Comparing the NHPT task times to George's perceived capability (from the final questionnaire), this pattern of improvement generally fits with the way that George described his capabilities: he felt more capable up to the end of the exercise sessions (session 13) he performed his best score using the NHPT. Four weeks later, this score had declined slightly (a slower time) which matched his perception of his statement that he no longer felt more capable with his impaired arm.

Figure 5.13 shows George's scores for the BBT protocol throughout the trial. George was able to move more blocks in the 60 seconds allotted time with his unimpaired (right) arm than with his left arm. Throughout the trial, no significant improvements in BBT scores were seen, maintaining a maximum of 19 blocks transferred from week four (session 2) through to the final assessment session at week 12: the improvements that were seen in the NHPT results were not mirrored in the BBT results.

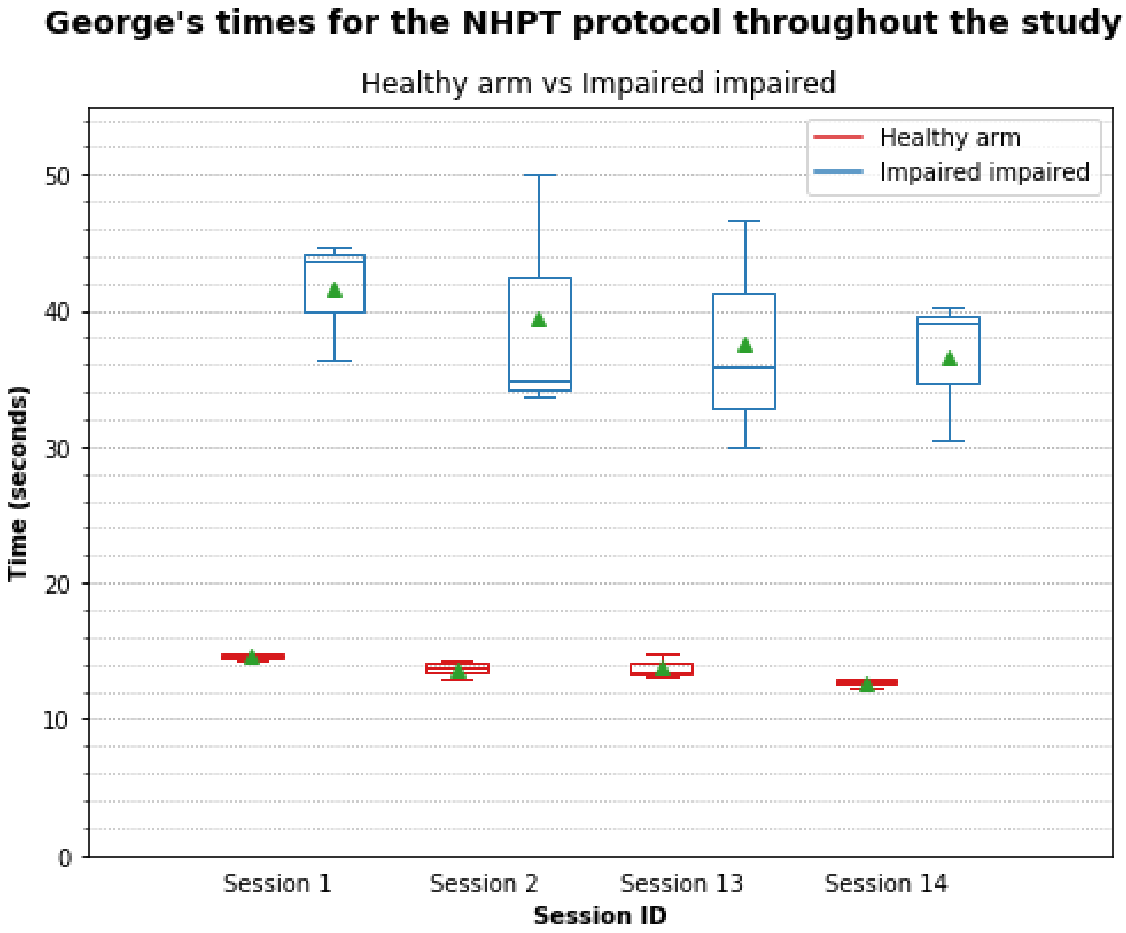


Figure 5.12: **George's NHPT times** throughout the course of the 12 weeks. George's best times improved from sessions 1 to 13, his mean time to complete the task in session 14 regressed, matching his perception of his own performance.

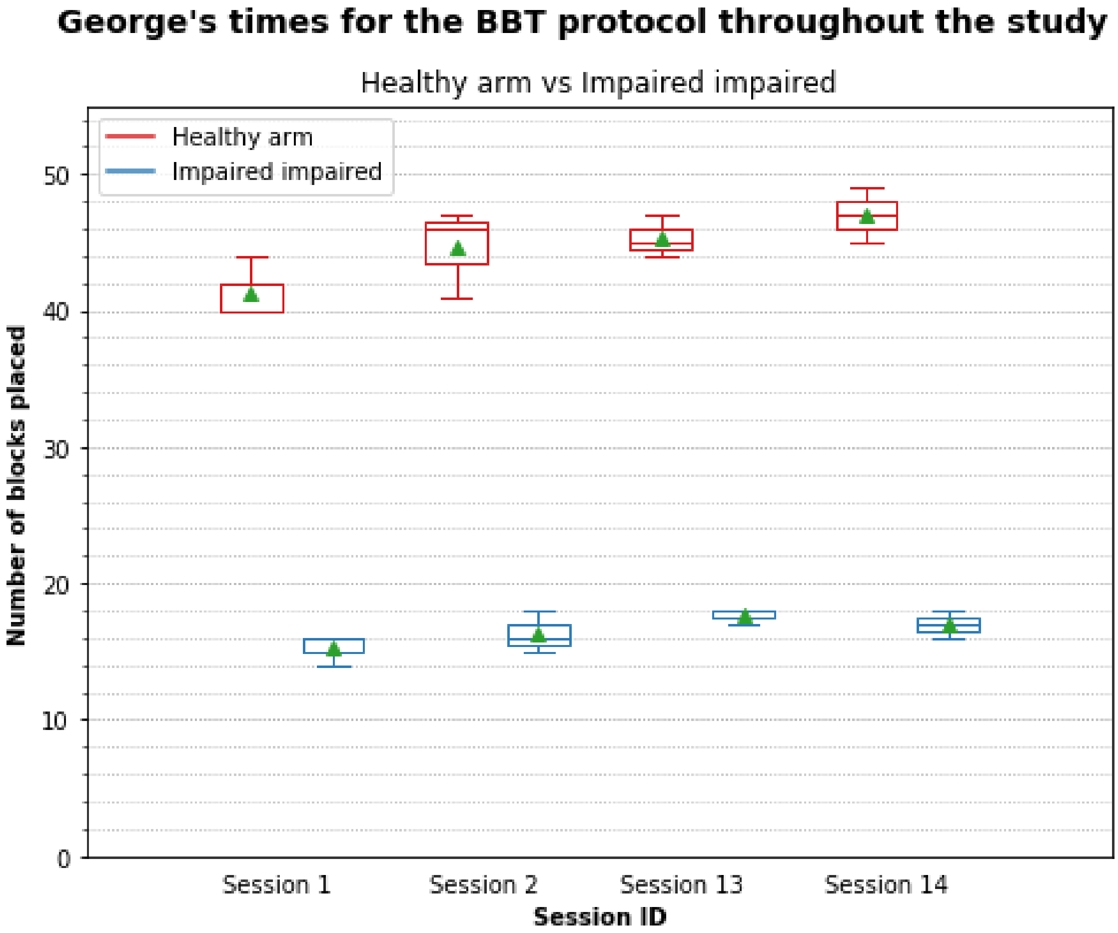


Figure 5.13: **George's BBT scores** throughout the course of the 12 weeks. George's mean score for his healthy arm improved throughout the trial, yet the score for his impaired arm regressed from session 13 to 14, although these differences are not significant.

5.5.1.1 Embedded NHPT

In our previous work, we compared a real NHPT setup to a virtual and an embedded setup (*see chapter 3*), where our findings suggested that an embedded reality NHPT (that included physical, virtual, and haptic elements) enabled a more accurate and consistent set of data between subjects than that of a purely hapto–virtual reality approach.

In this study, we also gave participants the Embedded NHPT (ENHPT) to complete during the course of the four weeks of exercise sessions. Due to some data corruption, only three of the ENHPT sessions are presented here. Figure 5.14 shows George's impaired arm results for the ENHPT as a box plot. Between the three sessions (exercise weeks 2, 3, and 4), George showed improvements in both time and standard deviation (from week 2 to week 4). Suggesting, not only better performance at the ENHPT task but also more consistency in between attempts to complete the task, where the attempts times (three attempts at each session) differed by a standard deviation of ~1 second. Being able to complete a task in a consistent amount of time regardless of the number of attempts is a good measure that the task can be used to measure improvements over time (Mathiowetz, Weber, et al., 1985).

5.5.1.2 Virtual Tasks and RMSE

Another aspect of the exercise session that was investigated was the reduction of root mean square error (RMSE) in the Virtual NHPT, the Targets game, and the Haptic Guidance task. The RMSE metric can be used to suggest improvements in the ability to follow a path - it shows the deviation from the predicted path at given points along the path to arrive at a number that can be used to compare tasks to each other at different intervals, or in this case, different sessions.

We can define RMSE as a quadratic scoring rule that also measures the average magnitude of the error. It is the square root of the average of squared differences between prediction and actual observation, where P is the predicted path, O is the observed path, and i is the interval:

$$RMSE = \sqrt{\frac{1}{n}\Sigma_{i=1}^{n}(P_i - O_i)^2}$$

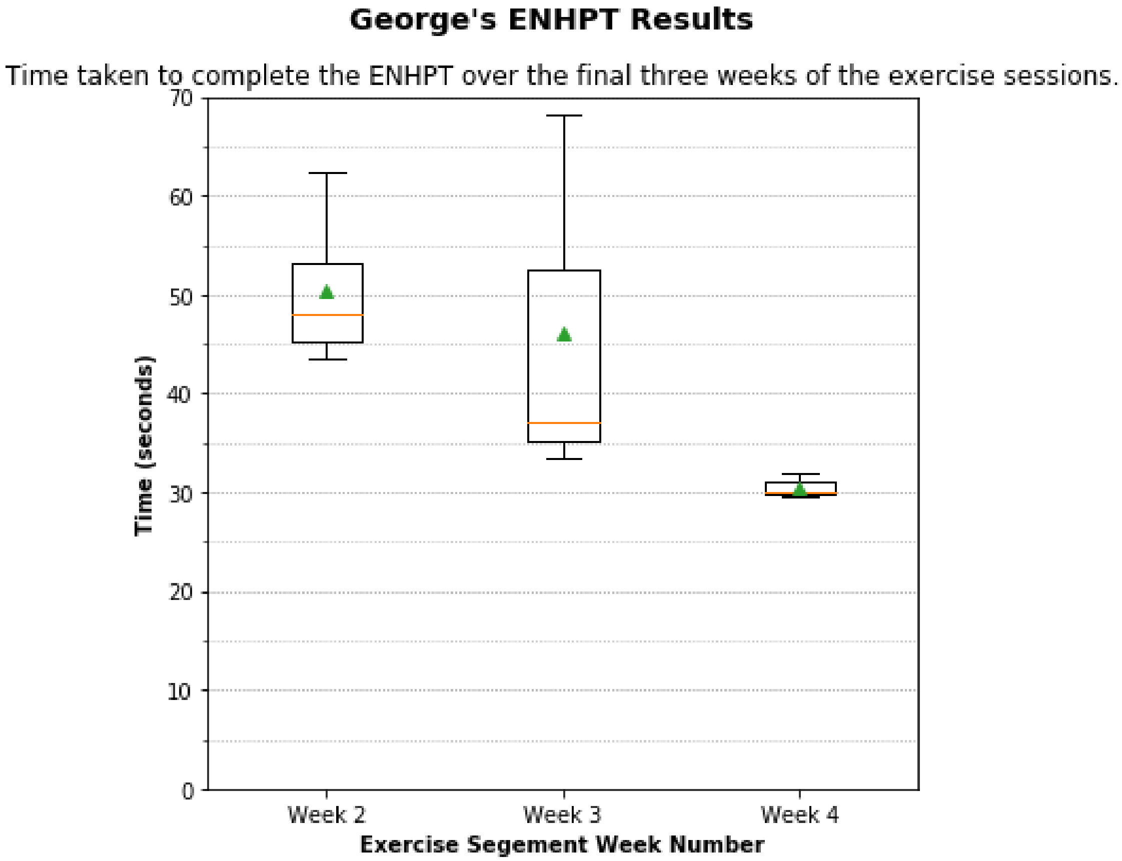


Figure 5.14: **George's Embedded NHPT task times** taken during the exercise sessions. George's times improved from session to session.

In our case, we define the predicted path to be a movement, at any interval recorded between the start and end of an event (where an event may be placing a peg for example) that would move the stylus closer to the goal (e.g. a peg hole). Figure 5.15 describes errors in the context of RMSE and the predicted path (the optimal path between the start and target points defined as the shortest distance between these two points). Calculations were performed on the datasets using Python and the Numpy package.

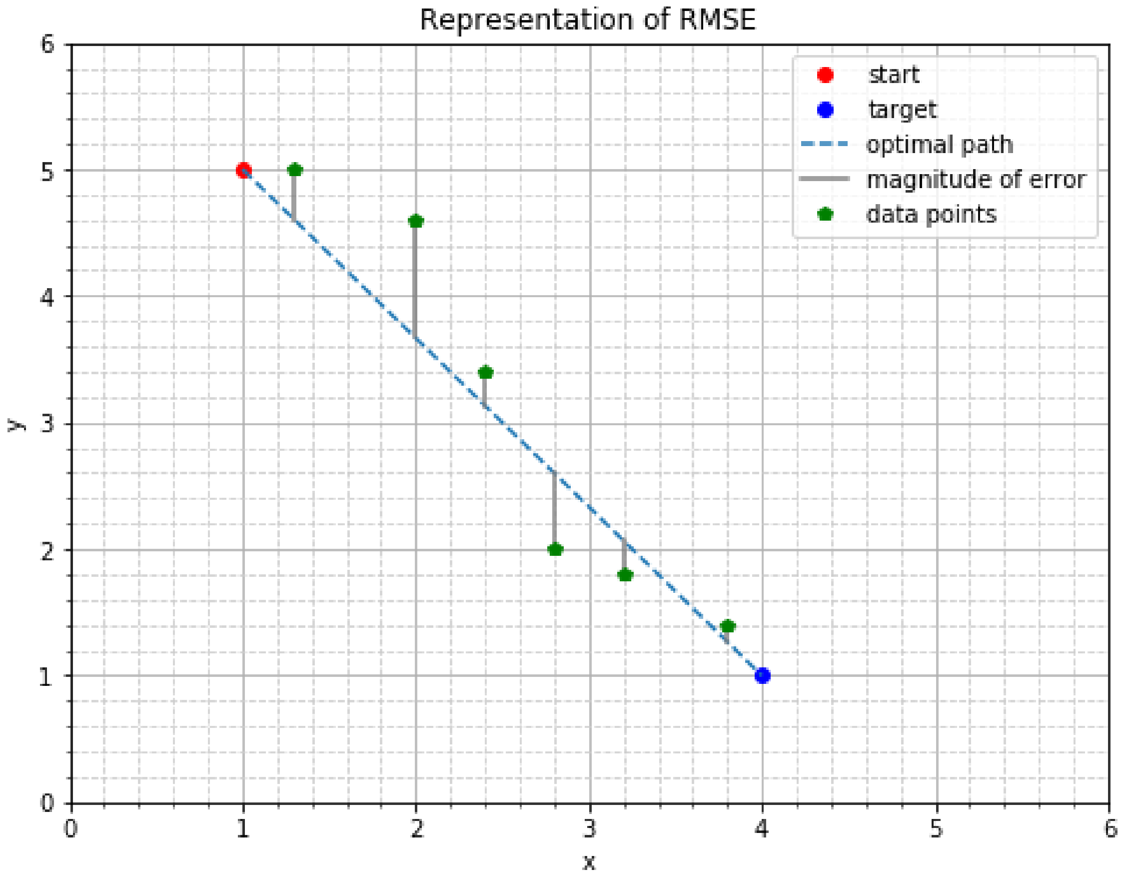


Figure 5.15: **Representation of RMSE.** This figure describes the errors in relation to the optimal path from start to target. The square of each error is summed, and then the square root of the average of this sum is taken as the RMSE. A reduction in RMSE over time indicates an improvement in accuracy which could relate to improved function.

5.5.1.2.1 Virtual NHPT

Figure 5.16 shows George's virtual NHPT (VNHPT) times and RMSE values for completing the task at three separate sessions: session 4 (end of week 4), session 12 (end of week 8) and session 13 (end of week 12). The mean RMSE metric for this task could broadly be used to describe improvements in the efficiency of movement: moving more directly toward the peg hole once grasping the peg. An improvement in this value could relate to better arm function, although a more extensive trial would need to be conducted before stating any improvements seen in this session as a measure of improvement in arm function. Over the three sessions presented here, George improved his time taken to complete the VNHPT task using his impaired arm, and mean RMSE also improved between sessions 4 and 12; however, regressed slightly in the result for session 13.

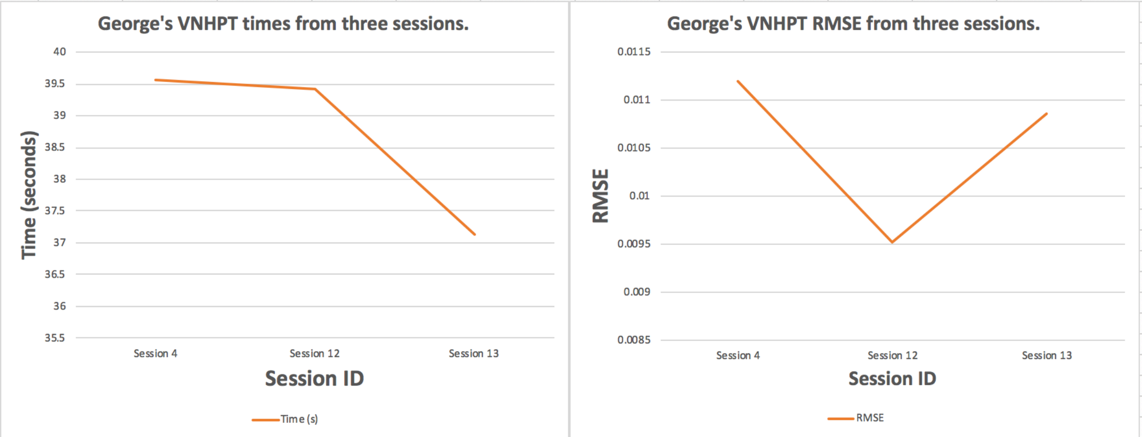


Figure 5.16: **George's Virtual NHPT times and RMSE** using his impaired (left) arm. Overall, task completion time improved from session 4 to session 13, however, the mean RMSE metric regressed between sessions 12 and 13, i.e. after four weeks of no intervention following the exercise sessions.

5.5.1.2.2 Targets

In the Targets game, participants had to move from a central point to eight individual points similar to directions on a compass face (figure 5.5.1.2.2). After each attempt, a perturbation force was added perpendicular to the movement required to reach the target from the centre of the board. This pattern continued through all five attempts at the task up to a maximum perturbation force set in the game. The RMSE metric here can be broadly used to show a better reaction to perturbation forces. Reaction to perturbation has been found to be a good measure of arm function, where the ability to be less affected by a perturbation generally relating to better arm function (Patton & Mussa-Ivaldi, 2004).

George showed an increase in mean RMSE using his impaired arm over the four sessions presented here (figure 5.17). It is likely that there are some learning effects at play here whereby George required more time and practice to better understand the goal of the task.

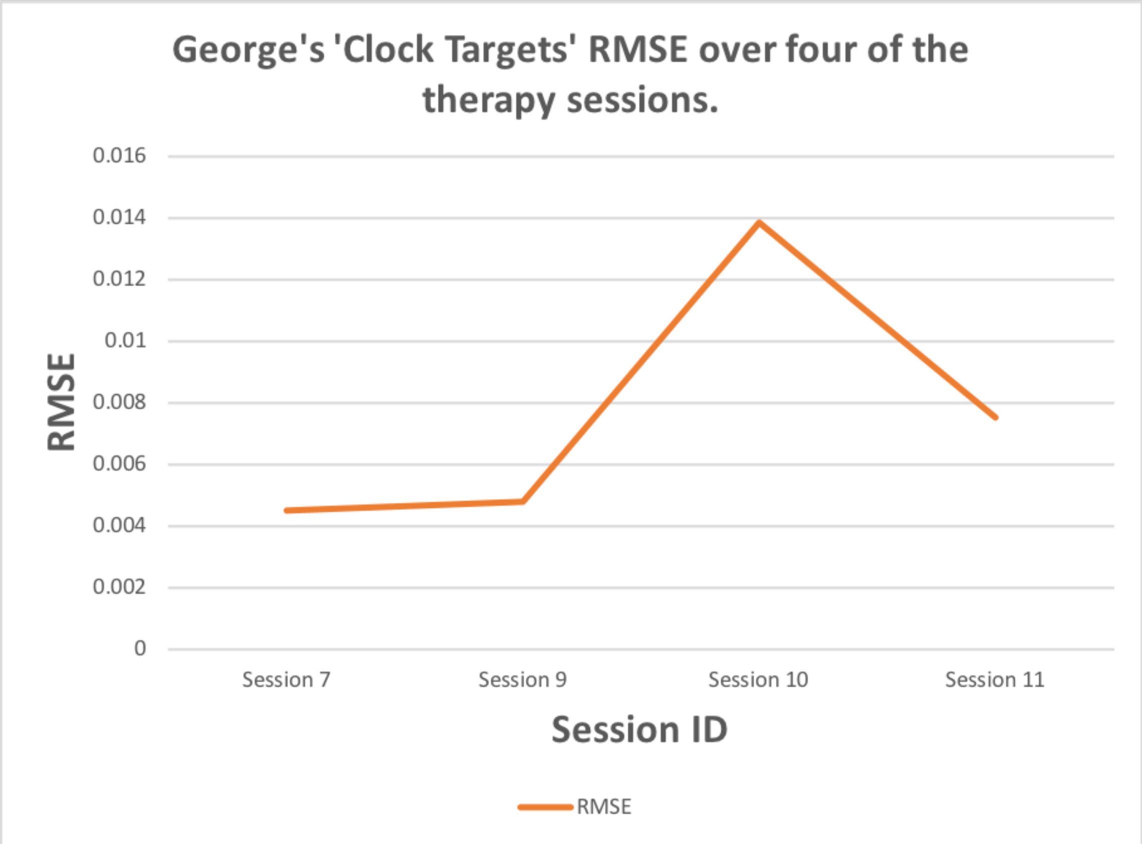


Figure 5.17: **George's Clock Targets RMSE** (impaired left arm). The graph shows no improvement in mean RMSE over the course of exercise sessions 7 through to 11 for the clock targets task.

5.5.1.2.3 Haptic Guidance

In the haptic guidance task, the participants were ‘locked’ onto a virtual ball which then guided them to various areas of the virtual world (figure 5.8). Improvements in mean RMSE in this task could suggest more flexibility and reduction of stiffness or resistance in movement.

In figure 5.18, the results of the mean RMSE metric are presented for four of the exercise sessions. George displayed a reduction of mean RMSE between session 5 and session 11 when using his impaired arm. This is a positive result that potentially shows some level of improvement, either in arm function, or the ability to perform the task.

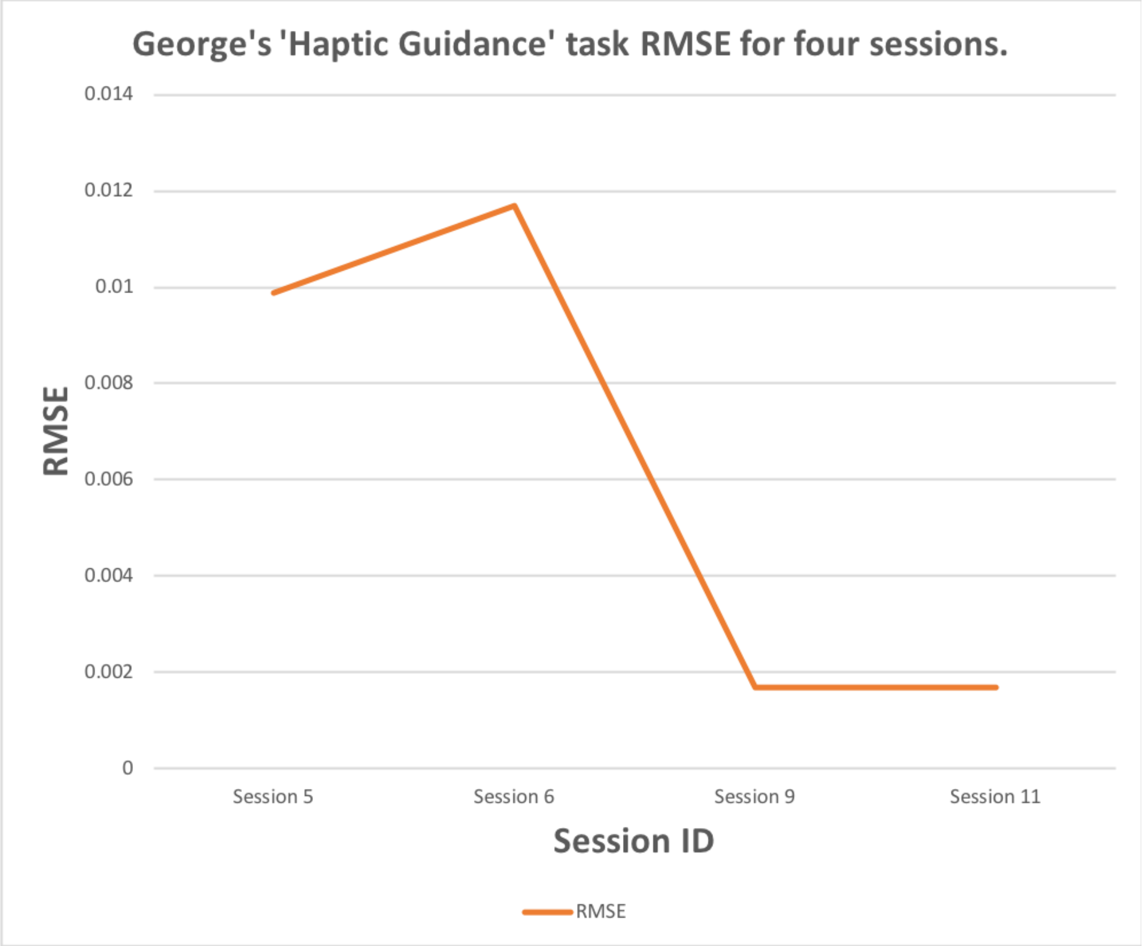


Figure 5.18: **George’s Haptic Guidance task RMSE** (impaired arm). By session 11, the mean RMSE metric had reduced significantly suggesting that George’s ability to perform the task had improved - either from functional improvement or learned skill.

We also investigated peak velocity and mean absolute error to determine whether or not these metrics correlated with the RMSE findings, but the results were inconclusive.

We have looked at George's journey through the course of the 12-week experiment using a haptic assessment and exercise system that incorporated the PHANTOM Omni® haptic controller, and custom-built virtual environments designed to assess and to rehabilitate. George reacted positively to the system and stated that he would like to have one in his own home. From the NHPT scores, we saw that George made improvements to his NHPT time whilst the exercise sessions were in progress; these improvements only diminished slightly in the four weeks following the intervention. Again, to match this finding, George also stated that he felt more capable with his arm, and could move his arm and hand more in the weeks where he was regularly using the device at the exercise sessions (three times per week for four weeks).

Findings for metrics measured other than the questionnaire data and NHPT/BBT times were less conclusive; however, some positive findings were found that would warrant further investigation: George showed improvement in the ENHPT for both time and standard deviation; George also showed improvement in RMSE for the haptic guidance task. The number of times that George completed these tasks was too few to draw any direct conclusions but, these positive findings are good candidates for future investigation using this, or a similar, setup.

As part of the experiment, George rated the system using the Systems Usability Scale. George rated the system favourably, with an overall score of 80, generally seen as a good to excellent rating, suggesting that the system is easy to use which bodes well for future experimentation.

5.5.2 Linda

Linda was motivated throughout the trial and was keen to make sure she could complete all the tasks that were given to her. She considers herself reasonably active and goes to pilates and keep fit classes every week. Since her stroke, she has some mobility issues and impairments with motor skill in her right (dominant) arm and leg.

Linda performed the NHPT and BBT tasks in the initial session, giving us her baseline measurement of fine and gross-motor arm function to be compared with at the end of the 12-week experiment. Tables 5.5 and 5.6 show Linda's NHPT and BBT task results.

Table 5.5: **Linda's task times for the NHPT.** Linda performed better with her non-dominant, non-impaired arm (left) than with her impaired arm.

Attempt Number	Right	Left
1	30.6s	13.28s
2	21.06s	14.15s
3	22.08s	11.78s

Table 5.6: **The number of blocks that Linda managed to move** from one side of the box to the other. As with the NHPT test, Linda performed better with her left arm.

Attempt Number	Right	Left
1	23	36
2	33	47
3	30	55

Linda performed better at both the NHPT and BBT tests when using her non-impaired, non-dominant (left) arm. Linda was able to complete both tasks without assistance for the required number of attempts (three) and could, therefore, continue to participate in the experiment.

From the results of the questionnaire (reference appendix here), Linda responded positively to the system. When asked if she found the sessions helpful, she stated that she found them 'Very Helpful'. Linda found most of the tasks easy; however, Linda found week-3, session-3 very difficult. Week 3, Session 3 contained the most tasks in a single session and was potentially a factor for the perceived level of difficulty.

Linda described herself as motivated and confident in every session and enjoyed all of the sessions that were conducted. She found the virtual environments to be realistic and found the haptic interactions strong, and the audio cues helpful.

In the first questionnaire, Linda felt some discomfort in her shoulder when reaching across her body; however, in all the subsequent session, Linda felt no further discomfort.

Linda mostly rated her performance as average or poor, only once rating her performance in the tasks as 'Very Good', interestingly, Linda had been to a stretch class that day and attributed this performance improvement to that.

As with all participants, the final questionnaire required the participants to rate their arm function retrospectively throughout the experiment; this was done to ascertain any perceived benefits or impacts that the experiment may have had on the function of the participants' impaired arm. Linda's results are given in table 5.7. As with all the final questionnaires, we took the median score for each group of responses to visualise the perceived benefit of the exercise sessions (figure 5.19).

Table 5.7: **Linda's responses to the statements given in the final assessment** session of the study. The statements are all in the context of the impaired arm; 'arm' in these statements mean 'impaired arm'.

Statement	Response
In the weeks of the experiment, I felt more capable with my arm	Strongly Agree
In the weeks of the experiment, I felt more discomfort with my arm	Strongly Disagree
In the weeks of the experiment, I could move my arm more	Strongly Agree
In the weeks of the experiment, my arm felt stiff	Strongly Disagree
In the weeks of the experiment, I could move my hand more	Disagree
In the weeks of the experiment, my arm felt tired	Strongly Disagree

Statement	Response
In the week after the experiment, I felt more capable with my arm	Strongly Agree
In the week after the experiment, I felt more discomfort with my arm	Strongly Disagree
In the week after the experiment, I could move my arm more	Agree
In the week after the experiment, my arm felt stiff	Strongly Disagree
In the week after the experiment, I could move my hand more	Strongly Disagree
In the week after the experiment, my arm felt tired	Strongly Disagree
Since completing the experiment, I felt more capable with my arm	Strongly Agree
Since completing the experiment, I felt more discomfort with my arm	Strongly Disagree
Since completing the experiment, I could move my arm more	Strongly Agree
Since completing the experiment, my arm felt stiff	Strongly Disagree
Since completing the experiment, I could move my hand more	Strongly Disagree
Since completing the experiment, my arm felt tired	Strongly Disagree

From the graph (figure 5.19), we can see that Linda reacted extremely positively to all three groups of statements relating to the maximum perceived benefit of the exercise sessions immediately following, one week after, and four weeks after the conclusion of the exercise sessions.

In the weeks of the experiment, Linda strongly agreed with the statements that she felt more capable with her impaired arm, and could move her arm more. Linda disagreed with the statement that she could move her hand more and felt that she did not have strength in her hand. Linda strongly disagreed with all of the negative statements in the weeks of the experiment, suggesting that the experiment did not

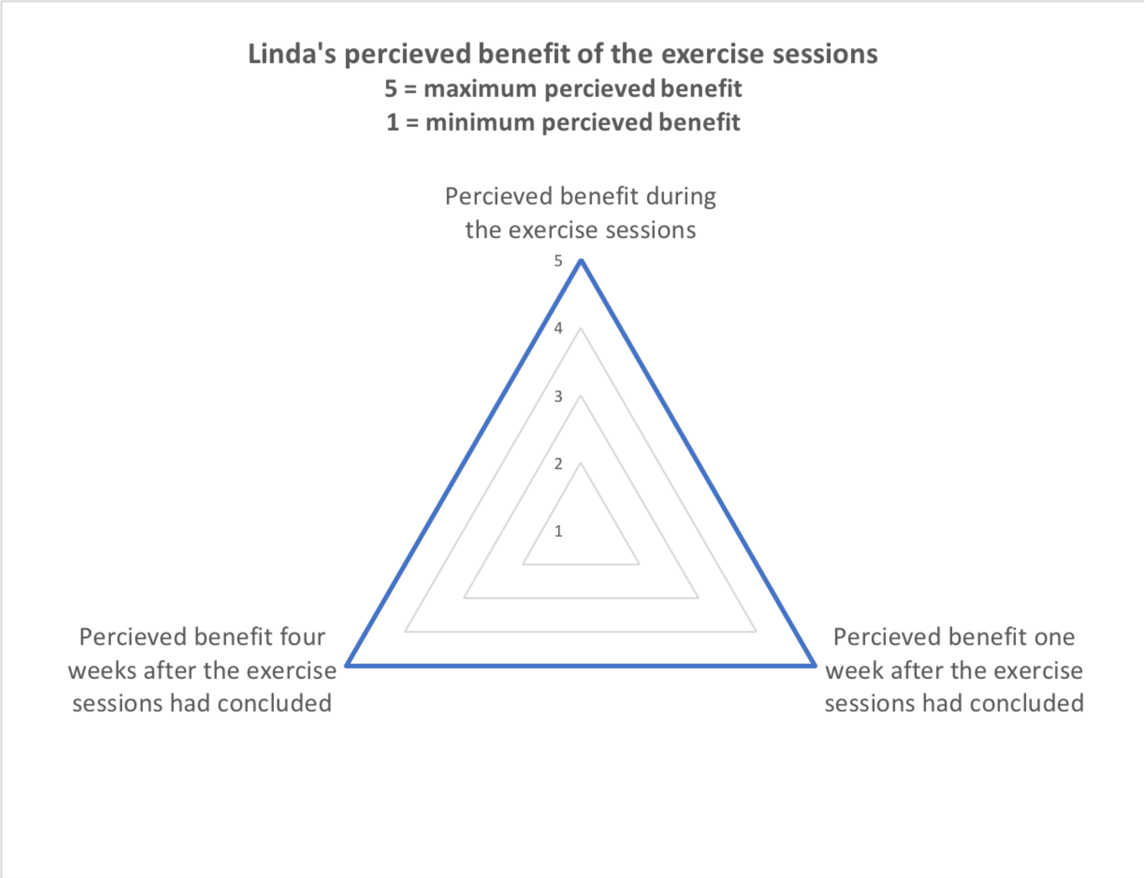


Figure 5.19: **Linda's perceived benefit from the experiment.** The three axes describe the scores that Linda gave for each of the periods following the conclusion of the exercise sessions: immediately after, one week after, and four weeks after. The axes run from 1 to 5, where 5 is the maximum perceived benefit that could be scored. The statements from the questionnaire are all in the context of the impaired arm.

have a negative impact on her arm function.

In the week after the experiment, Linda continued to agree with the statements regarding capability and impaired arm movement, and now strongly disagreed with the statement that she could move her hand more. Also, Linda strongly disagreed with all of the negative statements.

Since completing the experiment, Linda continued to maintain that she could move her arm more and felt more capable with her impaired arm, suggesting a continuation of these improvements even after a four-week period without intervention. As in the other statement groups, Linda strongly disagreed with all of the negative statements and continued to maintain strong disagreement with any improvement of hand function.

Figure 5.20 shows Linda's NHPT protocol times throughout the study. By the 13th session (end of week four) of the experiment (after four weeks of interactive exercise sessions using the PHANTOM Omni®), Linda had slightly improved her mean NHPT time using her impaired left arm, and then improved slightly more in the four-week gap between the last exercise session and the final assessment session. As to be expected, Linda performed the NHPT better with her unimpaired left arm.

When relating Linda's task times to her perceived improvements in capability and arm function, these scores match up well. Linda stated that she agreed that she felt more capable and could move her impaired arm more in all three segments of time since the exercise sessions: immediately following the session, one week later, then four weeks later, mirroring the continuation of improvement seen in the NHPT tasks.

Figure 5.21 shows Linda's BBT scores throughout the 12 weeks of the experiment. As to be expected, Linda was able to transport more blocks from one side of the box to the other by using her unimpaired left arm. Linda's final BBT score was two higher than her initial BBT score with her impaired arm showing no significant improvements in gross motor arm function. Comparing the BBT scores to Linda's NHPT scores, the improvements seen in the NHPT task times were not matched by improvements in the BBT scores.

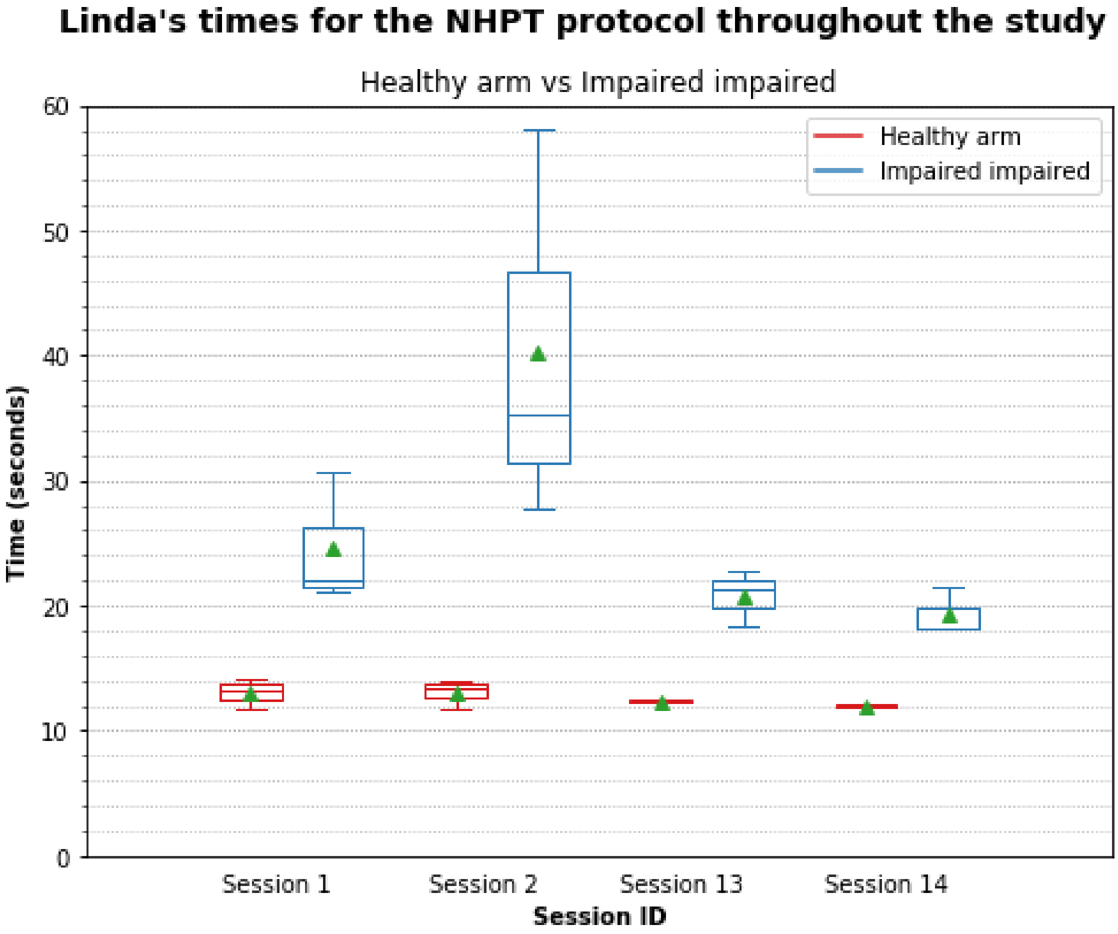


Figure 5.20: **Linda's NHPT times** throughout the course of the 12 weeks. By session 14, Linda's NHPT time with her impaired arm had improved.

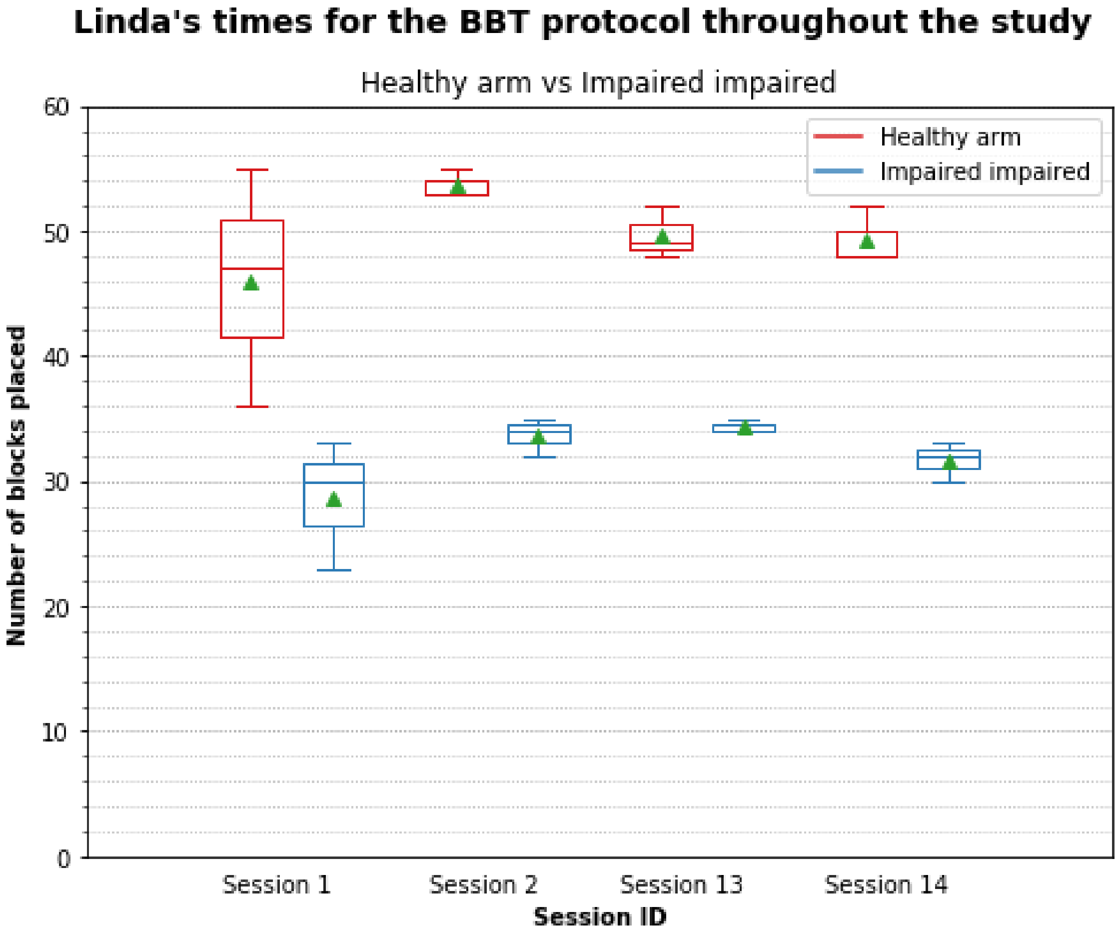


Figure 5.21: **Linda's BBT scores** throughout the course of the 12 weeks. Linda improved her mean BBT score with her impaired arm by one between session 1 and 14, with a peak improvement of four at session 13.

5.5.2.1 Embedded NHPT

Participants completed an Embedded version of the NHPT (ENHPT) throughout the four weeks of exercise sessions. Due to some data corruption, only three of the ENHPT sessions are presented here. Figure 5.22 shows Linda's impaired arm results for the ENHPT as a box plot. Over the three sessions presented here, Linda improved her best ENHPT time by approximately 5 seconds. Linda also showed improvement of the standard deviation metric between session 2 and session 4, hinting at improvements in being able to consistently show the same level of ability in a single session irrespective of the number of attempts to complete the task.

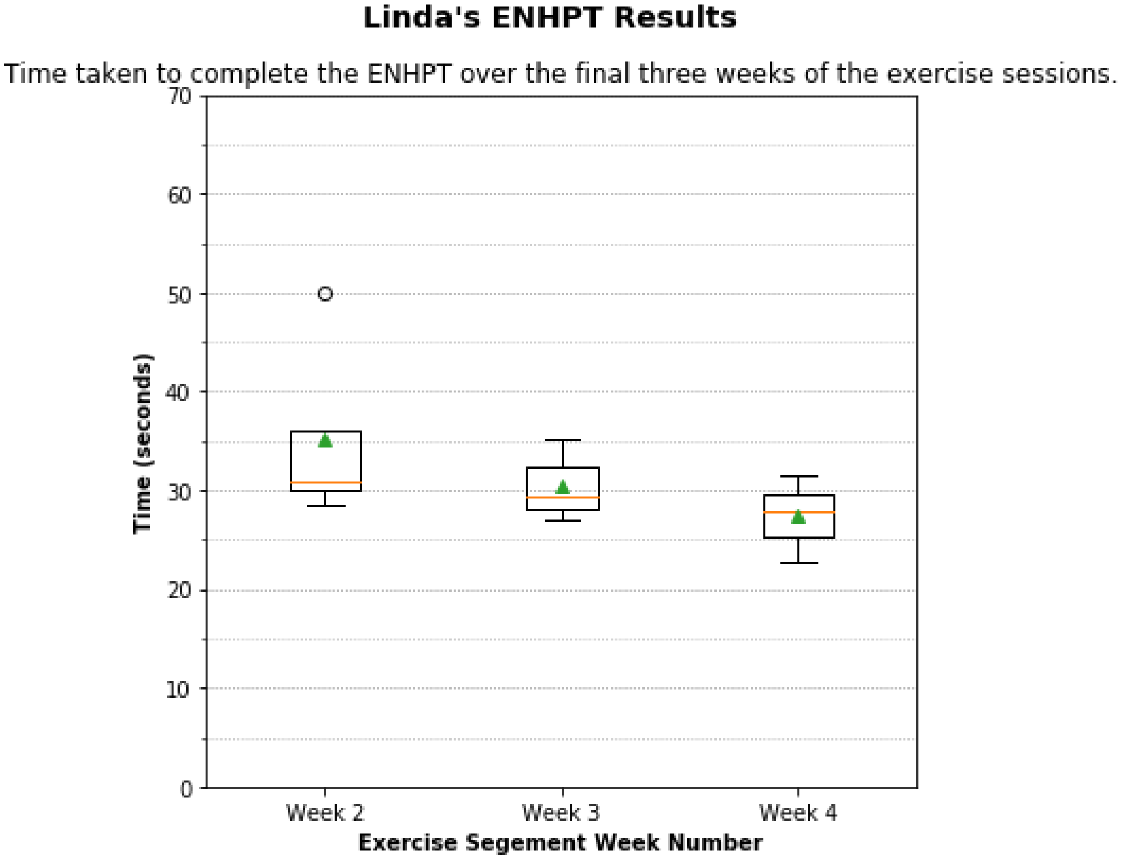


Figure 5.22: **Linda's Embedded NHPT task times** taken during the exercise sessions (impaired arm). Linda improved her mean ENHPT time each week.

5.5.2.2 Virtual Tasks and RMSE

As described in the section 'Virtual Tasks and RMSE' for the participant named 'George', we analysed the root mean squared error (RMSE) for the virtual tasks that were performed as part of the exercise sessions between weeks four and eight. The calculations for the RMSE metric were implemented in Python and the Numpy package.

5.5.2.2.1 Virtual NHPT

Figure 5.23 shows Linda's virtual NHPT (VNHPT) times and RMSE values for completing the task at three separate sessions: session 4 (end of week 4), session 12 (end of week 8) and session 13 (end of week 12). As previously described, improvements in RMSE could suggest improvements in the efficiency of movement, which in turn could relate to improvements in arm function. Over the three sessions presented here, Linda's time to complete the VNHPT increased, paired with an increase in RMSE, suggesting that no improvements were detected using this task or these measures.

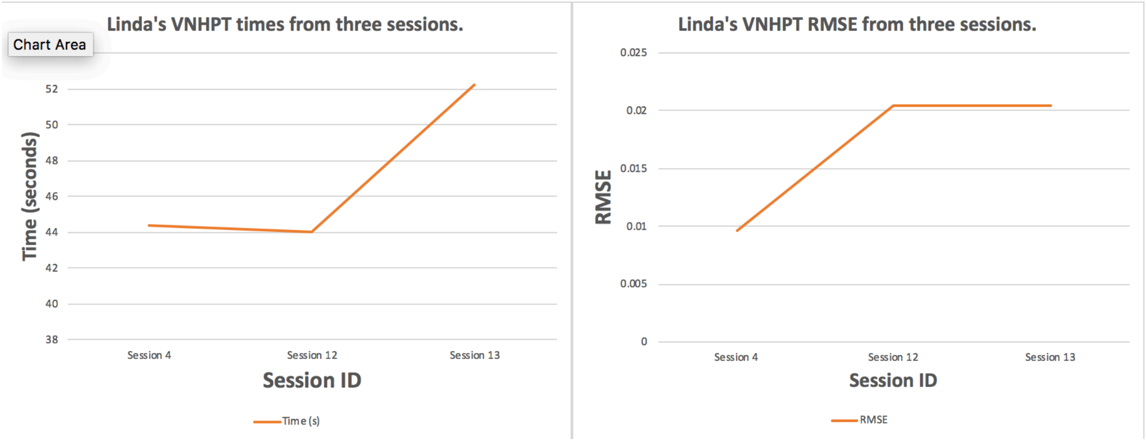


Figure 5.23: **Linda's Virtual NHPT times and RMSE** (impaired arm). Over the three sessions presented here, Linda's time to complete the VNHPT increased, paired with an increase in mean RMSE, suggesting that no improvements were detected using this task or these measures.

5.5.2.2.2 Targets

As described in the *Targets* section for the participant 'George', we measured RMSE for the Targets game in order to try to ascertain whether a participant's reaction to perturbation forces improved over the course of a number of individual exercise sessions. Figure 5.24 shows Linda's mean RMSE for the Targets game using her impaired arm. Her minimum mean RMSE was found a session 10, which then increased in session 11. Overall, from the first session using the targets game (session 7) to the last session with the game (session 11), there was a reduction in mean RMSE. This potentially could suggest some improvement in Linda's reaction to perturbation forces, but a longer study would need to be conducted with this task to ascertain what the learning affect component may be for this task.

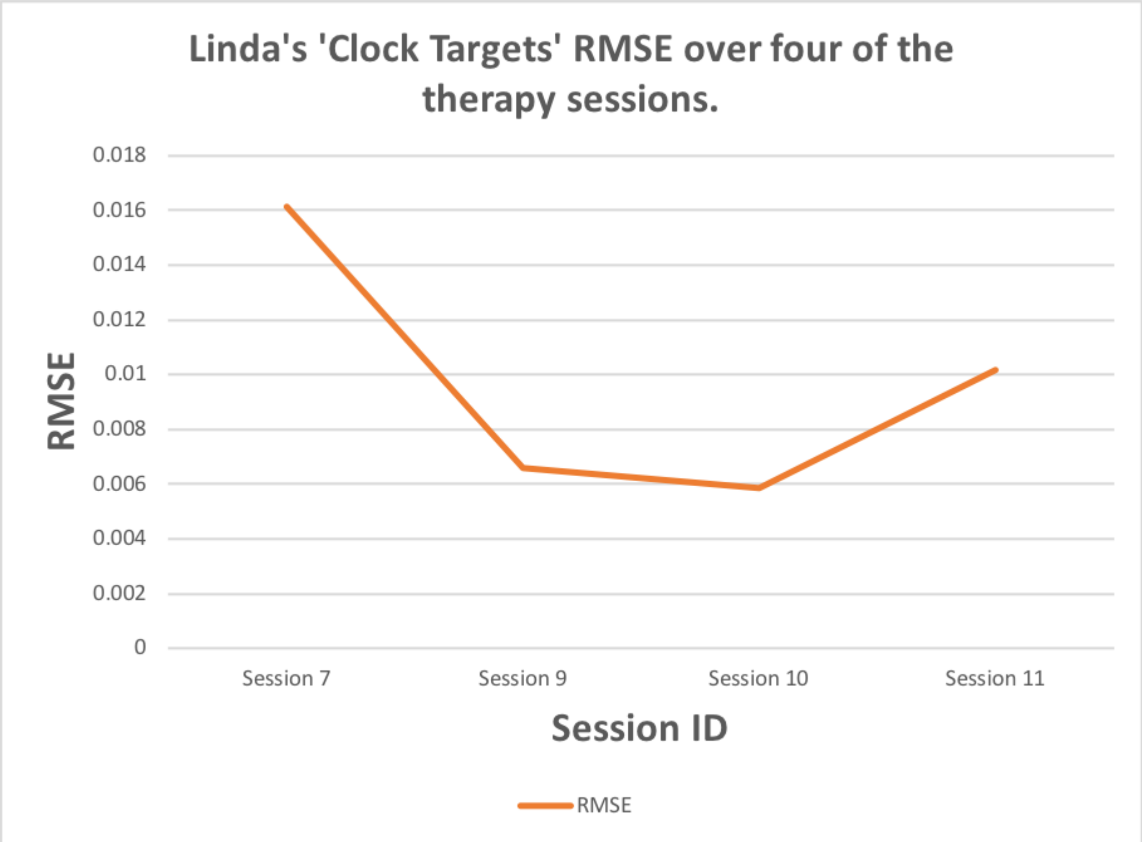


Figure 5.24: **Linda's Clock Targets RMSE** (impaired arm). The mean RMSE metric improved between sessions 7 and 10, suggesting learned skill or functional arm improvement, however, some of these gains were lost by session 11; however, still showing improvement over session 7.

5.5.2.2.3 Haptic Guidance

As previously discussed, the haptic guidance task required users to be guided from one part of the virtual environment to another. Improvements in RMSE for this task could suggest more flexibility and reduction of stiffness or resistance in movement.

In figure 5.25, the results of the RMSE metric are presented for four of the exercise sessions. Linda displayed a reduction of mean RMSE between session 5 and session 11 when using her impaired arm. This is a positive result that potentially shows some level of improvement, either in arm function, or the ability to perform the task.

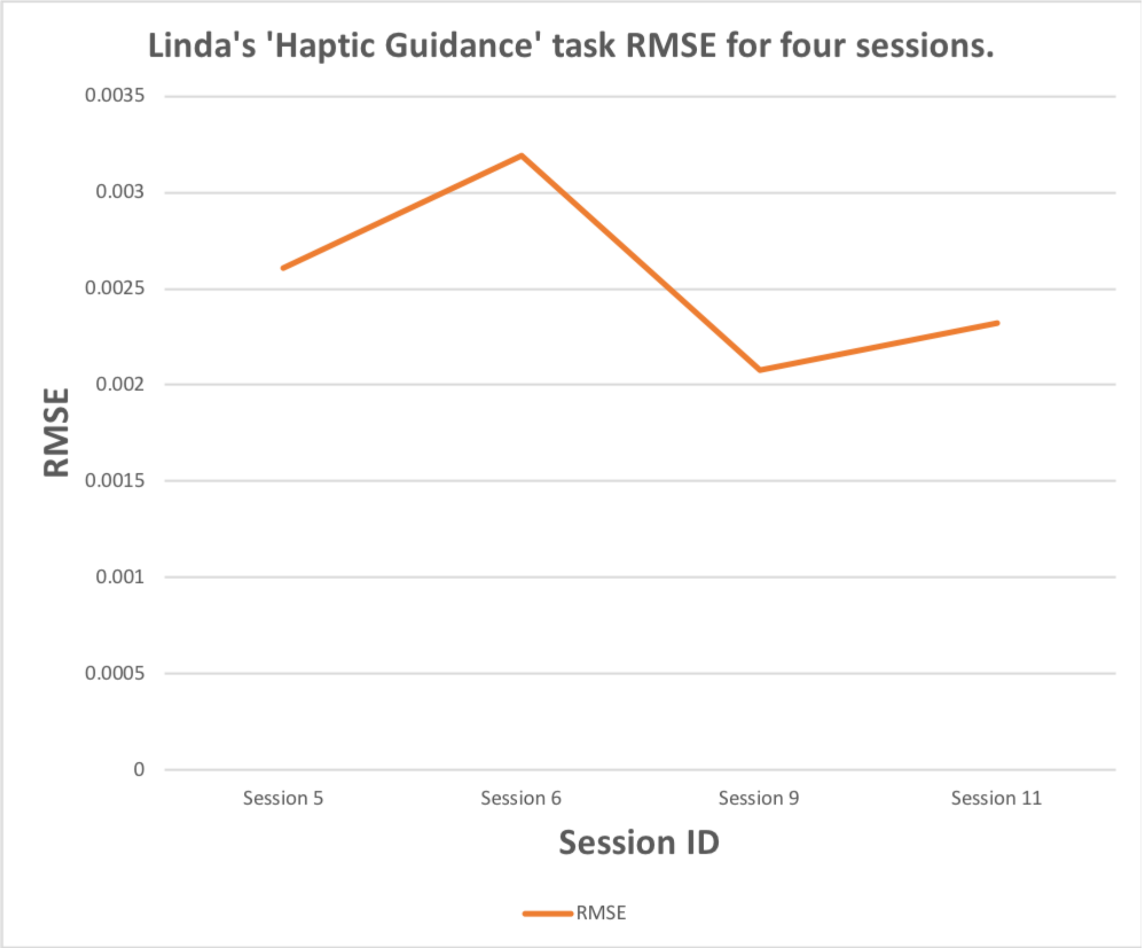


Figure 5.25: **Linda's Haptic Guidance task RMSE.** Overall, between session 5 and session 11, there was a positive reduction in mean RMSE suggesting some improvements were made either in arm function or learned skill.

As previously discussed, MAE (mean absolute error) and peak velocity were also analysed, but the findings were inconclusive.

Following Linda's journey throughout the course of the experiment, Linda stated that she felt more capable with her arm and that she could move her arm more even after the four-week period of no intervention following the exercise sessions. Linda also stated that she found the system fun and enjoyable; however, she did not feel confident that she would be able to use this type of system on a daily basis, and would only use it if somebody else was present. She rated the system 85 on the SUS which relates to a good to excellent level of usability in her opinion.

Linda showed improvement in her results for the NHPT using her impaired arm by the end of the trial that matched her perceived benefit of the system when discussion capability; and Linda also showed an improvement in the times for the ENHPT task. The analysis of the virtual tasks did show some potentially measurable improvements in both the targets game and the guidance task where the difference between the first session with the aforementioned tasks and the last session with those tasks did close with a net reduction in RMSE. Further studies into these tasks and the RMSE measure would need to be conducted to ascertain whether or not this could be used as a good measure of improvement in arm function.

5.5.3 Robert

Robert had his stroke ten months before starting the experiment and is not currently receiving any therapy for either his lower or upper limb impairments. His right (dominant) side has been most affected by his stroke, but also has some impairment in his left arm too.

From the questionnaires, Robert stated that he felt quite tired all throughout the first week of the exercise sessions, and again for the last week of the exercise sessions; although, he remained mostly confident and motivated throughout the experiment. In the penultimate session, Robert was very tired and was not very motivated.

As with all participants, Robert performed the NHPT and BBT tasks in the initial session to provide a baseline measurement of arm function. Tables 5.8 and 5.9 show Roberts's NHPT and BBT task results.

Table 5.8: **Robert's task times for the NHPT.** Although Robert stated that his right-hand-side had been most affected by his stroke, there are no significant differences between task times for his right and his left arm.

Attempt Number	Right	Left
1	21.34s	19.09s
2	16.31s	16.13s
3	15.68s	16.03s

Table 5.9: **The number of blocks that Robert managed to move** from one side of the box to the other. Robert was able to place more blocks using his left (non-dominant, less-impaired) arm.

Attempt Number	Right	Left
1	16	23
2	20	27
3	15	36

Robert completed the NHPT in a reasonable time with both his left and right hands, showing no significant favour for either arm. The BBT results did show better results for Robert's left arm for which he stated had been affected less than his right arm. Robert completed all three attempts for each of the assessment tasks, so he was a suitable candidate for this experiment.

Over the course of the study, Robert found that the tasks differed in difficulty, sometimes even rating the same tasks easy in one session and difficult in another; although, this could not be attributed to tiredness (from the questionnaire). On two occasions, Robert felt discomfort. This discomfort was while performing the Teacups game, where the teacup is effectively held using a spring, the weight of which can become quite heavy and unpredictable. Robert did not enjoy the Teacups game but enjoyed all of the other tasks.

When asked whether Robert found the tasks helpful, he stated that he found them quite to very helpful (in the session asked). Robert was varied in his response to rating his performance. Robert struggled to hear the audio cues and sounds in the haptic tasks so didn't find them very helpful.

Table 5.10 shows Robert's responses to the statements presented at the end of the final assessment from 'Strongly Disagree' to 'Strongly Agree'. As with the other final questionnaires, this data has also been aggregated into a visual representation in figure 5.26.

Table 5.10: **Robert's responses to the final survey** on arm function following the conclusion of the trial.

Statement	Response
In the weeks of the experiment, I felt more capable with my arm	Agree
In the weeks of the experiment, I felt more discomfort with my arm	Agree
In the weeks of the experiment, I could move my arm more	Agree
In the weeks of the experiment, my arm felt stiff	Neutral
In the weeks of the experiment, I could move my hand more	Agree
In the weeks of the experiment, my arm felt tired	Strongly Agree
In the week after the experiment, I felt more capable with my arm	Strongly Agree
In the week after the experiment, I felt more discomfort with my arm	Agree
In the week after the experiment, I could move my arm more	Agree
In the week after the experiment, my arm felt stiff	Agree
In the week after the experiment, I could move my hand more	Strongly Agree

Statement	Response
In the week after the experiment, my arm felt tired	Strongly Agree
Since completing the experiment, I felt more capable with my arm	Strongly Agree
Since completing the experiment, I felt more discomfort with my arm	Strongly Agree
Since completing the experiment, I could move my arm more	Strongly Agree
Since completing the experiment, my arm felt stiff	Strongly Agree
Since completing the experiment, I could move my hand more	Strongly Agree
Since completing the experiment, my arm felt tired	Strongly Agree

In figure 5.26 we can see Robert's perceived benefit of the exercise sessions on the function of his impaired arm. Interestingly, Robert described the most positive benefit (a score of $4.5/5$) one week following the conclusion of the exercise sessions.

Robert agreed with almost all of the positive statements and every single one of the negative statements when considering his arm and hand function in the weeks during, one-week after, and four-weeks after; answering 'Strongly Agree' to all statements regarding arm function in the four weeks after the exercise sessions.

Figure 5.27 shows Robert's NHPT protocol times throughout the study. Robert's task times for his unimpaired (left) and impaired (right) arm were very similar. In terms of improvement, Robert's times improved most in the four week period between the initial assessment and the start of the exercise sessions: before any haptic intervention had been carried out. Robert performed the NHPT task marginally better with his right (impaired) arm. Robert states that his stroke has affected his right arm more, but considers both to be impacted; however, his tasks times were reasonably good for the NHPT task.

Robert agreed with statements relating to improved arm function, but also agreed with statements that related to negative effects on arm function. From the times

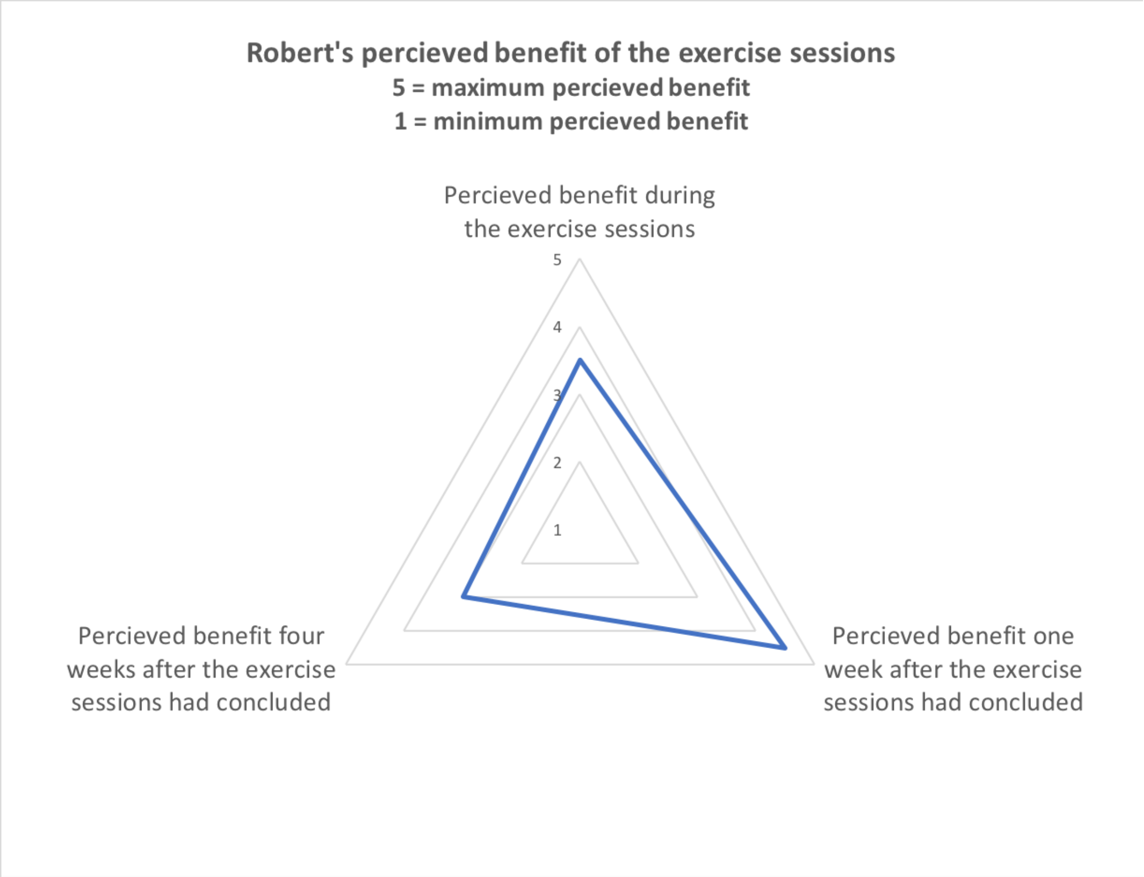


Figure 5.26: **Robert's perceived benefit from the experiment.** The three axes describe the scores that Robert gave for each of the periods following the conclusion of the exercise sessions: immediately after, one week after, and four weeks after. The axes run from 1 to 5, where 5 is the maximum perceived benefit that could be scored. The statements from the questionnaire are all in the context of the impaired arm.

achieved when performing the NHPT protocol, there is no significant improvement or deterioration of arm function that could be declared.

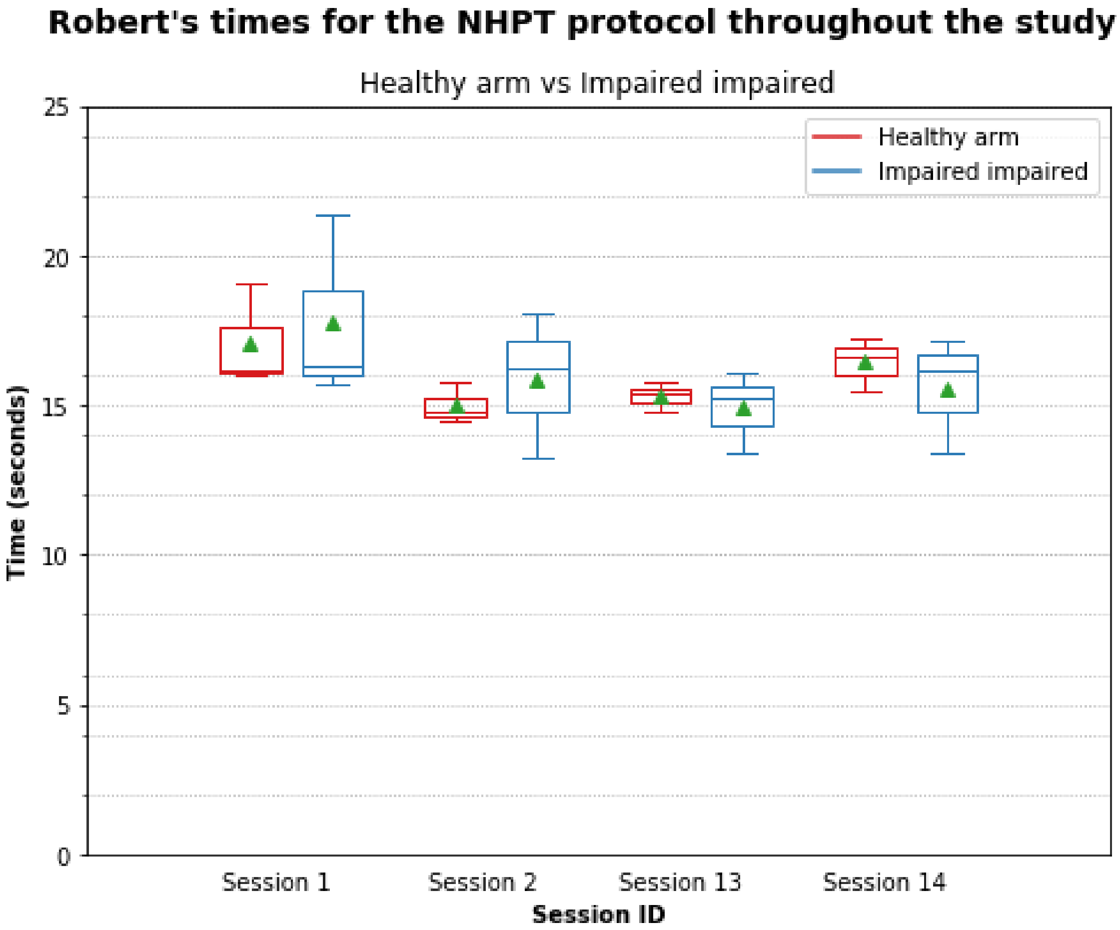


Figure 5.27: **Robert's NHPT times** throughout the course of the 12 weeks. There were no significant differences in Robert's tasks times throughout the course of the study. Robert performed the NHPT marginally better with his right (impaired) arm.

Figure 5.28 describes Robert's BBT scores throughout the course of the experiment. Unlike with the NHPT task, Robert performed better at the BBT with his less-impaired left arm. Over the 12 weeks of the experiment, Robert improved his BBT scores with both arms, scoring higher for his final BBT with his right (dominant, impaired) arm than the score when using his left arm. This result was converse to the NHPT task times, where little to no improvement could be shown throughout the experiment.

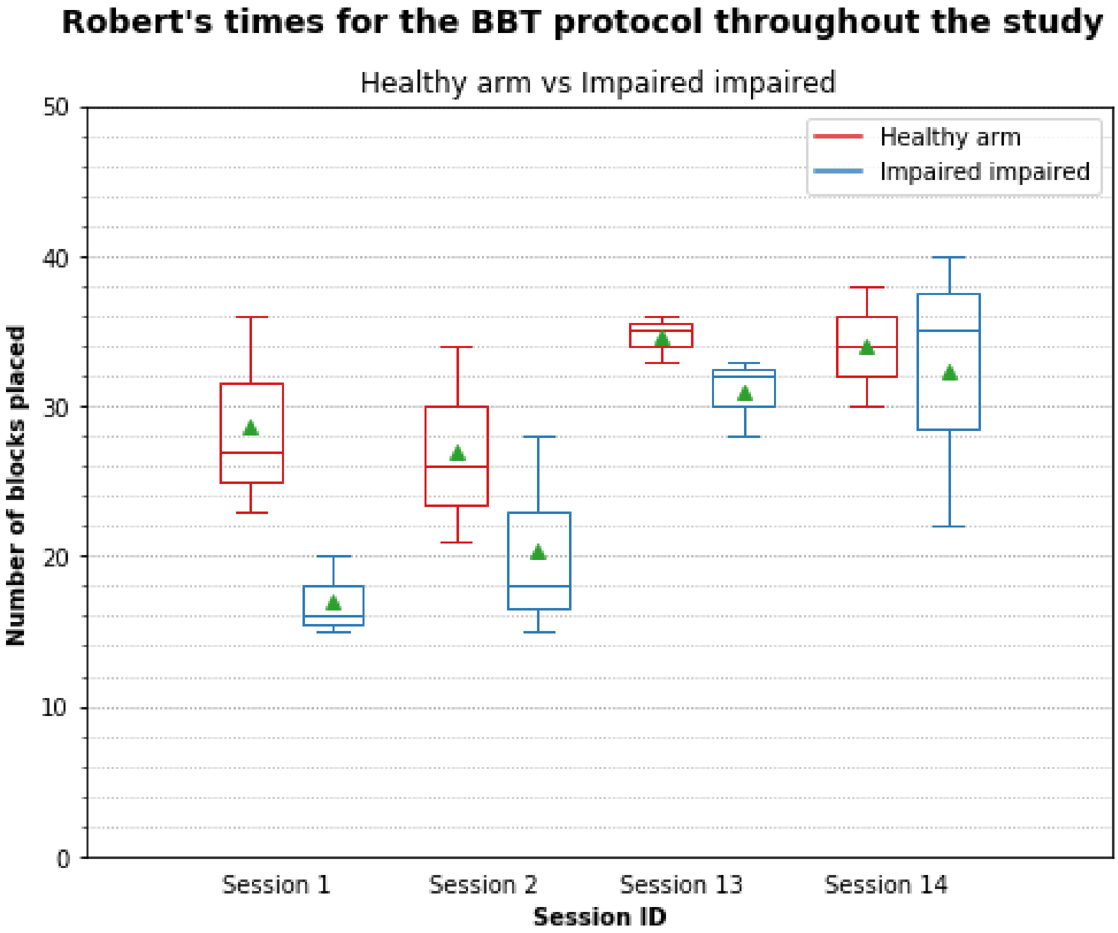


Figure 5.28: **Robert's BBT scores** throughout the course of the 12 weeks. Robert's mean BBT scores with his impaired arm increased by nearly 100% by the end of the study, suggesting some functional improvement of the arm.

5.5.3.1 Embedded NHPT

As part of the exercise sessions, Robert also had to perform an embedded version of the NHPT (ENHP, see chapter 3). Due to some data corruption, only three of the ENHPT sessions are presented here. Figure 5.29 shows Robert's ENHPT times with his impaired arm as a boxplot. Over the three sessions presented here, Robert made improvements to his best task time for completing the ENHPT protocol. Robert's task times remained varied (high standard deviation in this context >10 seconds), and the overall time to complete the task was also high. Robert appeared to struggle with the ENHPT, finding it hard to place the end effector into the holes in the pegboard using the stylus - potentially some more practice was required, or potentially, the level of proprioception required to perform this task was too high and thus too difficult for Robert to complete.

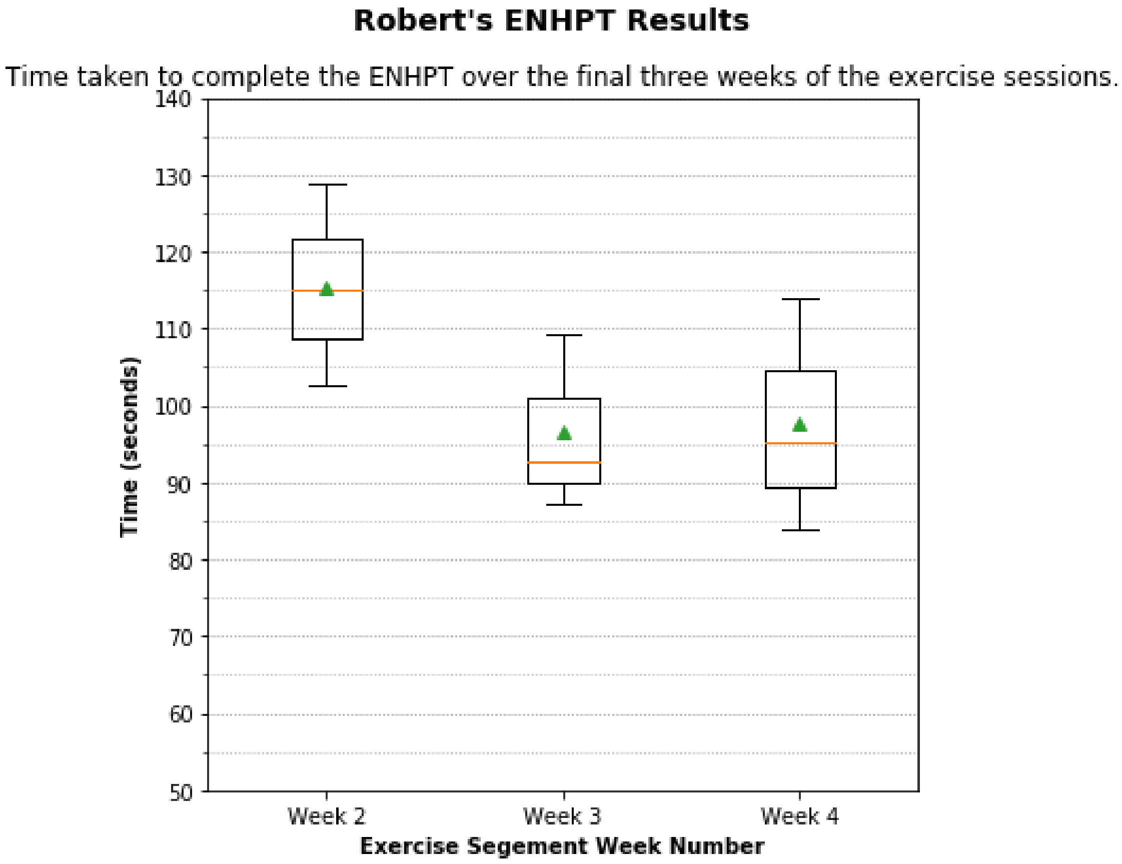


Figure 5.29: **Robert's Embedded NHPT task times** taken during the exercise sessions. Robert's times for the ENHPT task were relatively slow compared to the physical NHPT task and may have required more time to practice with the apparatus.

5.5.3.2 Virtual Tasks and RMSE

As described in the section ‘Virtual Tasks and RMSE’ for the participant named ‘George’, we analysed the root mean squared error (RMSE) for the virtual tasks that were performed as part of the exercise sessions between weeks four and eight. The calculations for the RMSE metric were implemented in Python and the Numpy package.

5.5.3.2.1 Virtual NHPT

Figure 5.30 shows Robert’s virtual NHPT (VNHPT) times and mean RMSE values for completing the task at three separate sessions: session 4 (end of week 4), session 12 (end of week 8) and session 13 (end of week 12). As previously described, improvements in mean RMSE could suggest improvements in the efficiency of movement, which in turn could relate to improvements in arm function. Over the three sessions presented here, Robert showed a net decrease in the time taken to perform the VNHPT with his impaired arm, and also a net reduction in mean RMSE for this task. This is a reasonably positive result and potentially shows some improvements in the efficiency of Robert’s movement within the VNHPT domain.

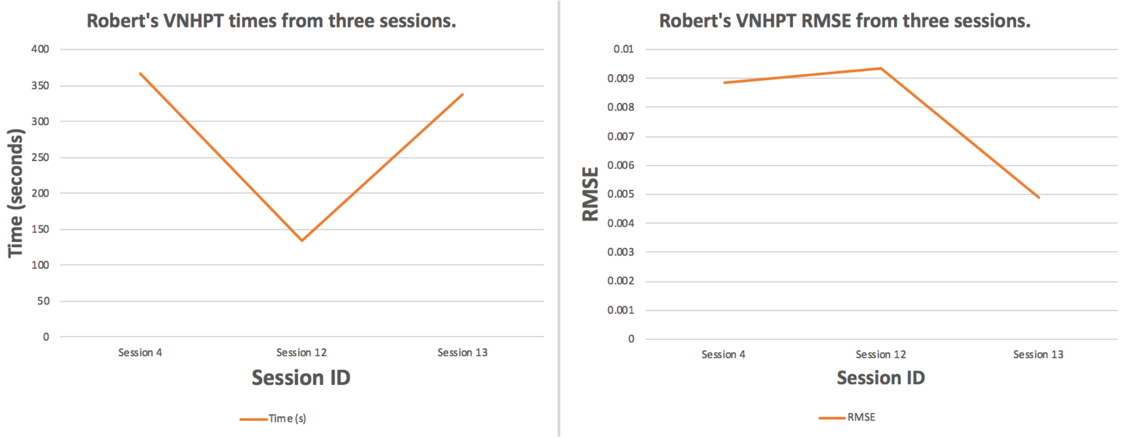


Figure 5.30: **Robert’s Virtual NHPT times and RMSE.** Robert showed a net decrease in the time taken to perform the VNHPT with his impaired arm, and also a net reduction in mean RMSE for this task. This is a reasonably positive result and potentially shows some improvements in the efficiency of Robert’s movement within the VNHPT domain.

5.5.3.2.2 Targets

As described in the *Targets* section for the participant ‘George’, we measured RMSE for the targets game in order to try to ascertain whether a participant’s reaction to perturbation forces improved over the course of a number of individual exercise sessions. Figure 5.31 shows Robert's mean RMSE for the Targets game using his impaired arm. His minimum mean RMSE was found in the first session, leading to a net increase in mean RMSE by session 11.

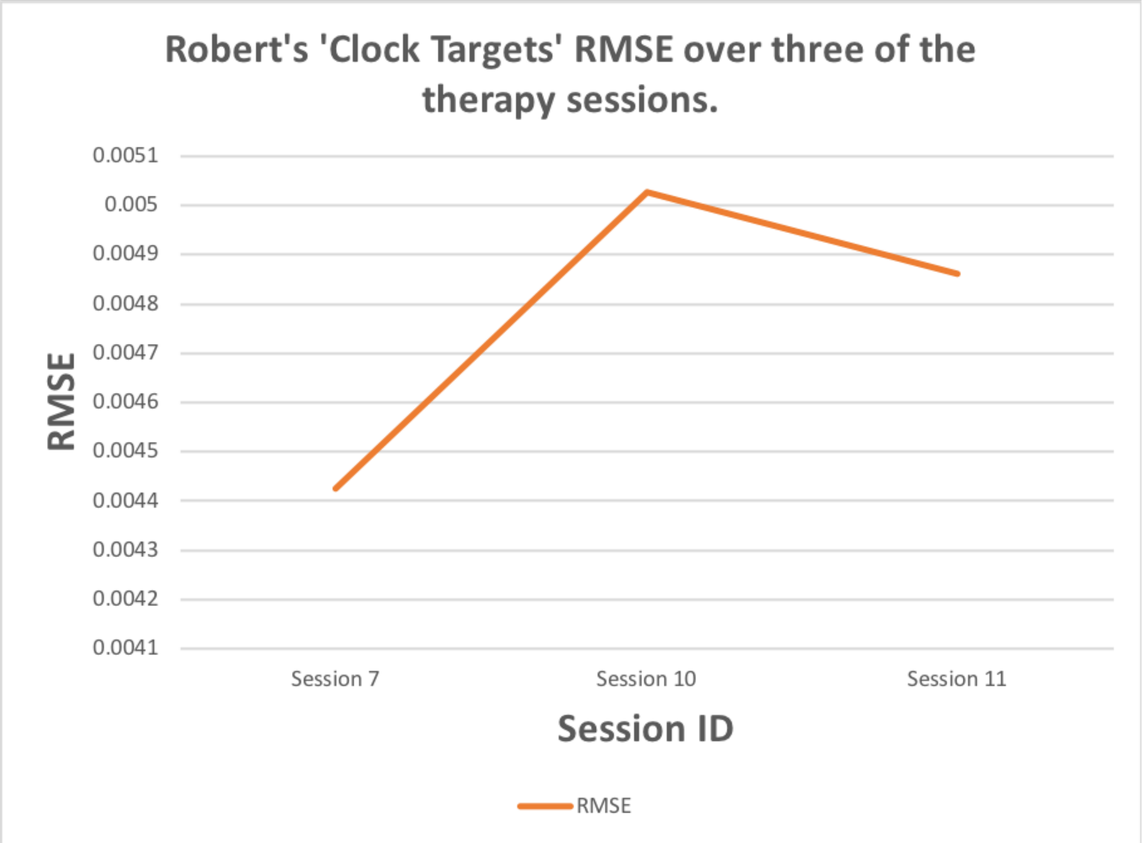


Figure 5.31: **Robert's Clock Targets RMSE.** Robert showed no improvement in the clock targets game when considering the mean RMSE metric.

5.5.3.2.3 Haptic Guidance

The benefits of measuring RMSE for this task were discussed in the section 'Haptic Guidance' for the participant 'George'.

In figure 5.32, the results of the RMSE metric are presented for four of the exercise sessions. Robert displayed a reduction of RMSE between session 5 and session 11 when using his impaired arm. This is a positive result that potentially shows some level of improvement, either in arm function, or the ability to perform the task.

As previously discussed, MAE (mean absolute error) and peak velocity were also analysed, but the findings were inconclusive.

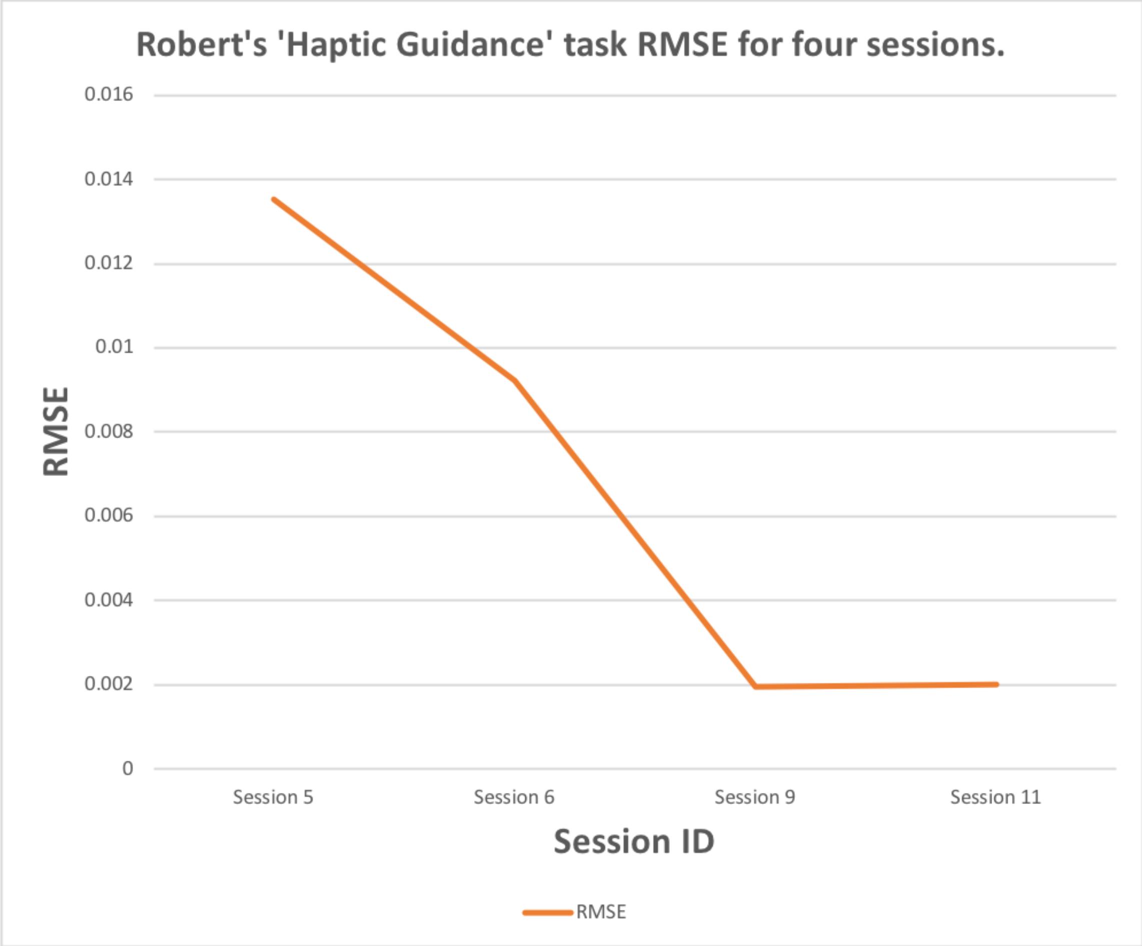


Figure 5.32: **Robert's Haptic Guidance task RMSE.** The mean RMSE metric reached its lowest point in sessions 9 and 11, improving over sessions 5 and 6, this potentially indicates some level of functional improvement or learned skill.

Over the course of the experiment, Robert showed more improvement with his impaired right arm when measuring his arm function using the BBT test than measured using the NHPT. Robert did show some improvement over the session measured with the ENHPT protocol, but these cannot be distinguished from learning effects that may have been present without an extended study into the efficacy of the ENHPT protocol. Similarly, Robert showed improvement in the RMSE metric when using the haptic guidance task, although the RMSE improvements were not mirrored by the other virtual tasks analysed.

Robert scored the system 60 using the SUS, a score that roughly translates to an average to good system in terms of usability. Robert also agreed that he felt more capable with his arm in the weeks of therapy, the week after therapy, and in the final assessment four weeks after therapy; however, he also stated that his arm felt stiffer, he felt more discomfort, and that he felt more tired throughout the trial. Robert stated that he found the system fun and enjoyable and would like to use one of these systems on a daily basis; however, would not like to have one in his own home.

5.5.4 Jennifer

Jennifer was extremely enthusiastic and happy to be a part of this study. She works part-time and is not receiving any form of physical therapy. Jennifer's stroke left her with severe impairment to her left (non-dominant) arm, and also blindness and hearing difficulties on her left side.

During the initial assessment session, Jennifer performed both the NHPT and BBT tasks. We used these measurements as a baseline of arm function.

Table 5.11: **Jennifer's NHPT times.** The times for her left hand were approximately twice as long as when she used her right hand.

Attempt Number	Right	Left
1	13.78s	29.31s
2	13.06s	25.94s
3	12.22s	26.68s

Table 5.12: **Jennifer's BBT times** showed that she was able to transport more blocks using her unimpaired, non-dominant right arm than with her left.

Attempt Number	Right	Left
1	28	19
2	30	21
3	36	22

Tables 5.11 and 5.12 showed that there was a visible difference in Jennifer's ability to perform the NHPT and BBT tasks with her impaired arm compared to her unimpaired non-dominant arm. She was able to complete all of the tasks fully and therefore was a good candidate for this study.

Jennifer found most of the sessions helpful when asked, and found that the tasks varied in difficulty: some being easy, some being difficult. Jennifer was motivated and confident throughout the task. Jennifer occasionally stated that she was quite tired through the course of the study but never stated that she felt any discomfort. Jennifer enjoyed performing most of the tasks in the experiment.

When asked to rate her performance for completing the tasks, Jennifer responded with 'Average' to 'Good' throughout the study, but this was not a linear improvement, nor could perceived performance be linked to perceived tiredness.

In the final questionnaire (Appendix E) participants were asked to score their arm function using Likert scale style questions. These questions were grouped by time since concluding the 12 exercise sessions (immediately after, one week after, and four weeks after). Jennifer's results are given in table 5.13. We also aggregated these into a visual representation of Jennifer's perceived benefit of the exercise session in figure 5.33.

Table 5.13: **Jennifer's responses to the final survey**, investigating the perceived benefit of the sessions in terms of arm function.

Statement	Response
In the weeks of the experiment, I felt more capable with my arm	Agree
In the weeks of the experiment, I felt more discomfort with my arm	Disagree
In the weeks of the experiment, I could move my arm more	Neutral
In the weeks of the experiment, my arm felt stiff	Strongly Disagree
In the weeks of the experiment, I could move my hand more	Agree
In the weeks of the experiment, my arm felt tired	Agree
In the week after the experiment, I felt more capable with my arm	Agree
In the week after the experiment, I felt more discomfort with my arm	Disagree
In the week after the experiment, I could move my arm more	Neutral
In the week after the experiment, my arm felt stiff	Neutral
In the week after the experiment, I could move my hand more	Agree
In the week after the experiment, my arm felt tired	Agree
Since completing the experiment, I felt more capable with my arm	Neutral
Since completing the experiment, I felt more discomfort with my arm	Disagree

Statement	Response
Since completing the experiment, I could move my arm more	Neutral
Since completing the experiment, my arm felt stiff	Disagree
Since completing the experiment, I could move my hand more	Agree
Since completing the experiment, my arm felt tired	Disagree

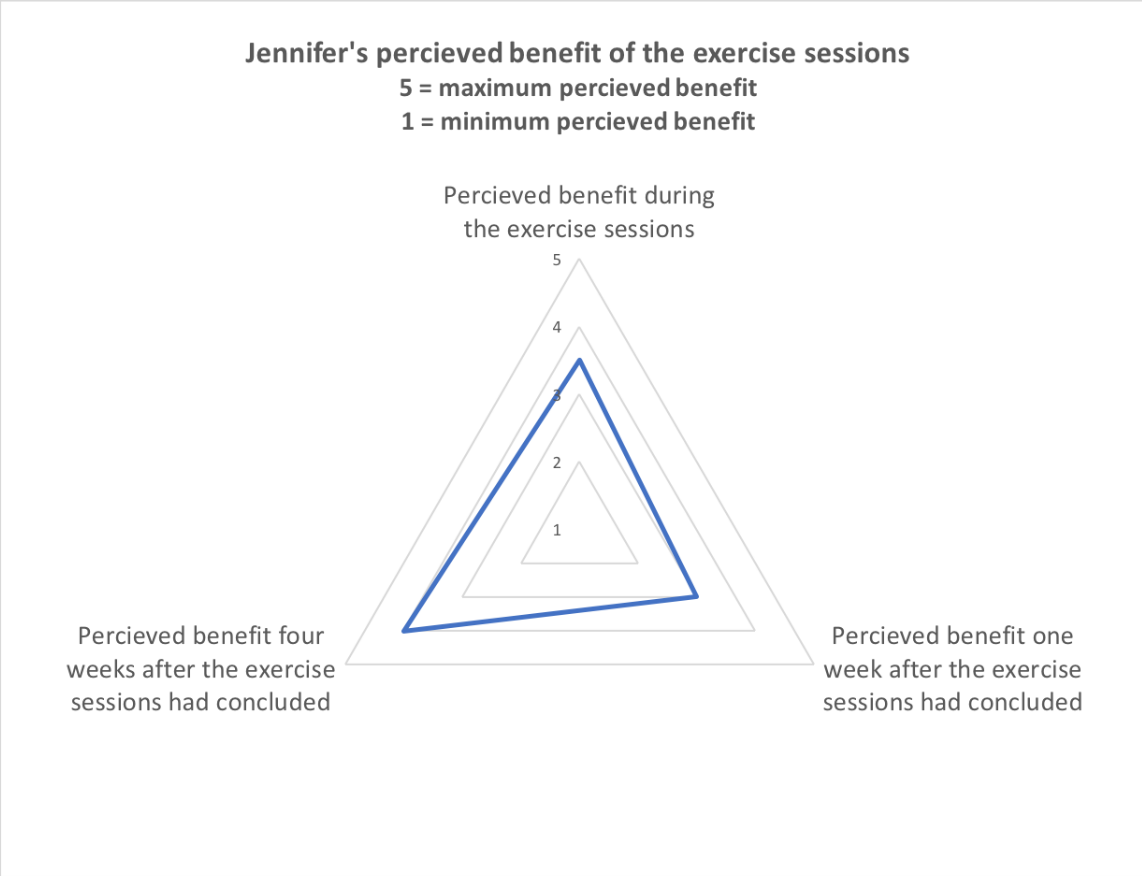


Figure 5.33: **Jennifer's perceived benefit from the experiment.** The three axes describe the scores that Jennifer gave for each of the periods following the conclusion of the exercise sessions: immediately after, one week after, and four weeks after. The axes run from 1 to 5, where 5 is the maximum perceived benefit that could be scored. The statements from the questionnaire are all in the context of the impaired arm.

In figure 5.33 we can see Jennifer's perceived benefit that the exercise sessions had on her arm function. Due to her responses regarding tiredness and stiffness, Jennifer perceived much less benefit immediately following the exercise sessions and in the week after them than she did four weeks after the conclusion of the exercise sessions where her perceived benefit was at its best (a score of $4/5$).

Jennifer's answers from table 5.13 describe that during the weeks of the experiment, Jennifer agreed with the statements that she felt more capable with her impaired arm and that she felt that she could do more with her impaired hand. She stated that her arm movement was neither better, nor worse, in the weeks of the experiment. She disagreed with the statement that she felt more discomfort in her impaired arm, and strongly disagreed that her arm felt stiff in the weeks of the experiment; however, she did agree with the statement that her arm felt more tired during the weeks of the experiment.

In the week immediately following the exercise sessions, Jennifer continued to feel more capable with her arm and also agreed that she could move her hand more. Jennifer disagreed with the statement that she could move her arm more in the week immediately following the exercise sessions. Jennifer agreed that her arm felt tired in the week following the exercise sessions, and disagreed that any discomfort. She neither agreed nor disagreed with the statement regarding stiffness in her impaired arm.

In the four weeks since completing the experiment, Jennifer maintained that she could move her hand more, suggesting some potential longer lived gains from the experiment. However, Jennifer responded neutrally to feeling more capable with her impaired arm, and to whether she felt that she could move her arm more. She disagreed with all the negative statements in the four weeks following the exercise sessions.

Figure 5.34 shows Jennifer's NHPT protocol times throughout the study. Jennifer performed the NHPT protocol better with her right (unimpaired, non-dominant) arm than with her left (impaired) arm. By session 13 (end of week four), Jennifer had improved her NHPT task time by approximately 5 seconds. This matched well with her perceived capability improvements: she felt more capable with her impaired arm and felt that she could move her impaired arm and hand more by the end of the exercise sessions.

Jennifer's impaired NHPT time had increased by the final assessment session by roughly 3 seconds. Conversely, Jennifer maintained that she still felt that she could do more with her impaired hand four weeks after the exercise sessions. Jennifer was neutral in responses to feeling more capable with her arm, and whether she felt that she could move her arm more which is possibly linked to the regression of performance time with her impaired arm in the final assessment session.

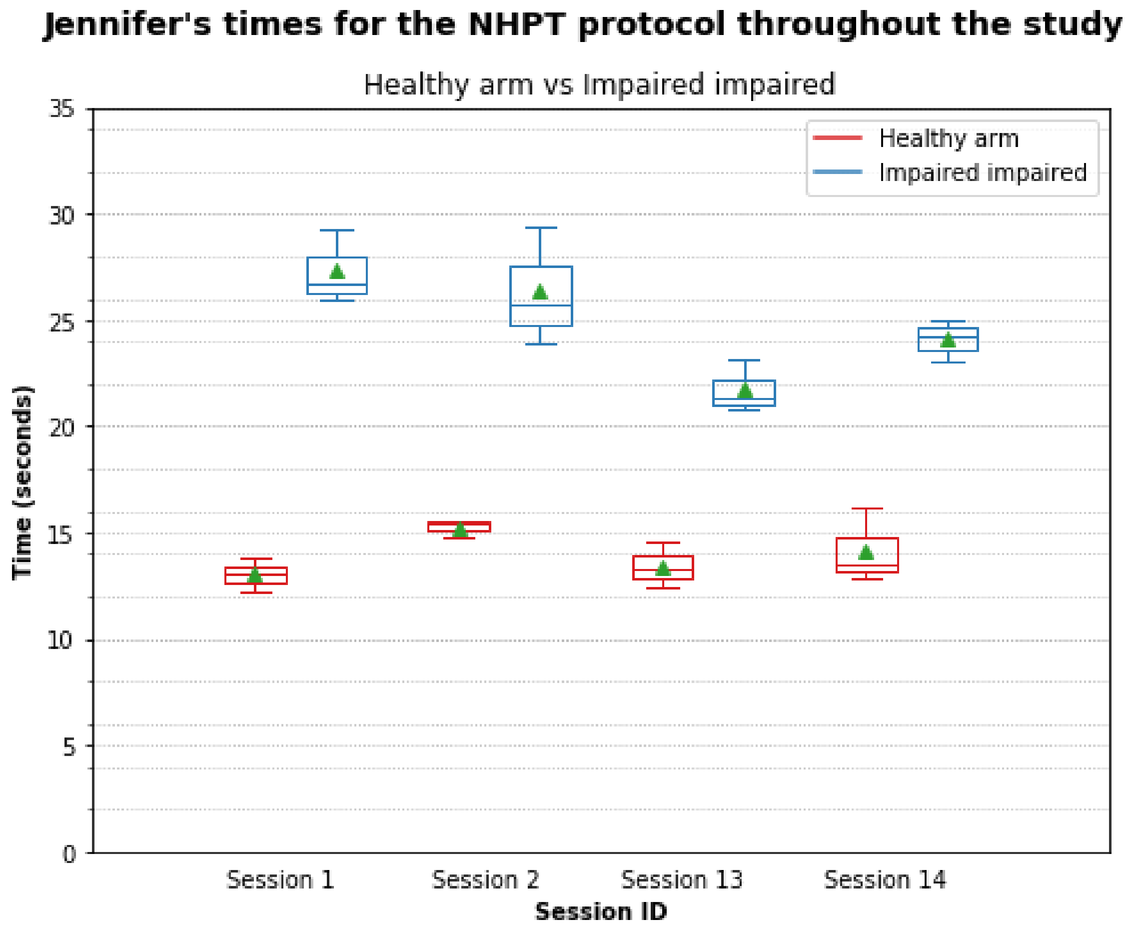


Figure 5.34: **Jennifer's NHPT times** throughout the course of the 12 weeks. Although Jennifer's impaired task time increased by the end of the study, Jennifer still stated that she felt more capable with her impaired hand four weeks after the exercise sessions.

Figure 5.35 shows Jennifer's BBT scores for the 12-week experiment. Jennifer performed better with her right (unimpaired, non-dominant) arm than with her left. Her scores improved very slightly (with both arms) over the course of the study. Interestingly, the pattern of improvement for her left (impaired) arm was similar between the two assessment tasks, achieving the best scores in session 13 after the four weeks of exercise sessions, before a slight diminishment of performance in the final assessment session.

5.5.4.1 Embedded NHPT

Figure 5.36 shows Jennifer's ENHPT times with her impaired arm. Over the course of the three sessions presented here, Jennifer's task time actually increased (wors-

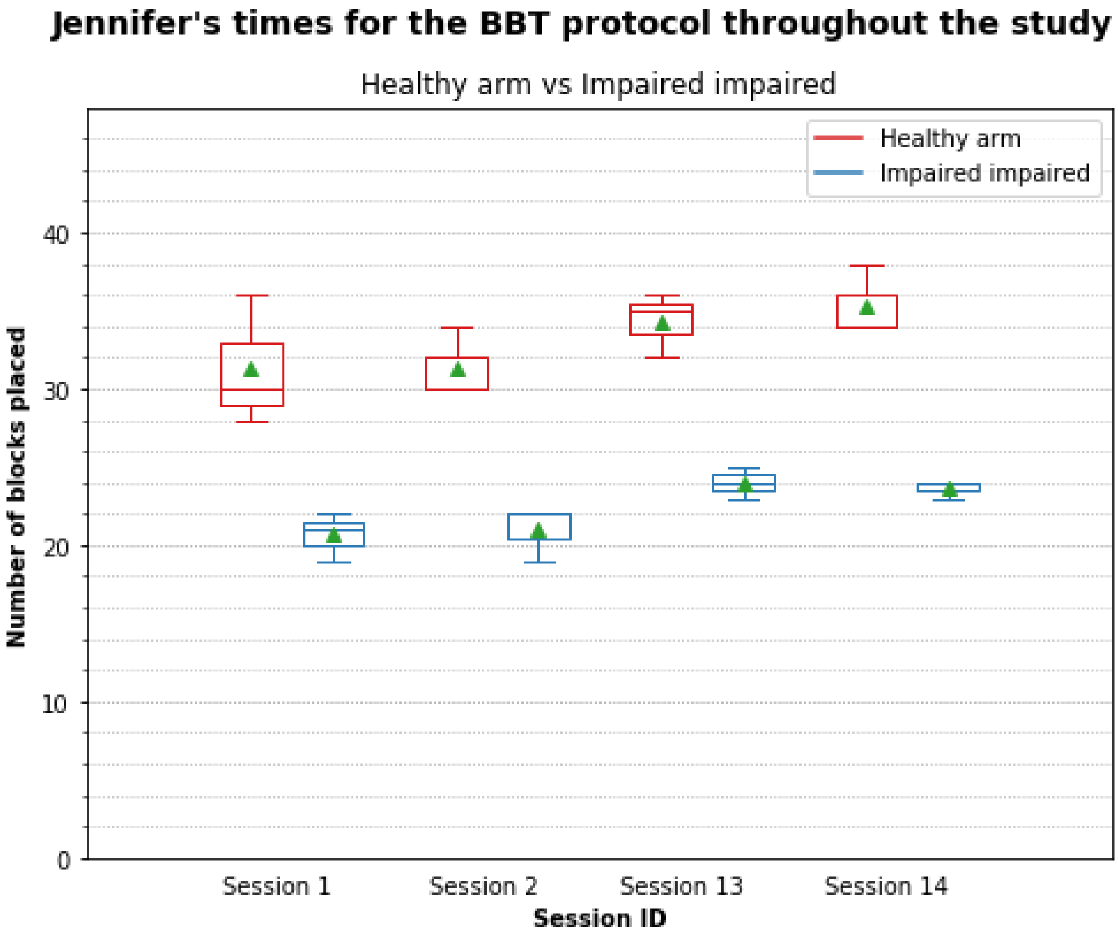


Figure 5.35: **Jennifer's BBT scores** throughout the course of the 12 weeks. Jennifer's scores slightly improved for both her impaired and healthy arm over the course of the study.

ened) whilst the standard deviation between attempts varied from session to session.

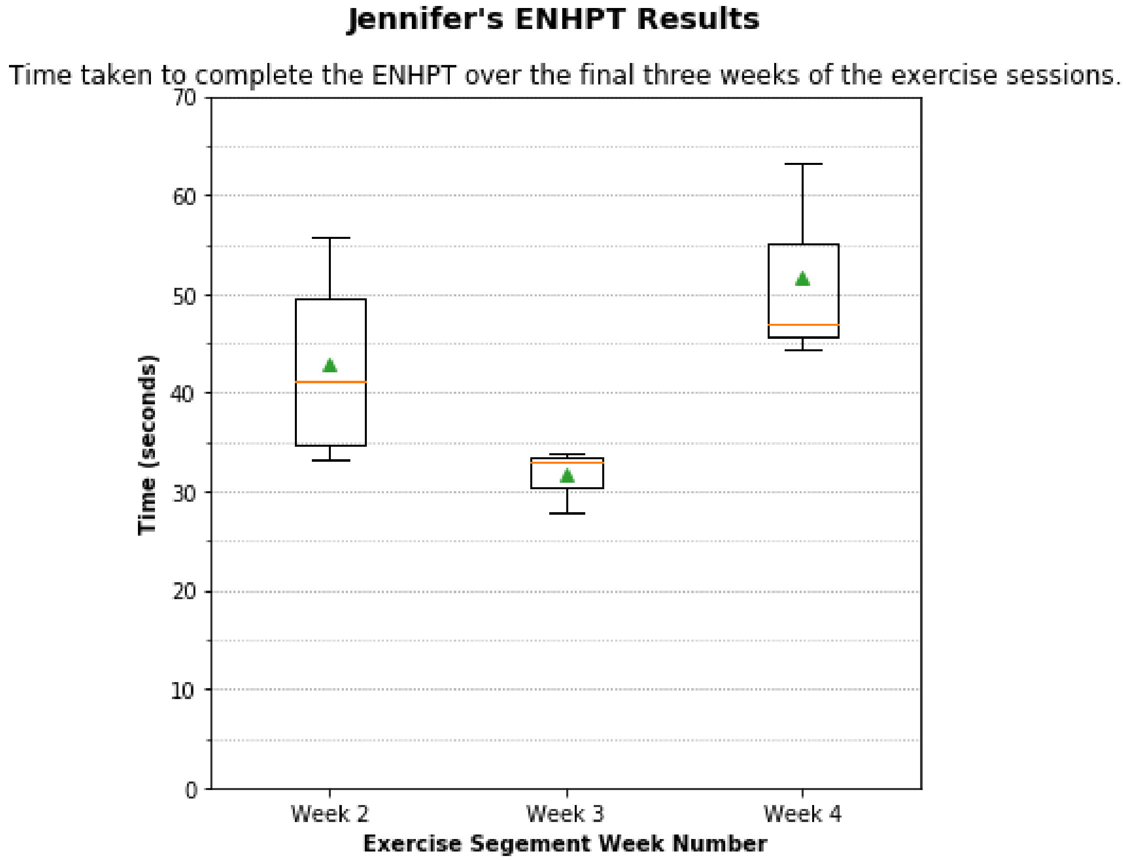


Figure 5.36: **Jennifer's Embedded NHPT task times** taken during the exercise sessions. Jennifer's task time increased by week 4. This may imply that there were some issues with the experiment setup or the task itself.

5.5.4.2 Virtual Tasks and RMSE

As described in the section 'Virtual Tasks and RMSE' for the participant named 'George', we analysed the root mean squared error (RMSE) for the virtual tasks that were performed as part of the exercise sessions between weeks four and eight. The calculations for the RMSE metric were implemented in Python and the Numpy package.

5.5.4.2.1 Virtual NHPT

Figure 5.37 shows Jennifer's virtual NHPT (VNHPT) times and RMSE values for completing the task at three separate sessions: session 4 (end of week 4), session

12 (end of week 8) and session 13 (end of week 12). As previously described, improvements in RMSE could suggest improvements in the efficiency of movement, which in turn could relate to improvements in arm function. Over the three sessions presented here, Jennifer's time to complete the VNHPT decreased; however, conversely showed an increase in RMSE, suggesting that the two measures not be related in this case.

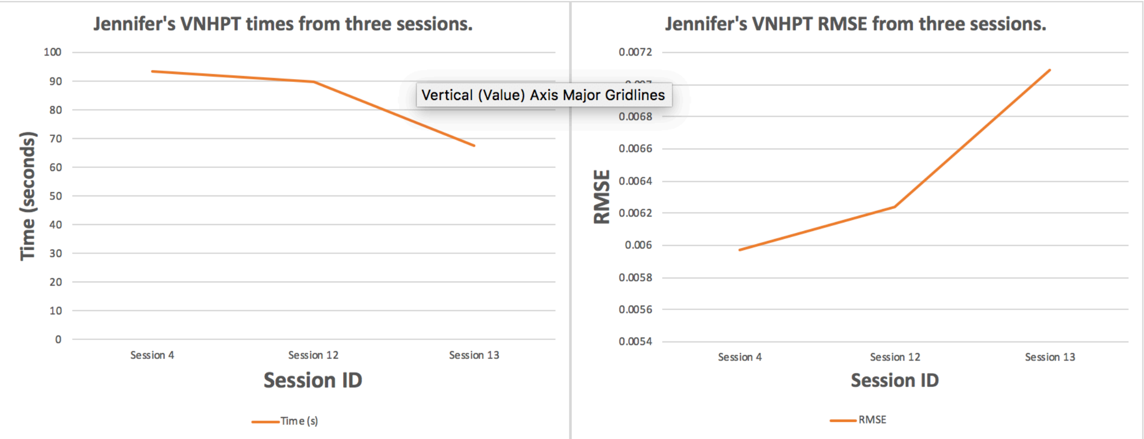


Figure 5.37: **Jennifer's Virtual NHPT times and RMSE.** Over the three sessions presented here, Jennifer's time to complete the VNHPT decreased, however, conversely showed an increase in RMSE, suggesting that the two measures not be related in this case.

5.5.4.2.2 Targets

As described in the *Targets* section for the participant 'George', we measured RMSE for the targets game in order to try to ascertain whether a participant's reaction to perturbation forces improved over the course of a number of individual exercise sessions. Figure 5.38 shows Jennifer's RMSE for the Targets game using her impaired arm. Over the course of five sessions that we recorded data for with Jennifer's impaired arm, we can see a net reduction in RMSE for the targets task. This potentially suggests some improvement in Jennifer's reaction to perturbation forces, but a longer study would need to be conducted with this task to ascertain what the learning affect component may be for this task.

5.5.4.2.3 Haptic Guidance

The benefits of measuring RMSE for this task were discussed in the section 'Haptic Guidance' for the participant 'George'.

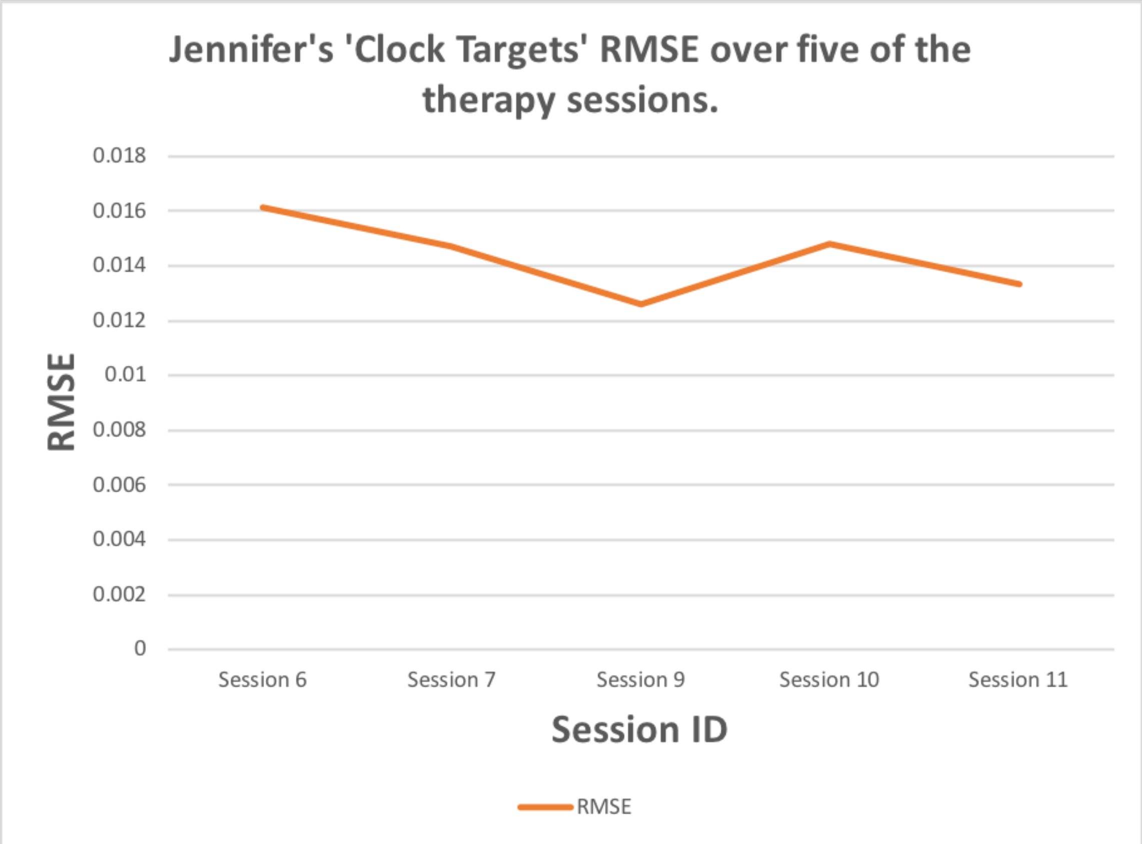


Figure 5.38: **Jennifer's Clock Targets RMSE.** Jennifer's mean RMSE for this task improved between sessions 6 and 11 which may relate to either functional improvement or learned skill.

In figure 5.25, the results of the RMSE metric are presented for four of the exercise sessions. Jennifer displayed a reduction of RMSE between session 5 and session 11 when using her impaired arm. This is a positive result that potentially shows some level of improvement, either in arm function, or the ability to perform the task.

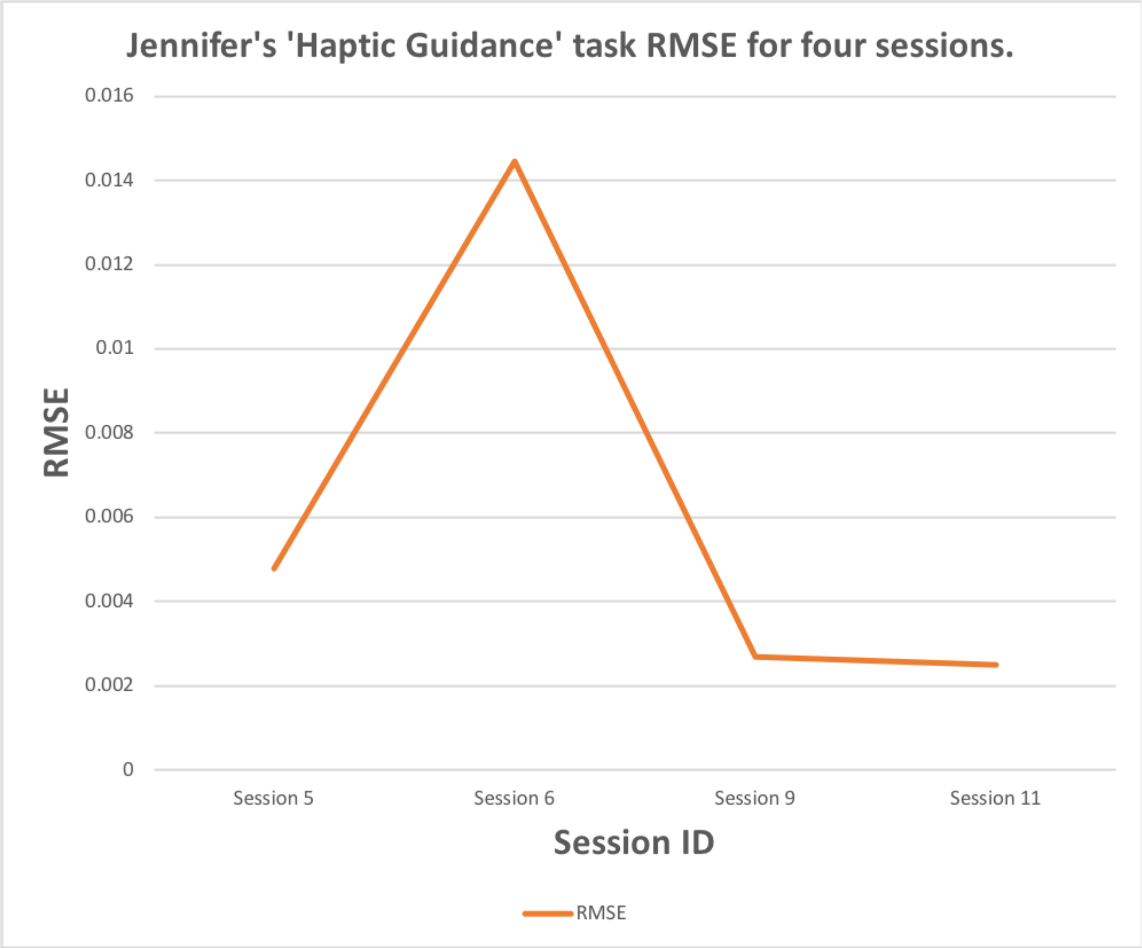


Figure 5.39: **Jennifer's Haptic Guidance task RMSE.**

We also investigated peak velocity and mean absolute error to determine whether or not these metrics correlated with the RMSE findings, but the results were inconclusive.

Over the course of the 12-week experiment, Jennifer showed a slight improvement in her NHPT time by the end of the exercise session which regressed slightly in the four weeks following the exercise sessions when measured in the final assessment session. This matched her perceived improvements in capability from the questionnaire results: she agreed that she felt more capable with her arm and could move her arm and hand more up to the week after the exercise sessions, but, by the final assessment session, Jennifer was only in agreement with the statement that she could move her hand more.

Jennifer did not show improvements in the virtual NHPT tasks (VNHPT and ENHPT); however, she made improvements in the targets game and the haptic guidance task. More studies would need to be conducted to see whether or not these tasks could be more appropriate for stroke survivors with differing levels and types of impairments.

Jennifer rated the system an 87.5 using the SUS - generally regarded as a good to excellent rating of usability; however, she stated in the final questionnaire that she would not want to own one of these systems and would not want to use the system on a daily basis, even though she found the system fun and enjoyable to use.

5.6 Conclusions

At the time of the study, this case study was used to test the feasibility of other studies that involve haptics and remote interaction. Further to the tasks that were analysed in this chapter, the participants also performed the same task as described in Chapter 4. The Interactive environment in Chapter 4 allows for remote collaboration over a network, and the use of such a virtual environment can feed into future work whereby participants could be assessed over-the-wire using the method of communication described.

This chapter has looked at individual case studies for the four participants involved: George, Linda, Robert, and Jennifer. Due to the study being conducted over the course of twelve weeks, and having a limited pool of available participants (one local stroke group), the data analysed here is limited, and is thus more relevant for showing future implications of the work rather than used to draw concrete conclusions.

5.6.1 Perceived and Measured Improvement of Arm Function

Over the course of the experiment, there were many positive findings. All participants showed net improvements in their NHPT times between the initial assessment session and the final assessment session. All participants also stated that they felt more capable with their impaired arm whilst the exercise sessions were on-going: the measured benefit matched the perceived benefit. Two of the participants (Linda and Robert) also stated that they continued to feel more capable with their impaired arms in the four weeks following the exercise sessions; however, George and Jennifer no longer felt more capable.

For two of the participants, the perceived benefits of the interventions did not last the four weeks post-termination of intervention. Potentially, if the participants had further interventions, they could improve and possibly maintain those improvements for a longer period of time. All participants stated that they felt more capable with their impaired arm, but were not asked if this prompted them to use their impaired arm more for tasks of daily living. Increased use of their arm following intervention could have led to further improvements in arm function following the experiment; this is something that should be investigated in future work.

The participants' scores for the BBT protocol did not show an improvement over the study. The lack of improvement in BBT scores is potentially due to the movement required for BBT (gross-reaching movements across the body) being outside of the domain of the PHANTOM Omni® - the maximum reachable x, y, and z planes of the PHANTOM Omni® stylus are well within the bounds of the BBT box. This mismatch between the surface area of the virtual environments and the domain of the BBT could explain why benefits that were measurable with the NHPT did not crossover to measurable benefit with the BBT which is more of a gross-motor arm function assessment technique.

5.6.2 Systems Usability Scale

All of the participants were asked to rate the usability of the system using the Systems Usability Scale (Brooke, 1996). Three participants rated the system good-excellent, and one participant rated the system average-good (table 5.14, full results in Appendix F). Overall this was a positive result in terms of describing the usability of the system, and thus the feasibility of its use in future experiments. One thing to note with the SUS scores is the fact that the questionnaire was taken immediately following the four weeks of haptic intervention: the ratings may have been subject to bias in that they were already well used to the system and comfortable with how to use it. A better measure may be to have participants use a single haptic task and rate its usability separately on first use to give a better indicator of how well the system can be used with minimal preparation and explanation.

Table 5.14: **SUS scores for all four participants.** *denotes a good-excellent score on the systems usability scale.

Participant	SUS Score
George	80*
Linda	85*
Robert	60
Jennifer	87.5*

5.6.3 Questionnaire Results

Looking at themes from the questionnaires (Appendix F), all participants found the system fun and enjoyable, all participants felt comfortable using the system, and all participants found the system easy to use. Participants occasionally felt discomfort when using the system with their impaired arms, but not so much as to cause them to have to stop participation. All participants also agreed that they would like to use the system frequently; however, only one participant would like to have one of these systems in their own home.

The positivity towards the system described by participants responses to questionnaires again goes towards validating the feasibility of this system as a device to be used for assessment and therapy in a stroke survivor's own home. Further studies should be conducted to see if the same would hold true for a larger cohort study.

5.6.4 ENHPT

Three (George, Linda, and Robert) participants also showed improvements in using the ENHPT setup over the course of three separate sessions of the experiment. As discussed in Chapter 3, the Embedded NHPT was found to provide more consistency in results when compared to a purely virtual approach to the NHPT. The ENHPT protocol is beneficial as it allows us to measure more than just the time taken to complete the task: we can analyse accuracy (RMSE), movement smoothness, and peak velocity too, all of which have been shown to be good measures of improvement of motor function (Daly et al., 2005).

There is likely a learning component to the ENHPT protocol, greater than that required to reproduce consistent times in the standard NHPT due to the inclusion of a stylus and a virtual display of the pegs that have been placed onto the board. Further experiments should be conducted with the ENHPT protocol to ascertain how many trials should be performed in order to produce stable, consistent times that could be directly compared to the NHPT.

5.6.5 RMSE

We also looked at the mean RMSE metric for the virtual tasks: VNHPT, Targets, and Haptic Guidance. The only task that showed positive improvement across the whole study cohort was the *Haptic Guidance* task. As described, this could broadly suggest improvements in joint stiffness and resistance to movement (a common upper limb impairment where someone suffering this will struggle to move there arm past a particular position (O'Dwyer NJ, Ada L, 1996)), but further experimentation with a larger subject group would need to be conducted in order to validate this.

5.6.6 Summary

Overall, the results from this study were reasonably positive: participants all showed improvements whilst having the haptic interventions, and some of these improvements continued past the exercise sessions. These measured improvements were also matched by perceived improvements described by participants responses to the questionnaires taken as part of the study.

In the introduction to this thesis, we proposed a question: *Is the PHANTOM Omni® a viable platform for producing home-based rehabilitation systems for hand function following a stroke?* This chapter has looked at four case studies with stroke survivors from a local stroke group. Using our haptic system, our users showed suggestions of functional improvement. This was recorded using standard clinical assessment tests: NHPT and BBT. Most strikingly was that these perceived improvements continued past the exercise sessions for two of the participants. This final experiment also incorporated tasks from the previous two studies - showing as a whole that this setup can be used for rehabilitation and assessment of arm function following a stroke. Given the outcomes of tasks as well as the outcomes from the surveys of the participants, this system is certainly fit for use as a home-based exercise and assessment tool following a stroke. Further studies with improvements described below should be conducted in order to improve the efficacy of the system and assessment techniques.

Some of the tasks were not analysed, this was due to either poor data (corruption or lacking data points) or that the tasks served best as practice sessions that were aimed at acquainting users with the system itself.

Some potential improvements could be made before using this setup in a long-term study with more participants:

- The number of tasks could be reduced in favour of allowing for more attempts at single tasks to be made. This would help to eliminate learning effects when analysing results such as time and RMSE.
- The ENHPT protocol could be included as an assessment tool in conjunction with NHPT and BBT.
- The BBT test could be potentially eliminated as a measure of assessment in this task due to the domain being outside of that of the PHANTOM Omni®, favouring data analysis of the metrics retrieved by the device in both the ENHPT and virtual tasks.

6

General Discussion

Stroke is the second leading cause of death worldwide (Lawrence et al., 2001; WHO, 2017), and it is estimated that more than 75% of stroke survivors suffer from arm weakness following their stroke which can make it hard to perform activities of daily living. Coupling these statistics with findings that shows that as much as 45% of stroke survivors feel abandoned when they leave the hospital (Stroke Association, 2018), it is clear that there is both a need to focus on the treatment and assessment of arm function following stroke and to increase and improve intervention following clinical discharge to reduce feelings of abandonment.

This PhD thesis has investigated ways in which the PHANTOM Omni® (a low-cost, small footprint, haptic device) can improve the assessment and treatment of impaired arm function. This work investigated using an embedded reality approach to the Nine Hole Peg Test (NHPT, chapter 3) that can provide valuable metrics while still being a reasonably accurate assessment of arm and hand function when comparing to the original NHPT protocol (Wade, 1992). The thesis also investigated how remote collaboration in haptic environments can be advantageous to enable different types of movements that have the potential to be used to design tasks suited at eliciting specific arm movements (chapter 4). Finally, it explored home-based rehabilitation via a 12-week-long experiment with four stroke survivors that incorporated exercise and assessment protocols utilising the PHANTOM Omni® (chapter 5) to determine the feasibility of such a method of rehabilitation.

6.1 Haptic Tools for the Assessment of Arm and Hand Function

The first experiment that was conducted for this thesis compared three implementations of the NHPT: the standard task, a virtual task, and an embedded reality version of the task that combined haptics with the physical pegboard. This experiment was designed to answer the first research question of this thesis: *'Can the PHANTOM Omni® be used as a method of assessing fine-motor control skills?'.* We hypothesised that an embedded reality approach to the NHPT (ENHPT), would provide more consistent results than a purely hapto-virtual approach, which in turn, would potentially relate to higher test-retest reliability. Our results suggest that haptic tools for assessment are more reliable when compared with elements of realism, providing the user with a physical anchor whilst working in the virtual environment.

We found that the embedded reality approach to the NHPT produced less-variable task completion times than that of the virtual NHPT task (both including the use of the haptic controller) in a study that we conducted with 60 healthy participants. We also noted that insertion time (placing the virtual peg entirely into the virtual peg-hole) was quicker in the embedded setup than without the physical pegboard and attributed this to the board acting as a guide to place the pegs into the holes. Transfer time (the total time from picking the peg to placing the peg) was also quicker in the embedded reality task. We attributed these findings to the presence of the physical board as the only variable between the two setups, with the assumption that having a physical guide in the real world helps users to better relate the virtual dimensions with the physical workspace, thus providing a more reliable assessment measure when compared to a virtual environment with no physical grounding. The limitations of pure virtuality in providing reliable inter-subject results in peg-in-hole tasks have also more recently been documented by the work of Tobler-Ammann et al. (2016), who also found high variability in their datasets when running an experiment with 31 chronic stroke patients.

The main aim of this study was to go towards validating a novel approach to the Nine Hole Peg Test. This was achieved, and our ENHPT produced more reliable results than that of a purely virtual approach to the NHPT. Further improvements to the system can be made following our conclusions that should improve the reliability of the ENHPT even further.

Although our embedded setup showed positive signals of improvement over the virtual setup, there are still some limitations that we observed that warrant further investigation. As noted in chapter 3, participants were referring back and forth from the physical workspace to the virtual workspace to maintain knowledge of the pegs that they had already picked and placed. This context switching has a potential impact on the time it takes for a user to complete the task in the embedded setup (although this was still much quicker, roughly half the time taken than in the VNHPT scenario). Furthermore, participants were not given a chance to practice the tasks before their attempts were timed, this could also have contributed to inter-subject variability as each of the tasks differed further from the original NHPT protocol by removing physical elements of the task (NHPT $\rightarrow$ ENHPT $\rightarrow$ VNHPT).

Our study recruited the participation of 60 healthy participants with no upper limb impairment. It is yet to be established whether or not this is a suitable task for the stroke population given the multitude of disabilities that they can suffer from that could hinder their ability to perform this task well, such as vision impairments, spatial awareness, and memory deficits. These concerns have also been raised by previous studies such as the work of Emery et al. (2010) which notes that there can be limitations in users' abilities to link virtual scenes on screens to the physical dimensions of the haptic workspace. These limitations should also be addressed in future studies to include the participation of stroke survivors.

In order to address some of the limitations in the task setup described above, we propose that future work could follow an improved protocol. Participants should be given a specific order in which to place the pegs for each task coupled with audio cues to notify the user of when a peg is picked up and when a peg is placed. By enforcing a set order in which to place the pegs, the different embedded tasks between subjects can be compared on a peg by peg transfer basis, which should give more comparable results. The improved embedded setup could be completed with and without the screen to determine the extent of which looking between the screen and workspaces has on impacting the time taken to complete the task. A further addition to the environment could be to add weight in the form of a small downward force to signify the holding of a peg as per the work of Amirabdollahian et al. (2005). The experiment setup would then consist of the following tasks in random order (n optimum number of times to reach the stable time for a test, to be defined by a small pilot study at a later date):

- Standard NHPT n times
- Embedded NHPT no screen, no weight n times
- Embedded NHPT with a screen, no weight n times
- Embedded NHPT no screen, with weight n times
- Embedded NHPT with a screen, with weight n times

6.2 Collaborative Haptic Tasks and Movement Patterns

In chapter 4 we investigated one of the research questions laid out in the introduction to this PhD thesis: *'Can we identify key traits and movements of users of haptic environments to design better haptic rehabilitation environments?'*. The premise of this question was that by promoting different types of movements in a haptic environment, we could stimulate more varied hand and arm movements which employ a greater range of fine-motor skills.

Further to the requirements of the research question, we also wanted to investigate the use of collaboration in haptic environments to improve motivation in relation to stroke rehabilitation as advocated by studies preceding ours (Johnson et al., 2008; Lum et al., 2002; Schutzer & Graves, 2004). The system that we have designed to assess these requirements could be used in a home-based environment which could help to overcome the challenges of motivation and frequency of rehabilitation in the home. This setup could also incorporate concepts of the client-therapist interaction described by Amirabdollahian et al. (2014) which showed promising results with an average of 14 minutes of interactive game-based therapy per day.

We developed a system modelled on the sorting blocks game designed for children. This system allowed for remote collaboration in a shared haptic environment. We conducted two experiments with this setup: a three-day experiment at the London Science Museum with over 300 healthy participants, and a long-term study with four stroke survivors that used this system as part of their haptic exercise sessions. The data collected from these two experiments were analysed to determine the similarities and differences between the types of movements seen in both healthy participants and stroke survivors while performing collaborative haptic tasks. We were also interested in investigating how the choice of haptic shapes (flat-sided and curved-sided) could have an impact on the types of movements performed by participants in a rehabilitation context.

We found that forces were higher for manipulating flat-sided shapes, accuracies were higher when manipulating curved-sided shapes, and more work was required to move flat-sided shapes towards the goal. We observed that participants were more likely to move curved sided shapes (sphere, cylinder) directly towards the goal in a 'rolling' motion generally attributed to real balls. Flat sided shapes took participant pairs more effort to get the shapes to the goal due to competing forces on the objects.

The key objective of this study was to determine whether or not traits of movement could be identified using a collaborative haptic environment. Our results show that, through the use of haptic devices, specific patterns or types of movements can be identified in users when interacting with different shapes and when collaborating in pairs. The task described also lent itself well to a haptic collaborative task, and one that certainly has the potential for both remote and on-site exercise and training for stroke survivors, where we envisage therapist-led sessions using the task to promote movements to assist with different deficits that a user of the system may have.

The four case studies supporting this work provided an initial proof of concept for the utility of remote-haptics in home-based rehabilitation scenarios. The pilot results show promise for further investigation into movement-patterns in haptic environments and their application to assessment and rehabilitation of hand and arm function following a stroke. A more extensive study should be conducted based on these results with an increased sample size.

6.3 Home-based Rehabilitation

In chapters 3 and 4, we analysed haptic tasks to determine their efficacy as assessment tools and discussed how these tasks could be used to promote different movement techniques when working in collaborative pairs which could relate well to patient-clinician scenarios for assessing arm function. Chapter 5 explored the concept of a home-based rehabilitation with a 12-week feasibility study with four stroke survivors.

In order to investigate further the themes of home-based rehabilitation and assessment, we devised an experiment to be conducted at participants homes. The protocol consisted of an initial assessment session where the NHPT and BBT tasks were used to record baseline arm function for the experiment, followed by (four weeks later) 12 exercise sessions spread over the course of four weeks. In the first and last exercise sessions, the NHPT and BBT tasks were re-recorded, and then four weeks after the last exercise session, a final assessment session was conducted to measure arm function following four weeks without intervention.

As defined in the introduction of this PhD thesis, our final research question was: *'Is the PHANTOM Omni® a viable platform for producing home-based rehabilitation systems for hand function following a stroke?'*. We found many interesting results that certainly suggest that the PHANTOM Omni® is a viable platform for home-based rehabilitation. Notably, all four participants showed improvements in arm function measured with the NHPT at the end of the four weeks' of exercise sessions and this outcome was matched by the participants' perceived improvements in capability with their affected arms. Furthermore, we found that two of the four participants maintained these improvements after four weeks without intervention and we believe that the retention rate could be improved with an extended intervention period in the study.

Participants scored the usability of the system highly, all participants enjoyed the tasks and found the system easy to use, some of whom would also like to use it on a daily/regular basis. These results again point to the viability of this system for use as a home-based rehabilitation tool.

We were able to measure improvements in the tasks as well. We looked at the time taken to complete the tasks (ENHPT) and also measures of root mean square error as a metric to show improvements in accuracy and efficiency of task completion. Again, positive results were found here where we observed improvements for two of the participants in both the ENHPT and 'Clock Targets' tasks. We also saw improvements for all of the participants when measuring RMSE for the 'Haptic Guidance' task where participants had to follow the motion of a moving haptic ball without the use of the screen relating to improvements in response to stimulation for their impaired arm.

There were some limitations with our findings; in particular, the benefit of the exercise sessions did not show in the BBT scores. We attribute this to the fact that the range of motion required to perform tasks with the PHANTOM Omni® is far smaller than the range of motion required to perform the BBT task. Also, many of the tasks would have required a level of learned skill before a participant could provide reproducible scores, this learning factor was not taken into account in the analysis of any of the tasks as the sample size was too small to be able to establish what the learning factor may look like for each task. With this in mind, we could ask the question 'should the PHANTOM Omni® be used as a sole exercise and assessment device for the rehabilitation of arm function following a stroke?'. The answer is likely *no*, but it does show promise for the rehabilitation and assessment of fine motor arm movements within the dimensions of the haptic device itself. Future protocols, if established, could use this device as a complementary medium to other rehabilitation exercises and tools.

The system itself also has the potential for use as a remote assessment tool. In chapter 4 we presented the haptic collaboration game that we used in two experiments, the second experiment being as part of the exercise sessions with the four stroke survivors. From the data we collected, we were able to assess improvements in accuracy and observe different collaboration modes for the participant pairs. When analysing the results of the stroke group participants with collaborative exercise, we found that the interaction style with flat-sided shapes swayed toward a leader-follower style of cooperation as interaction partners repeated the task. We described this progression to a more efficient method of collaboration as acquisition learning where the participants had acquired the necessary level of skill to perform the task better.

The networking protocol we implemented for the collaborative was suitable for use over the internet. Remotely connecting the machines over the internet would allow one user to interact with another remote user physically via the medium of haptics - this has enormous implications for the potential as a remote therapy tool where a therapist could assess arm function remotely without the need to visit a patient's home.

When this study was conducted, 2011-2012, long-term experiments using haptic devices with stroke survivors in the home were extremely rare indeed. This study was conducted with four stroke survivors in their own homes and measured positive outcomes at differing levels for all four participants, thus allowing for us to explore the feasibility, utility and effectiveness of such interventions to drive future experimentation. The outcomes of the study met our objectives by producing a system that the four stroke survivors all benefited from, that is to say, that they all perceived some level of improvement whilst using it. This is an extremely important point; if users don't perceive the benefit of such a system, then they are highly unlikely to continue to use it in their own home.

6.4 Limitations

The main limiting factors of the work presented throughout this thesis are the lack of practice sessions for all of the haptic tasks. Haptic environments are still a relatively niche field of computing and are yet to make their way fully into the mainstream of computer games. This presents a problem: haptic technologies allow a method of immersion in virtual worlds far greater than through a screen on its own, yet people are very unfamiliar with the technology. Practice sessions for the tasks presented here are vital to establish a baseline of ability before commencing haptic assessment and therapy. Many of the results from the Science museum and the home-based experiment could be described by learning effects where the participants were still getting used to the system.

For the NHPT experiment, a lot of the variation in the task times for the embedded and virtual setup could potentially have been greatly reduced if the users were allowed some time to practice with the system beforehand. The practice would need to be for a substantial period, potentially over the course of multiple sessions to ensure that users were as familiar as possible with the system before commencing the studies. For virtual environments, the field of augmented reality commands a far greater interest than haptic technology in the mainstream, yet for research, haptic robot systems allow for highly precise measurement of movement which is extremely important when attempting to assess levels of motor skill and arm function. The drive for the first experiment comes from the potential of haptic devices to better measure and evaluate functional outcomes following rehabilitation.

6.5 Contributions to Knowledge

The main contribution to knowledge of this thesis is the embedded reality approach to the Nine Hole Peg Test. This is still a very novel technique that stands out from other peg-in-hole tests by providing a physical anchor to the real world while still allowing for a high level of measurement and feedback that comes from the use of robotic systems. This contribution couples well with our contribution to the practice of rehabilitation in the form of our home-based rehabilitation study. This system was received with very positive feedback and usability scores from stroke survivors themselves - the very people that need this to improve their arm function. As a desktop system for the rehabilitation of arm function in the home, this met our objectives of showing its feasibility. We believe we have shown a highly effective protocol for exercise and assessment with a haptic device in the home given the positive results and feedback from the study, and with further enhancements to the tasks this methodology could be delivered on a much larger scale for a reasonably low cost compared to standard costs of continued therapy following a stroke.

6.6 Conclusions

This PhD thesis has discussed a broad range of topics from assessment tools such as the NHPT and how to improve them - using an embedded approach to the NHPT, to home-based rehabilitation and providing an effective protocol and system to facilitate and measure improvements in arm function following a stroke.

From the experiments discussed, we have found that an embedded reality approach to the NHPT provides more reliable results than a purely virtual approach to the NHPT while still offering the benefits of haptic devices that allow us to measure position, velocity, and accuracy that can be used to gain a better understanding of arm function. We have also discovered that by providing different shapes to interact with in haptic environments, we can force users to perform different types of movements - this could be beneficial for creating tasks that are designed to improve a specific component of someone's fine-motor control and dexterity. Our home-based rehabilitation experiment showed that the PHANTOM Omni® was effective for exercise and assessment and that gains we saw throughout the trial were matched by users own perception of their capabilities with their impaired arm throughout the trial.

The results in this PhD thesis can be used to design further experiments with the PHANTOM Omni® as a tool for remote and on-site assessment of arm function following a stroke. We have outlined modifications to the experiments for future work in chapters 3, 4, and 5 so that readers can build on the ideas and themes presented here.

The data that we recorded for our tests was specific to our requirements of investigation; future work could benefit more if we were to record standard measures. There is a movement to try to standardise the data that is collected as part of stroke rehabilitation trials such as the VISTA program (Ali et al., 2013). If we collected some of this data via the haptic device, we would have a way of comparing our results with those of other trials which could help the design of future experiments. Standardised data could also assist with the adoption of haptic tools in clinical settings: the data from the experiment will be more accessible and relatable to clinicians and therapists.

Therapists and physicians should also be keen to see the results that we, and many others, have now found: haptic technology can be used to improve and assess arm function following a stroke. Small form-factor devices such as the PHANTOM Omni® are good candidates for use as complementary techniques in a rehabilitation programme, and can continue to be used even after the clinical intervention has finished.

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Appendix A

ENHPT Consent and Demographic Form

Embedded Nine Hole Peg Test for Haptic Assessment

Section 1: Information about haptic assessment and the LIREC project

LIREC is a collaboration of 10 European partners specialized in psychology, ethology, human-computer interaction, human-robot interaction, robotics and graphical characters.
The LIREC network aims to create a new generation of interactive, socially intelligent companions that is capable of long-term relationships with humans.
The research team focuses on both virtual companions and physical embodiments such as robots. They also examine how people react to a familiar companion when it migrates from a robot body into a virtual form, for example on a mobile PDA screen.

Haptic technologies allow the user to feel objects in a virtual environment. The purpose of the Nine Hole Peg Test is to gather data regarding the use of haptic devices in the context of rehabilitation of a neurological impairment. As part of the Lirec project, this information will be used to further develop systems that enhance communication between remote peers whereby the haptic device acts as a social mediator. During the experiment you will be using a haptic device named 'PHANTOM Omni'.

The research will involve some questionnaires and collection of video material required for the analysis of the experiments. All data collected on individual participants will be treated with full confidentiality. At no time throughout the whole course of the research project will your name or any other personal details that you provide be identifiable, (i.e. your name will not appear in any internal or external publications). All evaluation work will be based on the participant numbers allocated to each subject. This ID code will form the basis of our evaluations, not your real name.

Participation in this study is entirely voluntary. If at any point you do not wish to continue with the study, you may withdraw, this will not reflect badly on you. The questionnaires provided do not have any right or wrong answers, nor should they be viewed as tests. However, you can decide not to answer certain questions in the questionnaires provided if you do not wish to.

Section 2: Consent to take part in the trials

Name of Researcher: Michael Bowler (PLEASE INITIAL BOXES)

I CONFIRM THAT I HAVE READ AND FULLY UNDERSTOOD THE INFORMATION PROVIDED FOR THE ABOVE STUDY. I UNDERSTAND THAT MY PARTICIPATION IS VOLUNTARY AND THAT I AM FREE TO WITHDRAW AT ANY TIME, WITHOUT GIVING ANY REASON. I AGREE TO TAKE PART IN THE ABOVE STUDY. ☐

WE WOULD LIKE TO USE SOME OF THE VIDEO FOOTAGE FOR FUTURE CONFERENCES AND PUBLICATIONS. I CONSENT TO MY VIDEO FOOTAGE RECORDED DURING THE EXPERIMENTS TO BE USED FOR THIS PURPOSE. ☐

ID NUMBER ☐☐☐☐

Name of participant: ________________________________

Signature: ________________________________

Date: ________________________________

If you have any questions regarding the above study, please contact the experimenter, Michael Bowler at: m.bowler@herts.ac.uk

Thank you.

Section 3: About You

Before we get started with the trials, we would be grateful if you could complete the questions below:

1. Gender: Male ☐ Female ☐
2. Age: ☐☐
3. Occupation or course if you are a student: ……………………………………………………
4. Dominant Hand: left hand ☐ right hand ☐ either ☐
5. Do you consider yourself to have any form of visual impairment? Yes ☐ No ☐

   If so please state: ____________________

6. Do you consider yourself to have any form of disability? Yes ☐ No ☐

   If so please state: ____________________

7. Please state your level of familiarity with 3D Computer Games (Console/PC based games for example)

1	2	3	4	5
Very unfamiliar	Quite unfamiliar	Neutral	Quite familiar	Very familiar

   Please state approximately, on average how many hours a week you spend playing computer games:

   ____

8. Have you used haptic technologies in the past? Yes ☐ No ☐
9. If you answered 'Yes' to question 8, do you remember the type of device you used?

   If so please state: ____________________

10. If you answered 'Yes' to question 8, what was the purpose of the haptic interaction?
    1) Leisure ☐
    2) Rehabilitation ☐
    3) Work/Research ☐

Appendix B

ENHPT Questionnaire

Embedded Nine Hole Peg Test Questionnaire

ID Number: ☐☐☐☐

---

1) How helpful did you find the training, in the form of 'practice attempts', in learning how to use the device?
(Please tick one box)

☐ Very Helpful
☐ Quite Helpful
☐ Neutral
☐ Quite Unhelpful
☐ Very Unhelpful

If you answered 'Quite unhelpful' or 'Very unhelpful' could you explain why?

____

____

____

2) How difficult was the standard task (pegs and board) to complete?
(Please tick one box)

☐ Very Difficult
☐ Quite Difficult
☐ Neutral
☐ Quite Easy
☐ Very Easy

If you answered 'Quite difficult' or 'Very difficult' could you explain why?

____

____

____

3) How difficult was the embedded task (stylus and board) **with screen** to complete?
(Please tick one box)

☐ Very Difficult
☐ Quite Difficult
☐ Neutral
☐ Quite Easy
☐ Very Easy

If you answered 'Quite difficult' or 'Very difficult' could you explain why?

____

____

____

4) How difficult was the embedded task (stylus and board) **without screen** to complete?
(Please tick one box)

☐ Very Difficult
☐ Quite Difficult
☐ Neutral
☐ Quite Easy
☐ Very Easy

If you answered ‘Quite difficult’ or ‘Very difficult’ could you explain why?

____

____

____

5) How comfortable did you find the PHANTOM Omni’s stylus grip?
(Please tick one box)

☐ Very Comfortable
☐ Quite Comfortable
☐ Neutral
☐ Quite Uncomfortable
☐ Very Uncomfortable

If you answered ‘Quite uncomfortable’ or ‘Very uncomfortable’ could you explain why?

____

____

____

6) How accurate was the virtual representation of the peg board?
(Please tick one box)

☐ Very Accurate
☐ Quite Accurate
☐ Neutral
☐ Quite Inaccurate
☐ Very Inaccurate

If you answered ‘Quite inaccurate’ or ‘Very inaccurate’ could you explain why?

____

____

____

7) How helpful were the audio cues when using the stylus (with and without screen)? (Please tick one box)

☐ Very Helpful
☐ Quite Helpful
☐ Neutral
☐ Quite Unhelpful
☐ Very Unhelpful

If you answered 'Quite unhelpful' or 'Very unhelpful' could you explain why?

____

____

____

8) Which was your preferred method of completing the Nine Hole Peg Test task? (Please tick one box)

☐ Using the stylus device **with** the screen present
☐ Using the stylus device **without** the screen present
☐ Completing the task manually

Do you have any further comments?

____

____

____

9) Did you enjoy using the device? (Please circle your answer) Yes / No

10) How would you rate your performance in the tasks? (Please tick one box)

☐ Very Good
☐ Quite Good
☐ Average
☐ Quite Bad
☐ Very Bad
☐ Unsure

If you answered 'Quite bad' or 'Very bad' could you explain why?

____

____

____

11) Would you use the device again for similar tasks involving virtual environments? (Please circle your answer) Yes / No

Please write any further comments relating to the experiment here:

Finally I would like to say a big THANK YOU for your participation in this experiment! If you would be happy to participate in future experiments, please leave your email so that we can contact you in the future (your email address will **not** be forwarded on to any other 3rd party).

e-mail:

Appendix C
Home-based Study: Consent and Demographic Form

Haptic Tele-Rehabilitation System for Therapy of a Person with an Impaired Upper Limb

Information about haptic assessment and the LIREC project

LIREC is a collaboration of 10 European partners specialized in psychology, ethology, human-computer interaction, human-robot interaction, robotics and graphical characters.
The LIREC network aims to create a new generation of interactive, socially intelligent companions that is capable of long-term relationships with humans.
The research team focuses on both virtual companions and physical embodiments such as robots. They also examine how people react to a familiar companion when it migrates from a robot body into a virtual form, for example on a mobile PDA screen.

Haptic technologies allow the user to feel objects in a virtual environment. The purpose of this system is to assess, monitor, and hopefully improve, performance of an impaired upper limb. Throughout this trial we will use standard assessment techniques for measuring fine motor control of upper limbs: the Nine Hole Peg Test (NHPT) and the Box and Block Test (BBT), the information provided by these tests will allow us to monitor progress throughout the course of the trial. Further to this, we will also present haptic tasks/games for the subject to perform; these will provide the exercise component of the therapy trial.

As part of the Lirec project, all information collected will be sent to a central server, where the experimenter can monitor real-time performance data and intervene remotely if necessary. This is an enhanced communication technique between remote peers whereby the haptic device acts as a social mediator, strengthening the communication between both parties. During the experiment you will be using a haptic device named ‘PHANTOM Omni’.

The research will involve some questionnaires and collection of video material required for the analysis of the experiments. All data collected on individual participants will be treated with full confidentiality. At no time throughout the whole course of the research project will your name or any other personal details that you provide be identifiable, (i.e. your name will not appear in any internal or external publications). All evaluation work will be based on the participant numbers allocated to each subject. This ID code will form the basis of our evaluations, not your real name.

Participation in this study is entirely voluntary. If at any point you do not wish to continue with the study, you may withdraw, this will not reflect badly on you. The questionnaires provided do not have any right or wrong answers, nor should they be viewed as tests. However, you can decide not to answer certain questions in the questionnaires provided if you do not wish to.

ID NUMBER ☐☐☐☐

Section 2: Consent to take part in the trials

Name of Researcher: Michael Bowler (PLEASE INITIAL BOXES)

I CONFIRM THAT I HAVE READ AND FULLY UNDERSTOOD THE INFORMATION PROVIDED FOR THE ABOVE STUDY. I UNDERSTAND THAT MY PARTICIPATION IS VOLUNTARY AND THAT I AM FREE TO WITHDRAW AT ANY TIME, WITHOUT GIVING ANY REASON. I AGREE TO TAKE PART IN THE ABOVE STUDY. ☐

WE WOULD LIKE TO USE SOME OF THE VIDEO FOOTAGE FOR FUTURE CONFERENCES AND PUBLICATIONS. I CONSENT TO MY VIDEO FOOTAGE RECORDED DURING THE EXPERIMENTS TO BE USED FOR THIS PURPOSE. ☐

PLEASE STATE WHETHER YOU WOULD PREFER TO COMPLETE THE TRIALS IN YOUR HOME OR AT THE UNIVERSITY. ☐

Name of participant: ________________________________

Signature: ________________________________

Date: ________________________________

If you have any questions regarding the above study, please contact the experimenter, Michael Bowler at: m.bowler@herts.ac.uk

Thank you.

Demographic Questionnaire

Before we get started with the trials, we would be grateful if you could complete the questions below:

1. Gender: Male ☐ Female ☐
2. Age: ☐☐
3. Occupation or course if you are a student: ……………………………………………………
4. Dominant Hand: left hand ☐ right hand ☐ either ☐
5. Do you consider yourself to have any form of visual impairment? Yes ☐ No ☐

   If so please state: ____

6. How long has it been since your stroke? ……………………………………………………...
7. Do you have problems with mobility? Yes ☐ No ☐
8. Do you have upper limb impairment? Yes ☐ No ☐

   If so please state the affected limb (left or right): ____________________________

9. If you answered 'yes' to question 8, are you receiving therapy for the affected limb?
   Yes ☐ No ☐

   If so please describe the frequency and type of therapy you are currently receiving:

   ____

10. Are you receiving any other types of physical therapy?
    Yes ☐ No ☐

    If so please describe the frequency and type of therapy you are currently receiving:

    ____

11. Please state your level of familiarity with 3D Computer Games (Console/PC based games for example)

1	2	3	4	5
Very unfamiliar	Quite unfamiliar	Neutral	Quite familiar	Very familiar

Please state approximately, on average how many hours a week you spend playing computer games:

____

12. Have you used haptic technologies in the past? Yes ☐ No ☐

13. If you answered ‘Yes’ to question 12, do you remember the type of device you used?

If so please state: ____

14. If you answered ‘Yes’ to question 12, what was the purpose of the haptic interaction?
    1) Leisure ☐
    2) Rehabilitation ☐
    3) Work/Research ☐

Appendix D

Home-based Study: On-Screen Questions

List of On-Screen Questions for the Tele-Rehabilitation Experiment

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On-Screen Questions

The onscreen questions will be presented to the subject once they have completed an individual task/game (usually lasting no more than 5 minutes). They will be asked one or two questions, selected randomly from the list below. Each week during the trial they will have answered each question at least once.

Task-related

1) How helpful did you find this training session?
(Please tick one box)
- ☐ Very Helpful
- ☐ Quite Helpful
- ☐ Neutral
- ☐ Quite Unhelpful
- ☐ Very Unhelpful

2) How difficult was this task to complete?
(Please tick one box)
- ☐ Very Difficult
- ☐ Quite Difficult
- ☐ Neutral
- ☐ Quite Easy
- ☐ Very Easy

3) Did you experience any discomfort when performing this task?
(Please tick one box)
- ☐ Yes
- ☐ No

4) Did you enjoy this task?
(Please tick one box)
- ☐ Yes
- ☐ No

5) How realistic was the virtual environment?
(Please tick one box)
- ☐ Very Realistic
- ☐ Quite Realistic
- ☐ Neutral
- ☐ Quite Unrealistic
- ☐ Very Unrealistic

6) How helpful were the audio cues when performing the task?
(Please tick one box)
- ☐ Very Helpful

☐ Quite Helpful
☐ Neutral
☐ Quite Unhelpful
☐ Very Unhelpful

7) How would you rate your performance in the tasks?
(Please tick one box)
☐ Very Good
☐ Quite Good
☐ Average
☐ Quite Bad
☐ Very Bad
☐ Unsure

8) How realistic was the haptic (sense of touch) interaction in this task?
(Please tick one box)
☐ Very Realistic
☐ Quite Realistic
☐ Average
☐ Quite Unrealistic
☐ Very Unrealistic

9) Were you aware of the haptic (sense of touch) interactions while performing this task?
(Please tick one box)
☐ Yes
☐ No

Emotionally-related

10) How motivated do you feel today?
(Please tick one box)
☐ Very Motivated
☐ Quite Motivated
☐ Neutral
☐ Quite Unmotivated
☐ Very Unmotivated

11) How confident do you feel today?
(Please tick one box)
☐ Very Confident
☐ Quite Confident
☐ Neutral
☐ Not Very Confident
☐ Not At All Confident

12) How tired do you feel today?
(Please tick one box)
☐ Very Tired

☐ Quite Tired
☐ Neutral
☐ Not Very Tired
☐ Not At All Tired

Appendix E

Home-based Study: Final Questionnaire

Final Questionnaire

1) In the weeks of the experiment, I felt more capable with my arm.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

2) In the weeks of the experiment, I felt more discomfort with my arm.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

3) In the weeks of the experiment, I could move my arm more.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

4) In the weeks of the experiment, my arm felt stiff.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

5) In the weeks of the experiment, I could move my hand more.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

6) In the weeks of the experiment, my arm felt tired.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

7) In the week after the experiment, I felt more capable with my arm.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

8) In the week after the experiment, I felt more discomfort with my arm.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

9) In the week after the experiment, I could move my arm more.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

10) In the week after the experiment, my arm felt stiff.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

11) In the week after the experiment, I could move my hand more.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

12) In the week after the experiment, my arm felt tired.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

13) Since completing the experiment, I felt more capable with my arm.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

14) Since completing the experiment, I felt more discomfort with my arm.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

15) Since completing the experiment, I could move my arm more.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

16) Since completing the experiment, my arm felt stiff.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

17) Since completing the experiment, I could move my hand more.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

18) Since completing the experiment, my arm felt tired.
(Please tick one box)
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

19) I would like to have one of these systems in my own home.
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

20) I would like to use one of these systems on a daily basis.
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

21) I found the system fun and enjoyable.
- ☐ Strongly Agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

22) How would you rate your performance in the task today?
(Please tick one box)
- ☐ Very Good
- ☐ Good
- ☐ Average
- ☐ Poor
- ☐ Very Poor

23) How motivated do you feel today?
(Please tick one box)
- ☐ Very Motivated
- ☐ Quite Motivated
- ☐ Neutral
- ☐ Quite Unmotivated
- ☐ Very Unmotivated

24) How confident do you feel today?
(Please tick one box)
- ☐ Very Confident
- ☐ Quite Confident
- ☐ Neutral
- ☐ Not Very Confident
- ☐ Not At All Confident

25) How tired do you feel today?
(Please tick one box)
- ☐ Very Tired
- ☐ Quite Tired
- ☐ Neutral
- ☐ Not Very Tired
- ☐ Not At All Tired

26) Does your arm feel any different than normal today?

Appendix F

Home-based Study: Questionnaire Results

Session 2 Questionnaire

		George		Linda		Robert		Jennifer	
		Key	Value	Key	Value	Key	Value	Key	Value
Q1	How helpful was this training session?	Quite Helpful	2	Very Helpful	1	Very Helpful	1	Quite Helpful	2
Q2	How difficult was this task to complete?	Quite Easy	4	Quite Difficult	2	Quite Easy	4	Quite Easy	4
Q3	Did you experience any discomfort?	Yes	1	Yes	1	No	2	No	2
Q4	Did you enjoy this task?	Yes	1	Yes	1	Yes	1	Yes	1
Q5	How realistic was the virtual environment?	Quite Realistic	2	Very Realistic	1	Quite Realistic	2	Neutral	3
Q6	How would you rate your performance in the tasks?	Quite Good	2	Quite Bad	4	Average	3	Quite Good	2
Q7	How realistic was the haptic interaction in this task?	Quite Realistic	2	Quite Realistic	2	Very Realistic	1	Quite Realistic	2
Q8	Were you aware of haptic interactions while performing this task?	Yes	1	Yes	1	Yes	1	Yes	1
Q9	How motivated do you feel today?	Very Motivated	1	Very Motivated	1	Very Motivated	1	Very Motivated	1
Q10	How confident do you feel today?	Very Confident	1	Quite Confident	2	Quite Confident	2	Very Confident	1
Q11	How tired do you feel today?	Not at all Tired	5	Not at all Tired	5	Quite Tired	2	Quite Tired	2

Session 3 Questionnaire

		George		Linda		Robert		Jennifer	
		Key	Value	Key	Value	Key	Value	Key	Value
Q1	How helpful was this training session?	Very Helpful	1	Very Helpful	1	Very Helpful	1	Quite Helpful	2
Q2a	How difficult was this task to complete? (teacups)	Quite Easy	4	Quite Difficult	2	Quite Difficult	2	Quite Difficult	2
Q2b	How difficult was this task to complete? (clock)	Very Easier	5	Very Easy	5	Quite Difficult	2	Neutral	3
Q3	Did you experience any discomfort?	Yes	1	No	2	No	2	No	2
Q4	Did you enjoy this task?	Yes	1	Yes	1	Yes	1	Yes	1
Q5	How helpful were the audio cues?	Very Helpful	1	Very Helpful	1	Quite Helpful	2	Quite Helpful	2
Q6a	How much easier or harder was with sound compared to without? (teacups)	No Different	3	A Bit Easier	2	No Different	3	A Bit Easier	2
Q6b	How much easier or harder was with sound compared to without? (clock)	A Bit Easier	2	A Bit Easier	2	No Different	3	A Bit Easier	2
Q7	Do you prefer the tasks with sound or without sound?	With Sound	1	N/A	3	N/A	3	N/A	3
Q8	Were there any sounds that you didn't like?	No	2	No	2	No	2	No	2
Q9a	How would you rate your performance in the tasks? (teacups)	Quite Bad	4	Quite Bad	4	Average	3	Average	3
Q9b	How would you rate your performance in the tasks? (clock)	Very Good	1	Quite Good	2	Average	3	Average	3
Q10	How clear were the objects on the screen?	Very Clear	1	Very Clear	1	Very Clear	1	Very Clear	1
Q11	Did you like the colours used in the tasks?	Yes	1	Yes	1	Yes	1	N/A	3
Q12	How motivated do you feel today?	Quite Motivated	2	Very Motivated	1	Neutral	3	Very Motivated	1
Q13	How confident do you feel today?	Quite Confident	2	Very Confident	1	Neutral	3	Very Confident	1
Q14	How tired do you feel today?	Not At All Tired	5	Not At All Tired	5	Quite Tired	2	Quite Tired	2

Session 4 Questionnaire

		George		Linda		Robert		Jennifer	
		Key	Value	Key	Value	Key	Value	Key	Value
Q1	How helpful was this training session?	Quite Helpful	2	Very Helpful	1	Quite Helpful	2	Quite Helpful	2
Q2	How difficult was this task to complete? (teacups)	Very Easy	5	Very Easy	5	Quite Difficult	2	Quite Difficult	2
Q3	Did you experience any discomfort?	Yes	1	No	2	Yes	1	No	2
Q4	Did you enjoy this task?	Yes	1	Yes	1	No	2	Yes	1

Q5a	Which task was easiest	Haptic no Board	3	Haptic no Board	3	Standard	1	Haptic no board	3
Q5b	Which task did you prefer?	Haptic no Board	3	All	4	Standard	1	Haptic with boa	2
Q6	How helpful were the audio cues?	Quite Helpful	2	Very Helpful	1	Neutral	3	Very Helpful	1
Q7	How would you rate your performance in the tasks?	Quite Good	2	Average	3	Average	3	Average	3
Q8	How clear were the objects on the screen?	Very Clear	1	Very Clear	1	Quite Clear	2	Very Clear	1
Q9	Did you like the colours used in the tasks?	Yes	1	Yes	1	Yes	1	N/A	3
Q10	How motivated do you feel today?	Very Motivated	1	Very Motivated	1	Quite Motivated	2	Very Motivated	1
Q11	How confident do you feel today?	Quite Confident	2	Quite Confident	2	Neutral	3	Very Confident	1
Q12	How tired do you feel today?	Not At All Tired	5	Not At All Tired	5	Quite Tired	2	Quite Tired	2
Q13	How does your arm feel today?								

Session 5 Questionnaire

		George		Linda		Robert		Jennifer	
		Key	Value	Key	Value	Key	Value	Key	Value
Q1	How helpful was this training session?	Very Helpful	1	Very Helpful	1	Very Helpful	1	Neutral	3
Q2	How difficult was this task to complete?	Very Easy	5	Neutral	3	Very Easy	5	Quite Difficult	2
Q3	Did you experience any discomfort?	Yes	1	No	2	No	2	No	2
Q4	Did you enjoy this task?	Yes	1	Yes	1	Yes	1	N/A	3
Q5	How strong was the haptic guidance?	Weak	4	Strong	2	Very Strong	1	Strong	2
Q6	How clear were the objects on the screen?	Very Clear	1	Very Clear	1	Average	3	Very Clear	1
Q7	Do you think that there are too many tasks?								
Q8	How motivated do you feel today?	Quite Motivated	2	Very Motivated	1	Very Motivated	1	Very Motivated	1
Q9	How confident do you feel today?	Very Confident	1	Quite Confident	2	Very Confident	1	Very Confident	1
Q10	How tired do you feel today?	Not At All Tired	5	Not At All Tired	5	Not At All Tired	5	Not Very Tired	4
Q11	How does your arm feel today?								

Session 6 Questionnaire

		George		Linda		Robert		Jennifer	
		Key	Value	Key	Value	Key	Value	Key	Value
Q1	How helpful did you find this weeks sessions?	Quite Helpful	2	Very Helpful	1	Very Helpful	1	Quite Helpful	2
Q2	How difficult were the tasks to complete?	Very Easy	5	Quite Easy	2	Quite Easy	4	Neutral	3
Q3	Did you experience any discomfort?	Yes	1	No	2	No	2	No	2
Q4	Did you enjoy these tasks?	Yes	1	Yes	1	Yes	1	Yes	1
Q5	How motivated do you feel today?	Quite Motivated	2	Quite Motivated	2	Quite Motivated	2	Very Motivated	1
Q6	How confident do you feel today?	Very Confident	1	Quite Confident	2	Very Confident	1	Very Confident	1
Q7	How tired do you feel today?	Not At All Tired	5	Not At All Tired	5	Not At All Tired	5	Quite Tired	2
Q8	How does your arm feel today?								

Session 7 Questionnaire

		George		Linda		Robert		Jennifer	
		Key	Value	Key	Value	Key	Value	Key	Value
Q1	How difficult were the tasks to complete?	Very Easy	1	Very Easy	1	Neutral	3	Quite Difficult	2
Q2	Did you experience any discomfort?	Yes	1	No	2	No	2	No	2

Q3	Did you enjoy these tasks?	Yes	1	Yes	1	Yes	1	Yes	1
Q4	How motivated do you feel today?	Very Motivated	1	Very Motivated	1	Quite Motivated	2	Quite Motivated	2
Q5	How confident do you feel today?	Very Confident	1	Very Confident	1	Quite Confident	2	Quite Confident	2
Q6	How tired do you feel today?	Not At All Tired	5	Not At All Tired	5	Not At All Tired	5	Quite Tired	2

Session 8 Questionnaire

		George		Linda		Robert		Jennifer	
		Key	Value	Key	Value	Key	Value	Key	Value
Q1	How difficult were the tasks to complete?	Very Easy	5	Neutral	3	Quite Difficult	2	Quite Difficult	2
Q2	Did you experience any discomfort?	Yes	1	No	2	No	2	No	2
Q3	Did you enjoy these tasks?	Yes	1	Yes	1	Yes	1	N/A	3
Q4	How would you rate your performance today?	Very Good	1	Average	3	Good	2	Average	3
Q5	How motivated do you feel today?	Very Motivated	1	Very Motivated	1	Quite Motivated	2	Quite Motivated	2
Q6	How confident do you feel today?	Very Confident	1	Very Confident	1	Quite Confident	2	Quite Confident	2
Q7	How tired do you feel today?	Not At All Tired	5	Not At All Tired	5	Not At All Tired	5	Neutral	3

Session 9 Questionnaire

		George		Linda		Robert		Jennifer	
		Key	Value	Key	Value	Key	Value	Key	Value
Q1	How difficult were the tasks to complete?	Very Easy	1	Quite Difficult	4	Neutral	3	Quite Difficult	2
Q2	Did you experience any discomfort?	Yes	1	No	2	Yes	1	No	2
Q3	Did you enjoy these tasks?	Yes	1	Yes	1	No	2	Yes	1
Q4	How would you rate your performance in the tasks today?	Good	2	Average	3	Average	3	Average	3
Q5	How strong was the haptic guidance?	Very Strong	1	Quite Strong	2	Weak	4	Very Strong	1
Q6	How motivated do you feel today?	Very Motivated	1	Very Motivated	1	Neutral	3	Quite Motivated	2
Q7	How tired do you feel today?	Not At All Tired	5	Not At All Tired	5	Not Very Tired	4	Quite Tired	2

Session 10 Questionnaire

		George		Linda		Robert		Jennifer	
		Key	Value	Key	Value	Key	Value	Key	Value
Q1	How difficult were the tasks to complete?	Quite Easy	2	Quite Easy	2	Quite Easy	2	Neutral	3
Q2	Did you experience any discomfort?	Yes	1	No	2	No	2	No	2
Q3	Did you enjoy these tasks?	Yes	1	Yes	1	Yes	1	Yes	1
Q4	Was the solo task easier with assistance?	No	2	No	2	No	2	No	2
Q5	How would you rate your performance in the tasks today?	Poor	4	Very Good	1	Good	2	Average	3
Q6	How motivated do you feel today?	Very Motivated	1	Quite Motivated	2	Quite Motivated	2	Quite Motivated	2
Q7	How confident do you feel today?	Quite Confident	2	Very Confident	1	Quite Confident	2	Quite Confident	2
Q8	How tired do you feel today?	Not At All Tired	5	Not At All Tired	5	Quite Tired	2	Neutral	3
Q9	How does your arm feel today?	A little stiffer than norm		No different to normal,		No		No	

Session 11 Questionnaire

		George		Linda		Robert		Jennifer	
		Key	Value	Key	Value	Key	Value	Key	Value

Q1a	How difficult were the tasks to complete?	Very Easy	5	Very Easy	5	Quite Easy	4	Quite Easy	4
Q1b	How difficult were the tasks to complete? (collab)	Very Easy	5	Very Easy	5	Quite Difficult	2	Quite Difficult	2
Q2	Did you experience any discomfort?	No	2	No	2	No	2	No	2
Q3a	Did you enjoy these tasks?	Yes	1	Yes	1	Yes	1	Yes	1
Q3b	Did you enjoy these tasks? (collab)	Yes	1	Yes	1	Yes	1	N/A	3
Q4	How would you rate your performance in the tasks today?	Very Good	1	Average	3	Poor	4	Good	2
Q5	How strong was the haptic guidance?	Very Strong	1	Strong	2	Weak	4	Average	3
Q6	How motivated do you feel today?	Very Motivated	1	Very Motivated	1	Not Very Motiva	4	Quite Motivated	2
Q7	How tired do you feel today?	Not At All Tired	5	Not At All Tired	5	Quite Tired	2	Quite Tired	2

Final Questionnaire

		George		Linda		Robert		Jennifer	
		Key	Value	Key	Value	Key	Value	Key	Value
Q1	In the weeks of the experiment, I felt more capable with my arm	Strongly Agree	5	Strongly Agree	5	Agree	4	Agree	4
Q2	In the weeks of the experiment, I felt more discomfort with my arm	Strongly Disagree	1	Strongly Disagre	1	Agree	4	Disagree	2
Q3	In the weeks of the experiment, I could move my arm more	Strongly Agree	5	Strongly Agree	5	Agree	4	Neutral	3
Q4	In the weeks of the experiment, my arm felt stiff	Strongly Disagree	1	Strongly Disagre	1	Neutral	3	Strongly Disagre	1
Q5	In the weeks of the experiment, I could move my hand more	Strongly Agree	5	Disagree	2	Agree	4	Agree	4
Q6	In the weeks of the experiment, my arm felt tired	Strongly Disagree	1	Strongly Disagre	1	Strongly Agree	5	Agree	4
Q7	In the week after the experiment, I felt more capable with my arm	Agree	4	Strongly Agree	5	Strongly Agree	5	Agree	4
Q8	In the week after the experiment, I felt more discomfort with my arm	Strongly Disagree	1	Strongly Disagre	1	Agree	4	Disagree	2
Q9	In the week after the experiment, I could move my arm more	Strongly Agree	5	Agree	4	Agree	4	Neutral	3
Q10	In the week after the experiment, my arm felt stiff	Strongly Disagree	1	Strongly Disagre	1	Agree	4	Neutral	3
Q11	In the week after the experiment, I could move my hand more	Agree	4	Strongly Disagre	1	Strongly Agree	5	Agree	4
Q12	In the week after the experiment, my arm felt tired	Strongly Disagree	1	Strongly Disagre	1	Strongly Agree	5	Agree	4
Q13	Since completing the experiment, I felt more capable with my arm	Disagree	2	Strongly Agree	5	Strongly Agree	5	Neutral	3
Q14	Since completing the experiment, I felt more discomfort with my arm	Agree	4	Strongly Disagre	1	Strongly Agree	5	Disagree	2
Q15	Since completing the experiment, I could move my arm more	Disagree	2	Strongly Agree	5	Strongly Agree	5	Neutral	3
Q16	Since completing the experiment, my arm felt stiff	Agree	4	Strongly Disagre	1	Strongly Agree	5	Disagree	2
Q17	Since completing the experiment, I could move my hand more	Disagree	2	Strongly Disagre	1	Strongly Agree	5	Agree	4
Q18	Since completing the experiment, my arm felt tired	Agree	4	Strongly Disagre	1	Strongly Agree	5	Disagree	2
Q19	I would like to have one of these systems in my own home	Agree	4	Neutral	3	Disagree	2	Disagree	2
Q20	I would like to use one of these systems on a daily basis	Agree	4	Disagree	2	Strongly Agree	5	Disagree	2
Q21	I found the system fun and enjoyable	Agree	4	Strongly Agree	5	Strongly Agree	5	Agree	4
Q22	How would you rate your performance in the task today?	Poor	4	Average	3	Good	2	Average	3
Q23	How motivated do you feel today?	Very Motivated	1	Very Motivated	1	Quite Motivated	2	Quite Motivated	2
Q24	How confident do you feel today?	Quite Confident	2	Quite Confident	2	Quite Confident	2	Quite Confident	2
Q25	How tired do you feel today?	Not At All Tired	5	Not At All Tired	5	Not Very Tired	4	Quite Tired	2
Q26	Does your arm feel any different than normal today?	Very weak		Not so much		No!		No	