Development and Evaluation of a Virtual Reality Therapy System for Children with Hemiplegic Cerebral Palsy

by

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Abstract

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Children with hemiplegic cerebral palsy, or hemiplegia, can improve their motor skills through repetitive practice. A need exists for engaging home activities that can encourage such exercise. Virtual reality (VR) therapy involves immersive and interactive computer-mediated experiences designed to elicit specific neuromotor movements. This thesis details the development and testing of a low-cost, home-based VR therapy system for children with hemiplegia. One device, adapted from the PlayStation 2 with EyeToy (PS2-E), was evaluated with five primary school children with hemiplegia. The study found that the PS2-E elicited targeted neuromotor movements of the hemiplegic upper extremity (UE) at high rates (13.2 $\pm$ 4.0 movements/minute of play) over an extended period of game playing (18.6 $\pm$ 2.6 minutes). Surveys showed that participants also enjoyed using the device and would likely accept it as part of a home-based therapy program. Meanwhile, an adaptive hands-on interface in which the child performs fine motor skills while playing computer games was also developed and fabricated. The interface includes software that processes user inputs and adjusts the level of difficulty to maximize rehabilitation outcomes. Overall, these devices may be useful for the improvement of specific UE function of children with hemiplegic cerebral palsy.

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Symbol	Description
CAD	Computer-aided design
CAVE	Cave Automatic Virtual Environment
CIMT	Constraint-induced movement therapy
CP	Cerebral palsy
DSR	Data-Set-Ready
DTR	Data-Terminal-Ready
HMD	Head-mounted device
IC	Integrated circuit
PCB	Printed Circuit Board
PS2-E	PlayStation 2 with EyeToy
RF	Radiofrequency
RS-232	Recommended Standard 232 (serial port)
UE	Upper extremity
VR	Virtual reality

Preface

This thesis documents the design and development of a virtual reality (VR) therapy system for children with hemiplegic cerebral palsy. It provides complete details on the materials and methods, results, and conclusions in the research process. Notably, several sections of this thesis are self-contained documents, representing submitted, peer-reviewed abstracts or papers that contribute to the overall objective of this project. As a result, these sections provide a statement of the problem and rationale. The start of each chapter alerts the reader to the reprinted sections that it contains, as well as novel information.

Chapter 1

Introduction

This section provides context about hemiplegic cerebral palsy, identifies the gap or problem that motivates the work of this thesis, and introduces the virtual reality (VR) therapy system developed in this project. Finally, it outlines of the structure of the remainder of the document.

1.1 Context: Hemiplegic Cerebral Palsy

Cerebral palsy (CP) describes a group of disorders of the development of movement and posture, causing activity limitations, that are attributed to non-progressive disturbances that have occurred in the developing fetal or infant brain.[1,2] CP is common, with a prevalence in developed countries of 2-2.5 in 1000 children.[3] Children with hemiplegic cerebral palsy, or hemiplegia, have a brain injury or anomaly that often involves the unilateral motor cortex. A typical mechanism of injury is a unilateral middle cerebral artery infarction that injures the motor cortex and creates a sensorimotor impairment of the opposite upper extremity (UE), which consists of the hand and arm. The impairment consists of muscle hypertonia, weakness, impaired selective motor control, and decreased sensation and neglect. The hypertonia pattern involves the flexor muscles predominantly (shoulder adduction, elbow flexion, forearm pronation, wrist flexion, finger flexion and thumb opposition, flexion and adduction). The muscle weakness involves distal muscles more so than proximal, and extensor muscles more than flexor.

These effects lead to children holding their hemiplegic involved UE in a "hemiplegic posture" of shoulder adduction, elbow flexion, forearm pronation, wrist and finger flexion, and thumb opposed in the palm.[4] Children with hemiplegia also have difficulty with shoulder flexion/abduction, elbow extension, forearm supination, wrist and finger extension and thumb extension. They generally favour the use of their non-involved UE in everyday activities.[5] Hemiplegia can vary in severity; one framework for classifying the extent of impairment, the House classification system, uses a nine-point scale ranging from non-use to spontaneous use of the involved UE.[6] Overall, this impairment may limit the ability of children with hemiplegia to carry out activities of daily living, which may have a negative impact on their quality of life.

Clinical Interventions

Currently, children with upper extremity difficulties due to hemiplegia are treated by a multidisciplinary clinical team that may include developmental paediatricians, physiotherapists (PTs), and occupational therapists (OTs). For example, at Toronto's Bloorview Kids Rehab, a children's rehabilitation hospital, some clients with hemiplegia may receive botulinum toxin (Botox) injections into certain muscles to reduce hypertonia, thereby making it possible to move those muscles. "Standard" treatment may include physiotherapy, which focuses on gross motor skills, and occupational therapy, which emphasize the development of fine motor skills and the integration of those skills into daily activities. Central to these treatment approaches is the substantial evidence that suggest that, with repetitive practice, children with CP can make significant improvements to targeted neuromotor movements.[7]

Because time with therapists is limited, exercising the hemiplegic UE outside of therapy sessions is important. Over the past three decades, a family-centred approach to treatment of children with CP, in which clinicians collaborate closely with parents and other family members, has become the norm.[8] To augment therapy sessions, therapists often recommend a set of activities for families to practise neuromotor movements with their child. Some studies have found that home activities produce gains in motor function,[9,10] although others have not found additional benefits.[11] As a result of limited time with therapists and the desire for families to be involved in the care and development of their child, these home-based exercise activities with family members have become an important part of therapy programs.[12]

In constraint-induced movement therapy (CIMT), the child's non-involved UE is held in a sling, cast, or mitt and the hemiplegic UE is used in activities and exercises in intensive, therapist-supervised sessions. The child may also wear the constraint for several hours a day, thereby forcing the use of his or her hemiplegic UE in everyday activities. A number of randomized controlled trials have validated the effectiveness of CIMT in paediatric rehabilitation.[13,14] Furthermore, one recent study involving six hours of CIMT for ten consecutive days found significant improvements in 4-to-13-year-olds that were not age-dependent, which may suggest that younger and older children alike can benefit from intensive practice.[15]

Another recent approach is virtual reality therapy. Virtual reality (VR) is defined as an immersive and interactive computer experience that enables a user to perform movements on a simulated system and shows the effects in real time. Virtual reality therapy employs VR for rehabilitation purposes, eliciting movement and practice of specific neuromotor impairments. For example, one system, called the Interactive Rehabilitation to Exercise System (IREX) (GestureTek Inc., Sunnyvale, CA), is used in clinical settings. A video camera captures the patients' movements, and artificial intelligence and video control technology allow them to interact with virtual objects and virtual environments that they can see on a television screen. With this particular system, pilot studies have suggested that virtual reality play-based activities for children with cerebral palsy are enjoyable and may increase their seated postural control[16] and sense of self-efficacy.[17] One research group has found neurological changes in adult patients recovering from stroke as a result of VR therapy – a small control study with ten recovering patients used functional magnetic resonance imaging (fMRI) to detect significant cortical reorganization after 20 one-hour sessions using the IREX system.[18] Meanwhile, other forms of VR therapy use special interfaces such as gloves or joysticks equipped with sensors that target other types of movements. Fundamentally, these interactive and immersive computer-mediated experiences aim to promote targeted movements in an environment that engages the child.

1.2 Motivation: The Need for Home-Based Therapy Activities

The initial motivation for this project stemmed strongly from an issue identified by clinicians: the need to encourage children with hemiplegia to practice movements with their hemiplegic UE outside of therapy sessions. Given that most children with hemiplegia have a strong non-involved UE, they generally underutilize their hemiplegic side.[19] This can have far-reaching effects: the representation of the hemiplegic limb in the motor cortex may diminish, leading to even further difficulties in trying to develop motor skills.[20] Not surprisingly, therefore, the time required for parents and caregivers to administer prescribed therapeutic activities with their full attention is an issue, given the other pressures on their time associated with raising a child with a disability, often alongside able-bodied siblings, and other responsibilities. This leads to concerns about adherence to, and the effectiveness of, currently prescribed activities.[9]

Other existing solutions to encouraging such practice also have concerns. By constraining the non-involved UE, CIMT works because it forces the child to practice using his or her hemiplegic arm and hand in daily activities. However, despite these successes, this approach also raises concerns: while wearing the constraint, the child may have a higher risk of falling or lose independence because he or she may not be able to perform important activities with the hemiplegic UE.[21] These issues limit the suitability and acceptance of CIMT as a means of encouraging children to use their hemiplegic UE outside of therapy sessions.

Finally, VR therapy has shown promising results in institutional settings, but existing technologies have not been deployed in home settings due to their high cost and the need for specialized equipment. In addition, it is not entirely clear how existing systems would successfully elicit the use of the hemiplegic UE of children who heavily favour their non-involved side in everyday activities, particularly in unsupervised settings. Overall, while there appears to be potential for a VR therapy system as a home activity, no existing technology appears to meet all of the requirements of this particular need.

1.3 Proposed Design Goals and Specifications

Based on the above discussion, a need exists for a device, system, or method that can encourage children with hemiplegia to practice targeted neuromotor movements with their hemiplegic UE. These movements include shoulder flexion and abduction, elbow extension and flexion, wrist extension, forearm supination, finger flexion, and thumb extension and abduction. In addition to this main requirement, the solution should be enjoyable to use by the child and acceptable to caregivers, reasonably affordable, flexible enough to accommodate a wide range of abilities, and be usable in a home setting without professional assistance.

Based on these constraints, this thesis describes the design and implementation of a home-based VR therapy system for training UE function of children with hemiplegic cerebral palsy. Guided by fun, goal-oriented game scenarios presented by such a device, children may willingly spend more time practising neuromotor movements that they find difficult. If home-based therapy activities are engaging and immersive, then children may be motivated to gain sufficient practice. In addition, for clinicians, computer-based technologies may offer data-logging capabilities that may be useful to monitor compliance, track usage, and possibly provide relevant quantitative data that may help to inform clinical decision-making.[22] Problems that we sought to address include the high cost of existing systems, the need for specialized equipment usable only in an institutional setting, and the need to encourage the child to use his or her involved UE in the therapy activities.

Playstation 2 with EyeToy (PS2-E)

One off-the-shelf video game system meets many of the aforementioned requirements for proximal movements of the hemiplegic UE. The Sony PlayStation 2 features an accessory called the EyeToy, a small video camera that connects to the gaming system. With this system, players can see themselves on the television screen in a virtual environment in which they move their arms and hands to control fun, goal-oriented, and child-appropriate games. At less than $250.00, the style of play and the level of enjoyment offered by the PlayStation 2 with EyeToy (PS2-E) have been found to be the same as the IREX; in fact, one study discovered that patients recovering from stroke felt that some of the PS2-E games were actually more fun and engaging than those of the IREX system.[23] As a commercial product mass-marketed to the general public, the PS2-E has an intuitive and easy-to-use interface that is specifically designed to be easy for the lay public to set up and use. The system also offers fun, goal-oriented games and activities that can be enjoyed by family members of all ages and abilities. With some adaptations, one might hypothesize that the PS2-E would be useful as a VR therapy system for children with hemiplegia.

Adaptive Hands-On Interface

Along the same lines of adapting commercially available technologies for therapy purposes, interactive computer games are widely available. Instead of using a conventional keyboard, mouse, or joystick, an input device that requires certain targeted neuromotor movements might be a fun and engaging way to encourage the child to perform those exercises. Such a device could be usable with any computer software if it could generate keystrokes as opposed to being specific to one particular game. Moreover, as a system designed from scratch, it might be possible to make the system intelligently adaptive; in other words, it could interpret the input signals that the child generates and adjust the level of difficulty of the system. In similar systems that promote fine motor movements, the idea of being adaptive has been proposed but not implemented.[24] On the whole, these two systems could meet the need for home-based therapy activities with children with hemiplegia.

1.4 Thesis Outline

The remaining chapters of this thesis outline the efforts to design, construct prototypes, and evaluate the above VR therapy system concepts. In chapter 2, a review of the current literature on VR therapy provides some indication of how this project fits into current trends in this field. Chapter 3 discusses the implementation of the PS2-E therapy system, which promotes movements of the proximal UE, and the results of a usability study in which children with hemiplegia evaluated the system. Next, chapter 4 discusses the design and development of an adaptive hands-on interface as a VR therapy system that promotes fine motor skill. Finally, chapter 5 summarizes the main findings, limitations, areas of further work, and conclusions of this thesis.

Chapter 2

Review: Virtual Reality Therapy for Physical Rehabilitation

This section presents a literature survey of existing VR therapy technologies for physical rehabilitation. To broaden the search without sacrificing relevant to this thesis, this survey focuses on VR therapy systems that train UE function of patients with cerebral palsy or recovering from stroke. The content of section 2.1 has been adapted, with permission, from a paper submitted by the author to the course "ESC300: Engineering Communications."

2.1. Overview and Categories of Virtual Reality Therapy Technologies

Adapted, with permission, from Li, W., "Virtual Reality Therapy for Physical Rehabilitation," submitted to ESC300 (Engineering Communications), Division of Engineering Science, University of Toronto, March 2007.

2.1.1. Abstract

This article surveys the current state of research in the emerging field of virtual reality (VR) therapy for physical rehabilitation. It examines the theory that underlies VR therapy's ability to promote rehabilitation, the different types of VR therapy technologies that researchers are currently developing, and the evidence of clinical effectiveness of this form of therapy. In general, early studies with small numbers of patients have found that VR therapy technologies, particularly so-called augmented virtuality and mixed reality systems, successfully promote rehabilitation. Further studies, though, are needed to confirm the benefits of VR therapy for patients with physical impairments. Moreover, to realize the potential of VR therapy, neuroscientists, engineers, and clinicians must continue to collaborate to determine how to maximize the benefit of VR therapy, what new technological developments are necessary, and which

VR therapy technologies are most practical and beneficial to integrate into standard therapy for this patient population.

2.1.2. Introduction

Injuries to the brain's motor cortex can adversely affect an individual's movement and locomotion. Such injuries include stroke, which describes a blood clot that forms or deposits in this vital organ, depriving neurons of oxygen and potentially causing brain damage.[25] Cerebral palsy, meanwhile, describes a group of disorders of the development of movement and posture, causing activity limitations, that are attributed to non-progressive disturbances that have occurred in the developing fetal or infant brain.[1] Specifically, the motor cortex plans and coordinates the body's motor tasks, meaning that any damage to this region of the brain can cause physical impairments; thus, for example, patients with either stroke or cerebral palsy might find reaching or grasping activities difficult. The costs of these conditions to society are substantial – stroke afflicts more than 40,000 Canadians every year,[25] while cerebral palsy has a prevalence of approximately 2.5 per 1,000 live births.[3] Ultimately, these impairments can limit the activities in which patients may participate, affect their independence, and reduce their quality of life.

Virtual reality (VR) therapy is one possible clinical intervention for patients living with the effects of stroke or cerebral palsy. In VR therapy, a computer generates a virtual reality environment in which the patients must perform goal-oriented movements that they find difficult.[26] In essence, a VR therapy experience is similar to an activity in a video game; the key difference is that the main goal of the VR therapy system is to elicit certain physical movements. This treatment can be effective because the brain is a resilient, remarkable organ that can actually make new neural connections in response to external stimuli and activity to compensate for damage.[27] Therefore, a VR therapy system must include software that creates and controls the virtual reality environment, an input device that targets the appropriate physical activity, and audiovisual equipment that displays the virtual reality environment provides feedback to the patient.[16] By using such a system, patients may be able to improve their motor skills and reduce their physical impairments.

This review article surveys the current state of research into VR therapy technologies. First, it explores how VR therapy relates to the theoretical foundations of physical rehabilitation. Second, it discusses three different categories of technologies, examining whether they are clinically effective, merit further study, or face technological obstacles. In the last section, the paper assesses VR therapy from a broader, structural standpoint to examine the likely directions and needed research in the field as a whole. Overall, this approach aims to provide an in-depth review of specific technical issues in VR therapy in addition to an overview of this emerging field.

2.1.3. Scientific Rationale for Using VR Therapy Technologies

Physical rehabilitation therapy must provide patients with three elements: feedback about performance, repetition of exercises, and motivation to perform the targeted motor activities.[30] These requirements are rooted in theories and evidence of how people learn to move. First, people typically learn motor skills by trial and error: the successful achievement of a motor task acts as powerful positive reinforcement for remembering how to perform it. By carefully selecting appropriate therapy activities, patients can experience incremental levels of success. Second, repetition is essential – by repeating a certain physical movement, studies have found that the brain recruits previously silent motor neurons to participate in motor control activities.[28] Lastly, studies in rats have shown that movements that are goal-oriented are significantly more effective at promoting larger fields of dendrites (the branching protrusions of neurons that accept signals from neighbouring cells) than merely increasing the repetition of those movements. In other words, being motivated and focused on a particular motor task seem to cause more profound neurophysiological changes in the brain's motor cortex.[29] Evidently, by providing feedback, repetition, and motivation, therapy programs can reverse or mitigate the effects of brain injury or abnormal brain development.

VR therapy is a potentially useful intervention because it delivers on all three elements of successful physical rehabilitation therapy. To begin with, feedback is extensive – patients may see themselves performing the movements, receive positive audiovisual feedback when they perform a motor task successfully, or track progress with the VR therapy software. Next, repetition is linked closely to motivation – patients will likely spend more time exercising if they find the therapy activity enjoyable, engrossing, and appropriately challenging. To meet these requirements, VR therapy systems present the patient with engaging situations, with goal-oriented movements that motivate the patient to continue repeating the exercise. Moreover, therapists can customize VR therapy systems to motivate the patient further by setting the exercise activity at an appropriate difficulty level. These strengths offer strong theoretical grounds for VR therapy technologies as useful tools for promoting physical rehabilitation.

2.1.4. Categories of VR Therapy Technologies

To make useful insights about VR therapy as a research field, some classification of the systems that researchers are currently developing is necessary. One method of organizing them is by measuring the sense of "presence" in the virtual environment that the system provides to the patient.[30] To that end, as shown in Figure 2.1, this section discusses VR therapy technologies in terms of three categories on the virtual end of the virtual-real spectrum:

1. "Immersive virtual reality" refers to a therapy experience takes place entirely within a virtual context.
2. "Augmented virtuality" is somewhat less encompassing, incorporating some physical elements into the virtual environment.
3. "Mixed reality" places even more emphasis on real physical objects, possibly by having the patient manipulate those objects in order to control the virtual environment.

Granted, no consensus exists on the best way to sort these technologies into sub-groups for analysis – classifications include the patient population to which they are best suited, particular technical features of the technology, or the stage of research and validation of the system.[27] This method of classification, however, is useful because it arguably captures the essential differences in the experience with using these VR therapy systems.[31] In this way, accurate generalizations about the state of development of each of these three classes of technologies are possible.

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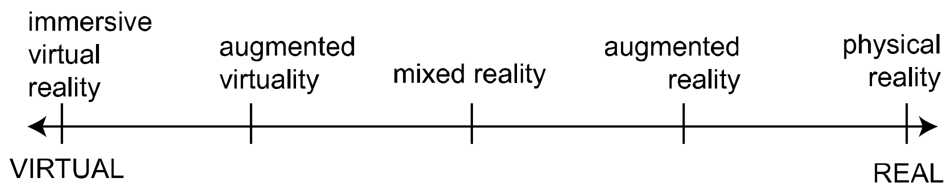

Figure 2.1: The real-virtual continuum, adapted from Milgram and Kishino.[34] VR therapy technologies may be categorized as "immersive virtual reality," "augmented virtuality," or "mixed reality."

2.1.4.1. Immersive Virtual Reality

In immersive VR therapy systems, the patient is completely oblivious to his or her actual physical surroundings. Most often, these systems use a head-mounted device (HMD) that blocks out all stimuli from the real physical environment. Such a device has video screens that occupy the patient's entire field of vision, earphones that prevent him or her from hearing any external noise, and sensors that track the movement of the patient's head so that the audiovisual feedback changes as a function its position and orientation of the patient's head. For physical rehabilitation, the patient might also wear gloves with motion and position sensors or other interfaces so that the system can present tasks that require certain goal-oriented movements.[27] Aside from HMDs, immersive virtual reality also occurs in a Cave Automatic Virtual Environment (CAVE), which involves an entire room equipped with sophisticated sensors, wall-to-wall video screens, and many audio sources that provide a highly immersive virtual reality experience.[32] Overall, these systems use the most current technologies to offer the most powerful immersion into virtual world.

Although immersive virtual reality is a powerful technology, its drawbacks have limited its clinical acceptance. Concerns persist about motion sickness and visual fatigue with HMDs, collectively termed "cybersickness" – some studies have found that up to 60% of healthy subjects experience this type of discomfort with prototype VR therapy systems that use HMDs.[33] Due to these issues, there are relatively few studies with immersive VR therapy systems for physical rehabilitation – existing research has involved only limited numbers of participants to date.[34] This technology still has some proponents: because neurological injuries leading to physical impairment may also affect other parts of the brain and cause cognitive difficulties, some argue that immersive virtual reality system might be beneficial for maintaining the attention of the patient on the physical activity. In addition, HMD systems may also be less expensive and more portable than systems that require a dedicated visual display, such as a television or computer screen.[35] CAVEs, meanwhile, have been used to study human gait and other biomedical applications, but they have not yet been evaluated as a technology for physical rehabilitation.[34] Overall, due to concerns about cybersickness with immersive virtual reality systems, researchers have generally been wary of this category of VR therapy technologies.

2.1.4.2. Augmented Virtuality

An augmented virtuality system incorporates some elements of the physical world into the virtual one. For most physical rehabilitation applications, the part of the patient's body that he or she must exercise is visible in the virtual environment. For instance, many augmented virtuality systems overlay a software-generated virtual world over the image of the patient, which it captures with a video camera. Then, the patient's movements directly affect what happens in the virtual reality environment – he or she can manipulate or reach for certain virtual objects that appear on the screen [6]. Other forms of augmented virtuality may involve wearing a glove equipped with force or position sensors; in this case, a virtual representation of the patient's hand is visible on the screen performing motor tasks. Overall, although elements from physical reality are part of these VR therapy systems, the result is that the patient still feels a strong sense of presence in the virtual environment.

Of the three categories of VR therapy technologies that this paper discusses, augmented virtuality has made the most progress in terms of clinical evaluation. Studies with one camera-based system have suggested that virtual reality play-based activities for children with cerebral palsy are enjoyable and may increase their seated postural control[16] and sense of self-efficacy.[17] In addition, one research group has found that, as a result of using this system, neurological changes occurred in adult patients recovering from stroke – functional magnetic resonance imaging (fMRI) detected significant reorganization of the motor cortex in ten patients after 20 one-hour therapy sessions.[18] Finally, studies are also underway to compare the rehabilitation outcomes of using this system and of conventional therapy, an important step in determining whether this form of VR therapy should become part of standard therapy for these patient populations.[36] For glove-based systems, meanwhile, a number of studies with up to eight patients recovering from stroke suggest they may result in improvements in motor skills.[27,37] Clearly, these findings provide strong evidence that augmented virtuality systems are effective at promoting physical rehabilitation.

2.1.4.3. Mixed Reality Systems

When physical objects have an even more prominent role in VR therapy systems, the result is a "mixed reality" VR therapy system. These are sometimes described as "fish tank" systems because patients can see the virtual reality environment on a monitor or television screen but are not usually a part of it.[36] Located in the middle of the virtual-real spectrum, patients typically affect the virtual reality environment, which is visible on a monitor or television screen, by handling certain physical controls. These controls may include conventional joysticks, touch screens, or "haptic" devices that can also exert forces on the patient. For more specialized therapy applications, researchers may equip other objects with sensors so that the VR therapy system can track their position and orientation.[38] By combining the physical and virtual worlds, patients can perform activities that are similar to real-world activities while benefiting from the customizability and immersion associated with VR therapy systems.

> The application of mixed reality systems to physical rehabilitation appears to be growing. One challenge is that the integration of real and virtual environments presents additional technical challenges – many recent papers have focused on technological development as opposed to clinical evaluation. One system, for instance, has kitchen items such as cups and coffee makers equipped with position and tilt sensors so that their manipulation by patients can be tracked and displayed in the VR therapy system. Due to technical limitations, though, it is still in its early stages of clinical evaluation.[35] With other devices, two single-subject pilot studies with patients recovering from are noteworthy: a joystick system found benefits to improving motor control,[39] while a haptic device called the "PHANToM" increased a patient's ability to manipulate objects in a

standardized test, the quality of reaching movements, and the strength of his grip.[39] On the whole, mixed reality systems require further technological development and clinical study to validate their efficacy for physical rehabilitation; however, based on these early findings, these technologies have promising prospects.

2.1.5. Analysis of Current State of VR Therapy Research

This section offers a broader examination of some of the structural characteristics of the field of VR therapy research. Specifically, it explores two issues: the research required in order to evaluate whether VR therapy should become part of standard therapy for patients with stroke or cerebral palsy, and the need to synthesize theories of physical rehabilitation with some of the conclusions drawn about the three types of the systems discussed in the previous section.

2.1.5.1. Next Steps in VR Therapy Research

Typical of new medical devices, numerous VR therapy technologies have been evaluated with small groups of patients in pilot studies. In particular, augmented virtuality systems appear to have been developed and studied most extensively; between mixed reality and immersive virtual reality systems, meanwhile, the former appears to have more potential than the latter. These preliminary research discoveries illustrate that some forms of VR therapy are useful in rehabilitation and that continued studies are warranted. In general, however, researchers have yet to compare the relative efficacy of VR therapy and conventional forms of therapy for physical rehabilitation. In some other forms of therapy, a small number of studies have found that VR therapy may be more effective in promoting the development than practicing the actual activities in real-world environments.[40,41] In physical rehabilitation, however, such evidence is very limited at this time.[27] Such studies are the necessary next step toward determining whether VR therapy should be integrated into clinical practice for these patient populations.

2.1.5.2. The Need to Link Theories of Physical Rehabilitation to the Selection and Design of New Technologies

Based on the current literature, there is a need to establish criteria for selecting the most appropriate VR therapy technology for different rehabilitation situations. One way to learn how to make such judgments would be to compare different forms of VR therapy in clinical trials. Not surprisingly, due to the emerging nature of this field, such research is still in its early stages.[27] As discussed in this article, however, the scientific rationale for using VR therapy for physical rehabilitation appears to be well developed because VR therapy uses many of the principles of other forms of therapy. As well, engineers and clinicians have developed a wide range of VR therapy technologies that have demonstrated at least some success in promoting rehabilitation. Arguably, therefore, linking these theories with existing technologies should be possible. Meta-analyses of current research by clinicians, neuroscientists, and engineers may be able to identify the underlying reasons why certain technologies have been successful while others have stalled. Such work would help clinicians select the right VR therapy technology for a particular patient need to optimize the rehabilitation outcomes.

From an engineering standpoint, meanwhile, having a better understanding of how to apply theories of rehabilitation to VR therapy technologies may also help to identify gaps in technology development. Along with creating the multimedia experience necessary in a virtual environment, computers have the capability to log immense amounts of data on usage as the patient does the therapy.[24] As well, little work has been done to investigate the potential of rehabilitation systems that process information from the patients' interactions with the system and make "intelligent" adaptations to the nature of the task to maximize the rehabilitation benefit. One joystick-based system collects and stores a large amount of usage data, but adaptive computer software has not been created. Another group has created a wearable system that regulates joint motion during resistance training for patients with cerebral palsy or recovering from stroke; at this point, only preliminary studies with healthy volunteers have been completed.[42] Overall, while VR therapy is an area with a growing body of literature, the idea of incorporating adaptive computer systems into this form of therapy is still in its infancy. Collaborations between clinicians, neuroscientists, and engineers are essential to determine which of these technologies are worth the costs associated with developing and evaluating them.

2.1.6. Conclusions

VR therapy is a growing and exciting area of research, with many researchers worldwide developing new technologies and evaluating them for clinical efficacy. Of the categories of VR therapy technologies, as classified on the virtual-real spectrum, augmented virtuality and, to a lesser extent, mixed reality systems have been the focus of most research efforts; consequently, these systems have the most evidence in support of their further development. While these results are promising, there is a need to validate these findings in studies that compare VR therapy with other forms of therapy to measure their effectiveness in the field of physical rehabilitation. As well, theoretical and experimental comparisons between different VR therapy technologies would be useful in order to identify which systems work best for particular patient populations. These steps will help ensure that this field progresses in a manner that maximizes positive rehabilitation outcomes for patients with brain injury or abnormal brain development and, in turn, improves the quality of their lives.

2.2. Implications for Thesis

This thesis focuses on developing new VR therapy systems. Notably, the PS2-E system falls into the "augmented virtuality" category of technologies, which have shown considerable success with patients recovering from stroke and, to a lesser extent, with children with cerebral palsy. The proposed adaptive hands-on interface, meanwhile, is a mixed-reality system, another promising area of development in which the user interacts with physical-world objects (knobs, squeeze sensors) to effect changes in the virtual reality environment presented on a computer screen. The early success of both of these categories of systems indirectly supports the hypothesis that the systems under design and development will be suitable as a tool to promote targeted neuromotor movements.

According to the literature review, the concept of intelligent adaptive systems for physical rehabilitation remains relatively unexplored. While many systems are adjustable by the supervising therapist to provide an appropriate level of challenge to the patient, little work has been done on the idea that the system itself could process user inputs and adjust the difficulty level of the therapy activity to maximize rehabilitation outcomes. The adaptive hands-on interface, therefore, is a device a device to test the validity of this idea and identify any problems. With few successful examples of how an adaptive system would respond to the user's performance, clinical experience will guide its development in this project

Chapter 3

PlayStation 2 with EyeToy (PS2-E) VR Therapy System

This chapter describes the design, implementation, and evaluation of the VR therapy system based on the Sony PlayStation 2 and EyeToy video camera. Constructing a prototype, developing the protocol for a usability study, conducting test sessions with five children with hemiplegic palsy, and analyzing the results were all part of this thesis. The results of this work were summarized and published in one abstract and two papers reprinted by permission the sections of this chapter. Although the publications repeat some of the context and findings of the study, they have different emphases. Section 3.1, an abstract, provides an overview of the implementation and evaluation of the PS2-E, with a summary of the results from the first round of usability testing. Section 3.2 presents a more in-depth discussion of the usability issues that were identified and corrected in the first round of testing. Next, Section 3.3 features a paper that describes the technical implementation of the system in detail. It also supplements the findings of the first two publications by including and discussing the results of second round of usability testing. Finally, appendix A contains additional documentation related to the system's technical implementation and the usability research study.

3.1. Abstract: A Home-Base Virtual Reality Therapy System for Children with Hemiplegic Cerebral Palsy

Reprinted, with permission, from Li, W., Lam-Damji, S., Chau, T., Fehlings, D., "A Home-Based Virtual Reality Therapy System for Children with Hemiplegic Cerebral Palsy," submitted to *61st Annual Meeting, American Academy for Cerebral Palsy and Developmental Medicine*, Vancouver, BC, Canada, October 2007.

Background/Objectives

Children with hemiplegic cerebral palsy can make improvements in motor skills through repetitive practice. A need exists for engaging home-based activities that can encourage such exercise. Virtual reality therapy (VRT) involves the use of computer-based technology for rehabilitation purposes, eliciting movement and practice of specific neuromotor movements. Our objective was to develop and test a low-cost, home-based virtual reality system for children with hemiplegia. The specific aim of the pilot study was to determine whether the system elicits targeted neuromotor movements, is enjoyable, and to identify design issues that affect the usability of the system.

Description

A Sony PlayStation 2 equipped with an "EyeToy" video camera was adapted. The camera captures the child's movements in fun and immersive games in virtual environments. To promote exercise of the hemiplegic upper extremity (UE) and avoid use of the non-hemiplegic hand, the child must be seated and hold down two wireless pushbutton switches, one underneath the chair that must be held with his or her uninvolved hand, and the other on the back of chair. A connected personal computer features fingerprint recognition and data logging to record the amount of time the child plays on the system.

Methods and Results: A volunteer sample of five children, four males and one female with hemiplegic cerebral palsy, between 6-9 years ($m = 8.1 \pm 1.4$ years), participated in two test sessions each in a supervised clinical setting. Using video review, we identified that the system elicited targeted neuromotor movements (10.4 ± 0.7 movements/minute of play), particularly reaching activities with the shoulder and elbow, over a continuous period of play time (18.9 ± 1.7 minutes). Proximal movements were elicited more than distal movements. One identified design issue was that some participants had difficulty pressing the back pushbutton because they were sliding out of the chair. Participants and caregiver surveys revealed that the system was highly enjoyable and would be accepted as part of a home-based therapy program.

Significance

The VRT system is effective in promoting targeted neuromotor movements of the proximal UE and has a high level of user satisfaction. Future studies will examine the usability of the system at home as well as evaluate the preliminary evidence of the effectiveness of the system using clinical outcome measures. Hardware and software modifications of the VRT system to promote more distal hand use are being explored.

3.2. Usability of a Virtual Reality Therapy System for Children with Hemiplegic Cerebral Palsy (Canadian Medical and Biological Engineering Conference)

Reprinted, with permission, from "Usability of a Virtual Reality Therapy System for Children with Hemiplegic Cerebral Palsy," accepted to *30th Canadian Medical and Biological Engineering Conference*, Toronto, ON, Canada, June 2007.

The accepted and formatted manuscript can be found in the next four pages.

USABILITY OF A VIRTUAL REALITY THERAPY SYSTEM FOR CHILDREN WITH HEMIPLEGIC CEREBRAL PALSY

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Children with hemiplegic cerebral palsy (hemiplegia) have difficulty performing motor tasks with their hemiplegic upper extremity (UE). Exercise and practice can result in improvements in motor skills. A Sony PlayStation 2 equipped with an "EyeToy" video camera was adapted for children to practice neuromotor movements. The system captures the child's movements in fun, immersive games in virtual environments. Pilot test sessions with five children with hemiplegia found that the system successfully elicited targeted neuromotor movements of the hemiplegic UE (10.4 ± 0.7 movements/minute of play), particularly reaching activities that involve the shoulder and elbow, over a continuous period of playtime (18.9 ± 1.7 minutes). As well, child and caregiver surveys revealed that the therapy was highly enjoyable and that it would be accepted as part of a home-based therapy program. Usability issues have been identified and will be addressed with system modifications and further testing.

BACKGROUND

Hemiplegic cerebral palsy (CP), or hemiplegia, refers to a brain injury or anomaly of the motor cortex that creates a sensorimotor impairment of the opposite upper extremity (UE). Neuromotor movements that are difficult for children with hemiplegia include shoulder flexion and abduction, elbow extension, forearm supination, wrist and finger extension, thumb extension, and thumb abduction. Consequently, they generally favour the use of their non-involved UE in everyday activities [1].

Current therapies focus on repetition and practice of motor activities with the hemiplegic UE [2]. Forcing such practice by applying a constraint to the non-involved UE is effective [3], but safety and loss of independence are concerns [1]. Virtual reality (VR) therapy, meanwhile, describes an immersive and interactive computer experience for rehabilitation purposes [4], and one camera-based system has induced cortical reorganization and associated motor recovery in adult patients recovering from stroke [5]. While promising, however, existing systems are not conducive to *home-based* therapy activities due to high costs and the need for specialized equipment.

Our aim, therefore, was to develop and evaluate a low-cost VR therapy system that elicits practice of neuromotor movements, accommodates a wide range of abilities, provides a simple way for clinicians to track usage, and could be used at home. In this paper, we describe the system and the results of early usability testing with children with hemiplegia. We evaluated whether users could achieve specified tasks with effectiveness (accuracy and completeness), efficiency (expenditure of resources with respect to achieved effectiveness), and satisfaction (freedom from discomfort and attitudes toward the use of the product) [6].

SYSTEM DESIGN

Video Game System

The setup uses a TV-based PlayStation 2 (PS2) and an accessory called the "EyeToy" (Sony Computer Entertainment America, Foster City, CA, USA). With the appropriate games, players see their mirror image on the screen, and their physical movements are inputs into the games. For this study, two games from the "Play 2" disc were chosen. In "Secret Agent," the player reaches for toys that appear on the screen; in "Mr. Chef," the player reaches for various food items.

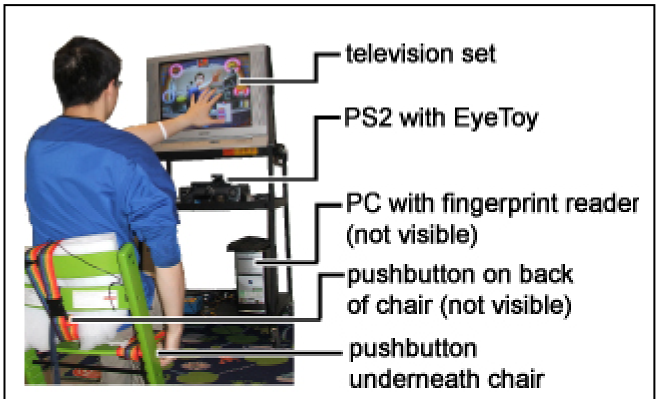

Figure 1: System setup. The participant sits approximately six feet away from the screen and "reaches" for virtual objects visible on the TV.

System Modifications

To play the games, participants sit on a chair with two pushbutton switches (Tash Inc., Richmond, VA, USA). As Figure 1 illustrates, one pushbutton is underneath the seat of the chair on the child's non-involved side and is held with the non-involved hand, while the other is on the back of the chair and must be pressed by sitting upright. These switches encourage movement and extension of the hemiplegic UE in the games. To ensure that they are pressed, the buttons activate an infrared transmitter/receiver (Velleman Inc., Fort Worth, TX, USA) that controls the TV display – if they are released, the TV screen goes blank.

Data Collection

To track usage, the user scans his or her fingerprint with a fingerprint reader (Microsoft Corporation, Redmond, WA, USA) connected to a personal computer (PC) to activate the system. Computer software then logs the amount of time that the pushbutton switches are held. Figure 2 summarizes the system schematically.

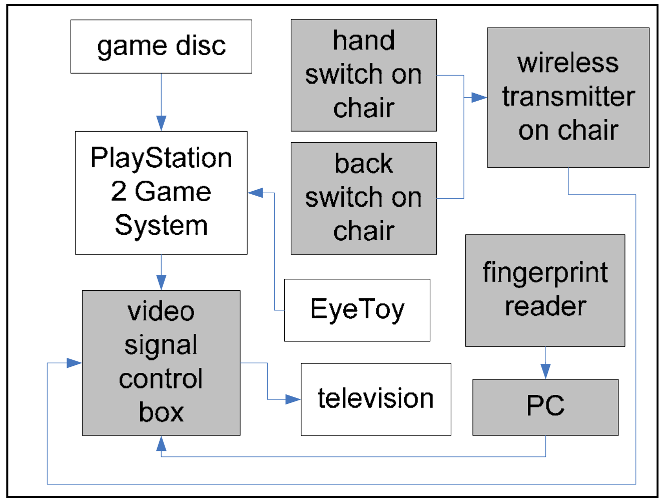

Figure 2: Schematic of VR therapy system. Shaded boxes denote components added to the unmodified PlayStation 2 with EyeToy system.

USABILITY EVALUATION

Test sessions were conducted with five children with hemiplegic cerebral palsy (4 males, 1 female, aged 8.1 ± 1.4 years). The participants had varying levels of fine motor difficulties as indicated by their scores in the House classification system (one participant at level 2, one at level 4, and three at level 5) and the Quality of Upper Extremity Skills Test (QUEST) (52.3 ± 18.2) [1]. The protocol was approved by the research ethics board of Bloorview Kids Rehab. Informed consent was obtained from all of the participants. In the study, participants played "Secret Agent" and "Mr. Chef" with a caregiver and occupational therapist (OT) present. The session was videotaped, and the number, type, and quality (greater or less than 50% range) of neuromotor movements were counted by an OT via video review. Child and caregiver surveys were administered to evaluate user satisfaction.

RESULTS

Figure 3 displays the average rates of each neuromotor movement observed for the five participants. The average playing time was 18.9 ± 1.7 minutes. Next, Figure 4 illustrates a positive correlation between the participants' rate of movements and their total QUEST score.

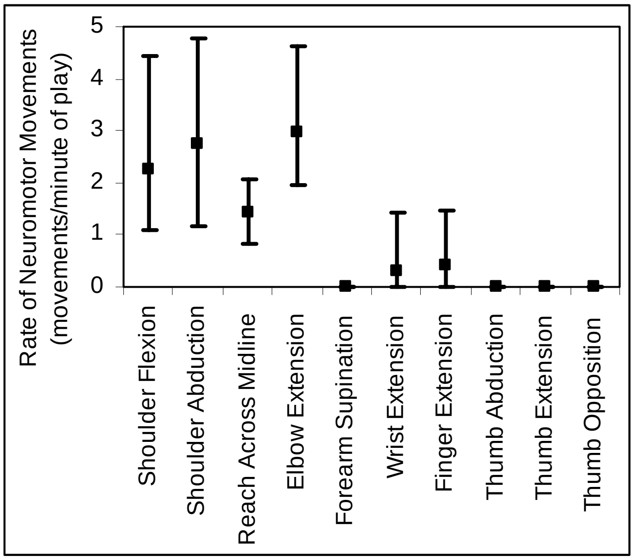

Figure 3: The average rate of targeted neuromotor movements. Error bars represent the maximum and minimum rates among the five participants.

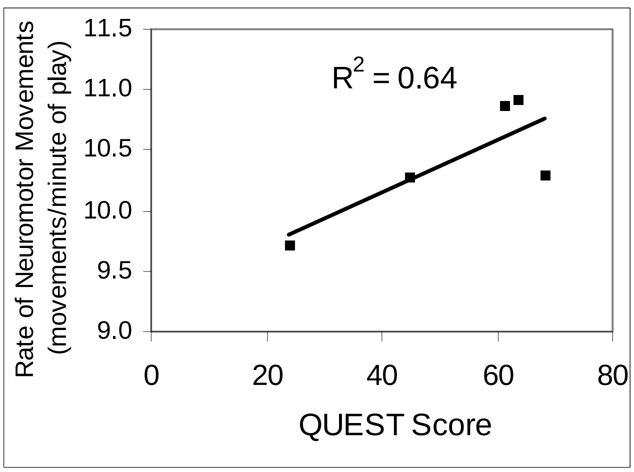

Figure 4: Relationship between average rate of targeted neuromotor movements and level of UE function (QUEST score) for the five participants.

Table 1: Summary Statistics of Test Sessions

Total neuromotor movements/minute	10.4 ± 0.7
Quality of movements (Percentage of movements greater than 50% range	72%
Pushbutton compliance (percentage of playtime that buttons were successfully pressed by user)	91.9% ± 8.9%

Table 2: Average Responses to Selected Questions from Child/Caregiver Questionnaires

1 – Strongly disagree; 2 – Disagree; 3 – Neither agree nor disagree; 4 – Agree; 5 – Strongly agree	
Child Questionnaire	**Average**
I had lots of fun today.	4.2 ± 1.1
I would like to come back another day to play the games again.	4.2 ± 1.1
I would like to take the video games home to play.	5.0 ± 0.0
Parent Questionnaire	**Average**
My child would enjoy using this virtual reality therapy system at home.	5.0 ± 0.0
I think that my child would practice therapy activities every day with this system at home.	4.8 ± 0.4
I would like to have this system at home.	4.6 ± 0.5

Some summary statistics are shown in Table 1. Meanwhile, Table 2 lists responses of the participants and their caregivers to selected survey questions. Caregivers commented that the system was "great to make [child] work" and "a way to make therapy fun." Their concerns included the speed and difficulty of certain game tasks.

DISCUSSION

<u>Effectiveness and Efficiency</u>

The system elicited movements of the proximal hemiplegic UE at high rates – shoulder abduction, for instance, was performed an average of 52 times per session. However, because the games generally involve gross reaching motions, fewer distal movements involving the wrist, finger, and thumb were seen. Meanwhile, the large spread in pushbutton compliance (91.9% ± 8.9%) occurred because some participants were sliding out of the chair during the games and releasing the back pushbutton. Further design iterations are needed to address this issue.

User Satisfaction

From the survey results in Table 2, the participants reported high levels of satisfaction with using the system. Acceptance was also high among caregivers. Some participants commented that the menus had large amounts of text and disappeared quickly. This may become less problematic as they gain more playing experience.

User Characteristics that Affect Usability

Children with higher baseline UE function, as measured on the QUEST, generally performed more targeted movements. This relationship is expected as higher QUEST scores reflect greater motor control of the hemiplegic arm. It is noteworthy, however, that all of the participants were able to access and enjoy the games, indicating that the system can accommodate a range of functional abilities.

Limitations and Other Applications

To address the need for promoting distal UE practice, our group is currently developing a physical "hands-on interface" in which children must perform movements such as squeezing pressure sensors of turning knobs in order to play computer games. The data logging and pushbutton switches are reused in this new system. Other potential applications of the system, meanwhile, might include home-based rehabilitation exercise for other populations, including adults. Usage logging might be useful for other forms of computer-based therapy to monitor progress.

CONCLUSIONS

We have described the implementation and pilot usability evaluation of a VR therapy system for training upper extremity function of children with hemiplegic cerebral palsy. Based on the evidence presented, the system is usable by children with hemiplegia and elicits targeted neuromotor movements. Further studies to investigate the system's potential for enhancement of specific upper extremity function are warranted.

ACKNOWLEDGEMENTS

This work was funded in part by the Canadian Institutes of Health Research (CIHR) Pfizer/IMHA/Rx&D Summer Studentships in Musculoskeletal Research

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[6] ISO 9241-11:1998(E): Ergonomic requirements for office work with visual display terminals (VDTs) – Part 11: Guidance on usability. International Organization for Standardization, Geneva, Switzerland.

[7] C. DeMatteo, M. Law, D. Russell, N. Pollock, P. Rosenbaum, and S. Walter, "The reliability and validity of Quality of Upper Extremity Skills Test," *Phys Occup Therp Pedi*., vol. 13, pp. 1-18, 1993.

3.3. Usability of a Virtual Reality Therapy System for Children with Hemiplegic Cerebral Palsy (Archives of Physical Medicine and Rehabilitation)

Reprinted, with permission, from Li, W., Lam-Damji, S., Chau, T., and Fehlings, D., "Usability of a Virtual Reality Therapy System for Children with Hemiplegic Cerebral Palsy," submitted to *Archives of Physical Medicine and Rehabilitation* (Prosthetics and Orthotics category).

3.3.1. Abstract

Objective: To evaluate the usability of a virtual reality (VR) therapy system designed to motivate children with hemiplegic cerebral palsy to practice neuromotor movements of their involved upper extremity while in a seated posture.

Design: Usability evaluation

Setting: A tertiary care, pediatric rehabilitation hospital.

Participants: Convenience sample of five primary school children with hemiplegic cerebral palsy.

Interventions: Not applicable.

Main Outcome Measures: Quantity and quality of targeted neuromotor movements; time spent playing game; caregiver and child surveys.

Results: The VR therapy system successfully elicited targeted neuromotor movements (13.2 ± 4.0 movements/minute of play) of the hemiplegic involved upper extremity; particularly reaching activities that involved the shoulder and elbow. This rate was sustained over an extended period of game playing (18.6 ± 2.6 minutes). Proximal arm movements were elicited to a greater extent than distal movements. Through parent and child surveys, participants indicated that they enjoyed the VR therapy system and would likely accept the technology as part of a home-based therapy program. Usability issues that need to be addressed include the inappropriate size and back angle (or recline) of the chair and broadening the range of difficulty in the VR games.

Conclusions: The proposed system is usable by school-aged children with hemiplegic cerebral palsy to practice targeted movements of the hemiplegic upper extremity within an institutional setting. Further study is required to evaluate the usability of this system in the home setting.

Key words: cerebral palsy; hemiplegia; virtual systems; occupational therapy; rehabilitation

3.3.2. Background

Cerebral palsy (CP) describes a group of disorders of the development of movement and posture, causing activity limitations that are attributed to non-progressive disturbances that have occurred in the developing fetal or infant brain.[1,2] Children with hemiplegic cerebral palsy (CP), have a brain injury or anomaly of the motor cortex that creates a sensorimotor impairment of the opposite upper extremity (UE). The impairments are multifactorial and consist of a combination of muscle hypertonia, weakness, impaired selective motor control, decreased sensation, and neglect of the involved UE. Movements that are typically difficult for children with hemiplegia include shoulder abduction, elbow extension, forearm supination, wrist and finger extension, and thumb extension. Consequently, through learned non-use, children with hemiplegia generally favour the use of their non-involved UE in everyday activities.[5]

Currently, therapy programs emphasize repetition and practice of motor activities with the hemiplegic UE.[7,26] Home-based practice, therefore, is essential. One treatment is constraint-induced movement therapy (CIMT), in which the child's non-involved UE is constrained in a sling, mitt or cast, thereby forcing the use of the hemiplegic UE in activities and exercises.[13,14] While effective, CIMT also raises concerns: it is time-consuming, can increase the risk of falls, and results in reduced independence and increased frustration for the child while they are wearing the constraint.[21] As a less-invasive alternative to CIMT, therapists often recommend sets of exercises for families to practice neuromotor movements with their child. However, given the numerous competing pressures on caregivers' time, adherence to such home programs may be difficult, and their effectiveness is questionable.[9]

Virtual reality (VR) therapy is defined as an immersive and interactive computer experience that promotes practice of specific neuromotor movements for rehabilitation purposes.[16] In one VR therapy system that involves a video camera, a computer with video control technology, and a visual display, patients reach for virtual objects in goal-oriented game environments that they can see on a television screen. Pilot studies with one such system designed for institutional use[a] have suggested that VR play-based activities for children with cerebral palsy may increase their seated postural control[16] and sense of self-efficacy,[17] while another study with patients recovering from stroke found that using the system induced cortical reorganization and motor recovery.[18] While promising, existing systems are not conducive to *home-based* therapy for children with hemiplegia, due to high costs and the need for specialized equipment.

Our aim, therefore, was to develop a low-cost, home-based VR therapy system that

[a] GestureTek, Inc., 530 Lakehead Drive, Suite 270, Sunnyvale, CA 94085.

promotes the use of the hemiplegic UE and targets movements that the child finds difficult. Guided by fun, goal-oriented games presented by a VR therapy system, children may willingly spend more time practicing neuromotor movements independently. Such a system should additionally accommodate a wide range of abilities, be enjoyable and usable in a home setting without professional assistance and, preferably, with minimal monitoring by caregivers, while providing a simple way for clinicians to track usage. In this article, we describe our development and implementation of such a device, constructed largely from off-the-shelf hardware, and the results of usability test sessions with children with hemiplegia.

3.3.3. Virtual Reality (VR) Therapy System

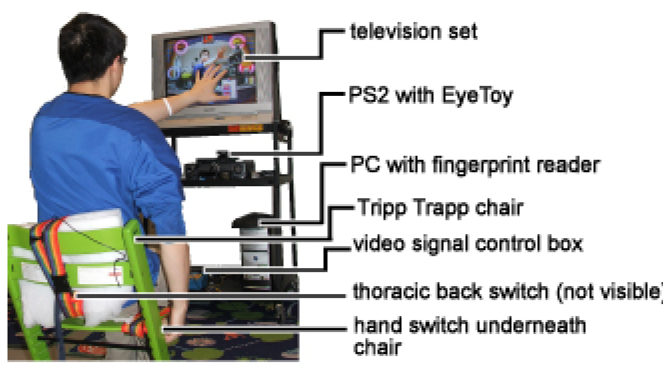

Figure 3.1: Photograph of system setup. The participant sits approximately six feet away from the screen and "reaches" for virtual objects visible on the TV.

The VR therapy system shown in figure 1 consists of the following components: an off-the-shelf PlayStation 2 (PS2) video game system with an accessory called the EyeToy,[b] an instrumented Tripp Trapp chair,[c] and a video signal control system comprised of a

[b] Sony Computer Entertainment America, PO Box 5888, San Mateo, CA 94402-0888.
[c] Stokke LLC, 1100 Cobb Place Blvd, Suite 100, Kennesaw GA 30144.

personal computer and a number of electronics components. Additional materials include a generic plastic box (10cm x 20 cm x 5cm) with seven composite audio/video sockets, two pushbutton switches (a #58200 soft switch and a #58750 pillow switch),[d] a CK1617A radiofrequency (RF) transmitter and receiver,[e] two integrated circuits (ICs) (the MAX232 serial driver/receiveru[f] and the 2233BD analog video switch[g]), and a personal computer equipped with a composite video output, serial port (COM1), Windows XP,[h] and no computer monitor. The purpose and assembly of each component is described in turn.

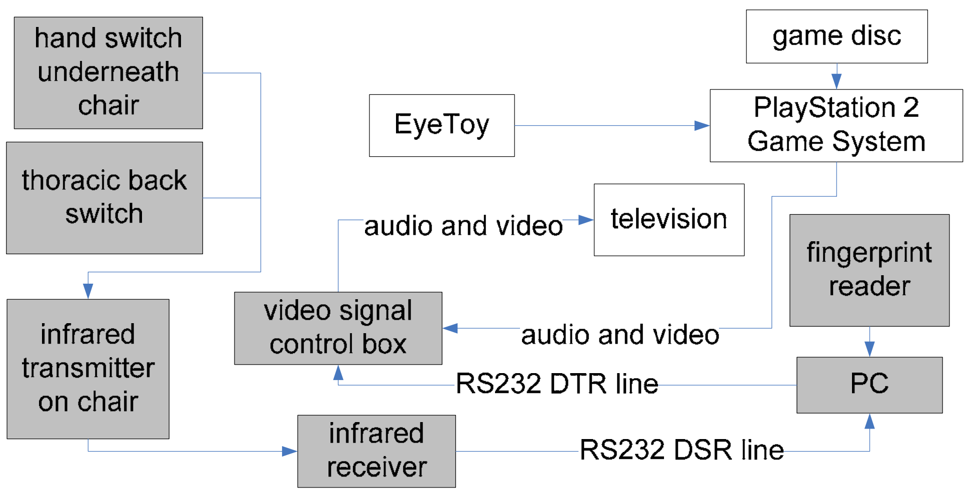

Figure 3.2: Schematic of VR therapy system. Shaded boxes denote components added to the unmodified PlayStation 2 with EyeToy system.

Video game system

The PS2[b] is a commercially available video game system designed for home use. Its visual display is a conventional television. The EyeToy[b] is a video camera designed specifically for the PS2. When these devices are used with appropriate game discs, the

[d] Tash Inc, 3512 Maryland Ct, Richmond, VA 23233.
[e] Carl's Electronics Inc., 484 Lakepark Ave, Suite 59, Oakland, CA 94610.
[f] Maxim Semiconductor, 120 San Gabriel Dr, Sunnyvale, CA 94086.
[g] NJR Corporation, 198 Stauffer Blvd, San Jose, CA 95125.
[h] Microsoft Corporation, 1 Microsoft Way, Redmond, WA 98052-6399.

video image of the player is shown in real time on the screen with virtual objects that can be manipulated with physical movements. For this study, participants played two games from the “Play 2” disc.[b] In “Secret Agent,” players earn points by reaching to “touch” toys while avoiding “spotlight” areas that appear throughout the screen. In “Mr. Chef,” the player performs such tasks as “shaking” milkshakes by making circular arm motions or “chopping” pickles with slicing motions. Along with the EyeToy, the PS2 includes an 8 megabyte (MB) memory card for storing game data[b] and a 7089 rechargeable wireless controller[i] (which avoids tripping hazards). The video game system is set up as per the manufacturer’s instructions, except that the audio and video outputs are connected to the video signal control box as opposed to being plugged directly into the television. Within the “Play 2” software,[b] the sensitivity was set to “high” and the difficulty level was set to “easy.”

Chair system

To use this system, the child sits on a Tripp Trapp chair.[c] Children with hemiplegia favour their non-involved UE in everyday activities; therefore, the goal of the chair system is to occupy the non-involved UE and encourage gaming with the involved UE only. To this end, the pillow switch[e] is attached underneath the chair and is held with the non-involved hand, as illustrated in figure 1. Additionally, the soft switch,[d] i.e., the thoracic back switch, is mounted on the back of the chair and must be pressed by leaning back. By enforcing an upright seated posture, this latter switch encourages elbow extension of the involved UE during gaming, as children with hemiplegia often lean forward to minimize the need for elbow extension during reaching movements. Only

[i] Intec, Inc., 5255 NW 159 St. Miami, FL 33014.

when the two switches are pressed simultaneously will the CK1617A RF transmitter be activated, making it possible to see and play the video games on the screen[f].

Video signal control system

The system requires additional circuitry connected to the television and PlayStation 2 to control whether the PS2 or PC video signal is seen in the screen. The MAX232[f] IC converts between the logic-level voltages of the PC serial port (-10V and 10V) and the CMOS/TTL components of the other circuitry (0 and +5V). The 2233BD[g] IC works to pass the PlayStation 2 video signal when the switches on the chair are pressed by the child. The components are assembled by the following procedure.

1. Attach seven composite audio/video sockets to the sides of the generic plastic box. These sockets represent the PS2 video and two audio signals, the PC video signal, and the video and two audio outputs to the television screen. Wire together the two pairs of audio sockets.
2. Prepare a prototype board or printed circuit board (PCB) for the MAX232f and 2233BDg ICs and their associated components (PCB design freely available from the authors). The typical application circuits are available from their respective manufacturers.
3. Wire and connect the RF transmitter, PC serial port, and audio/video sockets, electronics, and PS2 as per figure 3.

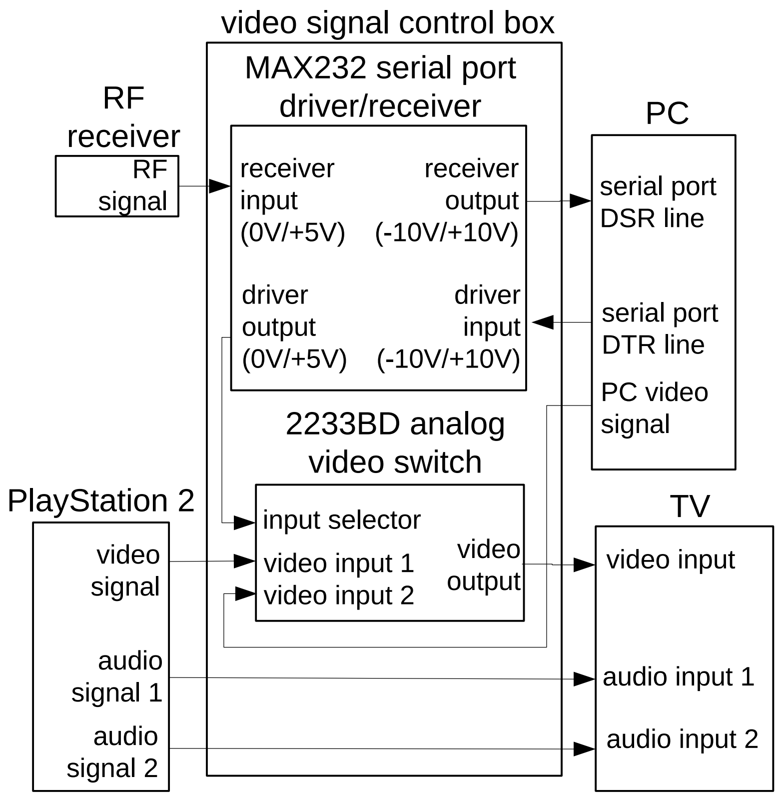

Figure 3.3: Block diagram of circuit that determines whether the computer or PlayStation 2 (PS2) video output should be seen on the television screen. Here, RF=radio frequency, DSR=data send ready, DTR=data transmit ready.

Fingerprint Recognition and Usage Logging

The user recognition and logging setup consists of (1) the USB fingerprint reader DG2-00002[h] connected to the aforementioned computer and (2) system software.

Fingerprint recognition

An important measure of the acceptance of the system in home settings will be the frequency and duration of use by the child. Thus, to turn on the system, the player who intends to play must scan his or her fingerprint into the commercially available USB fingerprint reader.

System software

The software serves three functions: video signal control, fingerprint recognition, and simple usage logging. It has been written in Visual Basic 6.0 (VB6) and is freely available from the authors. When the software program is launched, the computer's video output is seen on the television screen. Once a fingerprint is scanned and recognized, the software begins to monitor the signal in the Data Send Ready (DSR) line of the serial port, which indicates whether the child is pressing the switches on the chair. When the switches are pressed, the software changes the signal on the serial port's Data Transmit Ready (DTR) line so that the PlayStation 2 video signal is seen on the TV screen; when they are released, the computer display appears on the TV screen and reminds the user to press down the buttons. Fingerprint enrolment, fingerprint recognition, and switch activation and release events are time-stamped and logged in an Access[j] database for later analysis.

3.3.4. Usability Evaluation

Two rounds of supervised test sessions were conducted with five children with hemiplegic cerebral palsy (4 males, 1 female, aged 8.1 ± 1.4 years). The switch beneath the chair was positioned on the participant's non-hemiplegic side for each test. The participants had varying levels of fine motor difficulties as indicated by their scores in the House classification system (one participant at level 2, one at level 4, and three at level 5)[43] and the Quality of Upper Extremity Skills Test (QUEST)[44] (52.3 ± 18.2). The protocol was approved by the research ethics boards of Bloorview Kids Rehab. All participants freely consented to the study. The test sessions focused on measuring usability as defined by International Organization of Standardization. Specifically, as outlined in ISO 9241-11,

[j] Microsoft Corporation, 1 Microsoft Way, Redmond, WA 98052-6399.

we evaluated whether users could achieve specified neuromotor tasks with effectiveness (accuracy and completeness), efficiency (expenditure of resources with respect to achieved effectiveness), and satisfaction (freedom from discomfort and attitudes toward the use of the product).[45] In each session, participants were videotaped playing two games, "Secret Agent" and "Mr. Chef". An occupational therapist counted the number and type of neuromotor movements in each session via video review; as well, the computer logged the time and duration each time the participant released the switches. Child and parent surveys were administered to evaluate user satisfaction with the system. These methods are common for evaluating new technologies in healthcare and other settings in which the goal is to identify usability issues.[46,47] Based on the usability issues identified in the first round of testing, design changes were made and evaluated in the second round.

3.3.5. Results

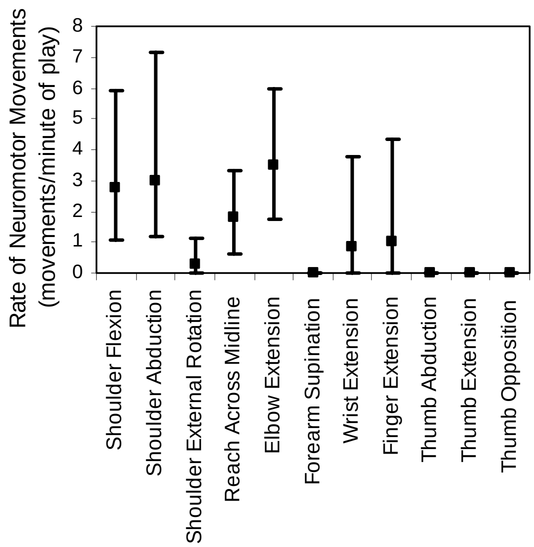

Figure 3.4 The average rate and type of neuromotor movements observed over the ten sessions. Error bars represent the maximum and minimum observed rate of movements among the five participants.

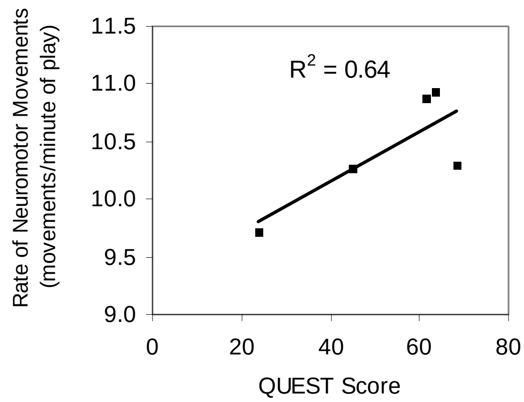

Figure 3.5: Relationship between average rate of targeted movements and level of UE function (QUEST score) for the five participants in the first round.

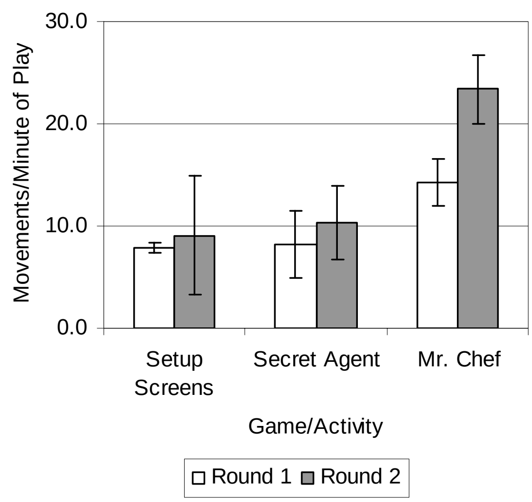

Figure 3.6: Comparison of the average rates of movements by game or activity. Error bars represent the standard deviation of the rate of neuromotor movements among the five participants.

Figure 3.4 displays the average rates of occurrence of each neuromotor movement observed over the ten test sessions, as determined through video review by one occupational therapist. Over the course of all of the test sessions, participants performed an average of 13.2 ± 4.0 movements per minute over a mean playing time of 18.6 ± 2.6 minutes per session. The count of neuromotor movements per minute of play in the first round of testing and the participants' total QUEST scores, depicted in figure 3.5, were positively correlated ($R^2 = 0.64$). Figure 3.6 summarizes the relative efficacy with which each game activity elicited targeted neuromotor movements.

Table 3.1: Summary statistics for usability test sessions

	Round 1	Round 2
Total neuromotor movements/minute	10.4 ± 0.6	16.0 ± 7.5
Quality of movements (Percentage of movements greater than 50% range)	72%	70%
Percentage of play time when switches were successfully pressed by user	91.9% ± 8.9%	94.4% ± 6.7%
Number of times that switches were released/minute of play	3.0 ± 2.7	1.9 ± 1.6

NOTE. Values indicate mean ± standard deviation

Table 3.2: Average responses to selected questions from child/caregiver questionnaires

Child Questionnaire	Average
I had lots of fun today.	4.2 ± 1.1
I would like to come back another day to play the games again.	4.2 ± 1.1
I would like to take the video games home to play.	5.0 ± 0.0
Holding down the buttons on the chair was easy.	3.2 ± 1.5
I don't feel tired.	3.1 ± 1.4
Parent Questionnaire	**Average**
My child would enjoy using this virtual reality therapy system at home.	4.8 ± 0.4
I think that my child would practice therapy activities every day with this system at home.	4.5 ± 0.8
I would like to have this system at home.	4.6 ± 0.5

NOTE. Values indicate mean ± standard deviation. 1 – Strongly disagree; 2 – Disagree; 3 – Neither agree nor disagree; 4 – Agree; 5 – Strongly agree.

Table 3.1 provides summary statistics for the two rounds of test sessions, portraying the extent to which targeted neuromotor movements were elicited by the system, the quality of those movements, and the adherence to the switches on the chair. In general, the participants maintained or improved the quantity and quality of movements with the system from the first to the second session. Finally, Table 3.2 lists the responses of the participants and their caregivers to selected survey questions as a measurement of user satisfaction with the system. The questionnaire scores in the two rounds were similar.

3.3.6. Discussion

The usability of the system is discussed below in terms of effectiveness, efficiency, and user satisfaction. Importantly, all the participants were able to access the system and play the games. Furthermore, Table 3.1 and Figure 3.6 suggest that the usability of the system was maintained with the design improvements that were introduced between the first and second rounds of testing.

Effectiveness

As figure 3.4 indicates, the VR therapy system effectively elicited movements of the proximal hemiplegic UE, including shoulder flexion and abduction, reach across midline, and elbow extension. This indicates that the participants responded to the game situations by performing certain targeted neuromotor movements, the key objective of this system. Fewer targeted movements of the wrist, fingers, and thumb were observed. This was expected: the EyeToy captures larger movements more reliably, meaning that the games were designed to be played with gross reaching motions. In addition, children with hemiplegia have more difficulty with distal compared to proximal movemnts.

A key issue was the Tripp Trapp chair. The chair's size and back angle (recline) of 20 degrees from the vertical made it difficult for some of the participants to sit upright and hold down the switches while performing reaching activities. As well, some participants slid out of the chair as the session progressed. To resolve these issues, an Ethafoam insert[k] was placed on the back of the chair to enable the participants to sit more upright and allow better activation of the thoracic back switch, while a non-slip Dycem mat[l] on the seat of the chair helped the participants to remain seated on the chair. These adaptations may have contributed to a decrease from 3.0 ± 2.7 switch releases/minute of play in the first round to 1.9 ± 1.6 releases/minute in the second round. Interestingly, the participants reported in the child questionnaire that it was more difficult to press the buttons in the second round. This, however, could be because they were more familiar with the system in the second round and were more able to respond to the questions with better insight. Overall, these findings suggest that a differently designed chair with a straight back and a non-slip seat surface may be necessary to improve the usability of the chair and the button switches.

Other issues of effectiveness were identified and addressed in the two rounds of testing. The fingerprint enrolment and recognition generated multiple errors in the first round; these problems were resolved with changes in the software, including lowering the threshold score for fingerprint recognition and clearer user prompts. As well, both rounds of testing involved the use of an infrared transmitter/receiver as opposed to the CK1617A RF device described earlier. Because the infrared transmitter on the chair needed to be in the line-of-sight of the receiver, the screen occasionally disappeared when the transmitter was slightly moved, which accounted for some of the time that the switches were considered “released”. It is anticipated that an RF device, which does not require a direct path to the receiver, will solve this problem.

[k] AliMed, Inc., 297 High Street, Dedham, MA, USA, 02026.
[l] Dycem Limited, Units 2-4, Ashley Hill Trading Estate, Bristol, UK,BS2 9BB

Efficiency

In order for the system to be viable as part of a home-based therapy program, it needs to elicit targeted neuromotor movements at substantial rates. Figure 3.3 illustrates that this occurred with shoulder and elbow reaching activities – participants performed shoulder abduction, for example, an average of 56 times per test session. In the child survey, the statement "I don't feel tired" received a score of 3.1 ± 1.4, which suggests that the physical demands of playing the games were challenging but reasonable. Meanwhile, as figure 3.5 illustrates, the game "Mr. Chef" yielded more movements per minute than "Secret Agent." Some of the participants were very wary of being "spotted" by the spotlights in "Secret Agent" and moved more infrequently as a result. In contrast, the time-limited nature of "Mr. Chef" encouraged higher average rates of movements. Game selection is an important consideration in designing a VR therapy program with this system.

User Satisfaction

Participants and their caregivers reported a high level of satisfaction with the system. In Table 2, the child questionnaire results show that the participants agreed that they had "lots of fun," and "would like to take the video games home to play." In addition, the acceptance among parents and caregivers observing the sessions was also strong. Comments from parents included that it was "a great system to make [child] work" and "a way to make therapy fun." The speed at which some of the screens with text changed and the difficulty of some of the activities were some of the concerns that parents raised. These issues, however, did not appear to prevent the participants from accessing and enjoying the games.

User characteristics that affect usability

As noted in figure 3.5, children with higher baseline function as measured on the QUEST generally had greater rates of targeted movements in the first round of testing. That said, despite the range of QUEST scores, all of the participants were able to play the games, which suggests that the system can accommodate a range of baseline function. A larger sample size is needed in order to determine whether age, experience with playing video games, or other user characteristics are important determinants of system usability as a home-based therapy program.

Limitations and other applications

The camera needs to be positioned at an optimal distance to make the games playable and accessible while still eliciting full-range reaching movements. Along these lines, it is possible to circumvent the system, particularly in unsupervised home settings, by moving the camera and chair closer together. A second limitation of using an off-the-shelf video game system is that the game software cannot be altered, meaning that the games cannot be customized to elicit distal UE movements or to further adjust the difficulty level of playing the games.

Other potential applications of the proposed instrumentation in physical rehabilitation research and practice might include home-based rehabilitation exercise for other populations, including adults. Usage logging and fingerprint recognition might be useful for other forms of computer-based therapy to monitor progress and compliance.

3.3.7. Conclusion

We have described the implementation and usability of a virtual reality therapy system designed for home use for training upper extremity function of children with hemiplegic cerebral palsy. Based on the usability evaluation presented herein, the system is usable by school-aged children with hemiplegia to practice targeted neuromotor movements within an institutional setting. Further study is planned to evaluate usability in the home environment and to investigate the potential for enhancement of specific upper extremity function via a virtual reality therapy program.

Chapter 4

Adaptive Hands-On Interface

This chapter describes the design and implementation of an adaptive hands-on interface. The purpose of the device, as described in Chapter 1, is to promote fine motor activities. The specific goal in this thesis was to design and implement of a working prototype ready for usability testing. First, section 4.1 describes the design and purpose of the overall system. Next, section 4.2 provides details about the physical hardware that the user handles and the electronics that permit interfacing with a personal computer (PC). Third, section 4.3 provides details on the software developed to process the user's inputs through the interface. Finally, section 4.4 examines the software interfaces for the clinician and the child. Additional technical documentation, including CAD drawings, is located in appendix B.

4.1. Overview of System Design

The overall concept of the hands-on interface system fits the overall concept of VR therapy: it provides repetition, feedback, and motivation to encourage the user to practice motor activities. In this case, the system targets distal upper extremity skills, including grip strength, finger individuation, wrist extension, and forearm supination. The hands-on interface is, as described in the literature review, a "mixed-reality" or "fish-tank" system – the user handles certain physical controls that indirectly effect actions in, instead of interacting directly with, the virtual environment that is visible on a screen. By employing hardware and software, the system converts the user's movements into electrical signals that the computer reads. If the signal represents a targeted movement, the software performs a certain action. The user manipulates these controls with his or her hemiplegic UE – once again, a button on the chair occupies his or her non-involved side. As well, fingerprint recognition verifies the identity of the user for tracking purposes. Finally, the system's software is generic in that it is usable with many different computer activities – instead of a custom-developed activity, clinicians can choose any game that normally requires a keyboard to use.

In addition to these basic features, the PC contains software that allows the hands-on interface to accommodate a wide range of abilities and to promote motor improvements. The system can effectively be individualized because the amount of skill required to use each control is specific to each user. Furthermore, the system is "adaptive" because the software contains algorithms that process the input signals from the user and adjusts the difficulty of the task to a level designed to maximize rehabilitation.

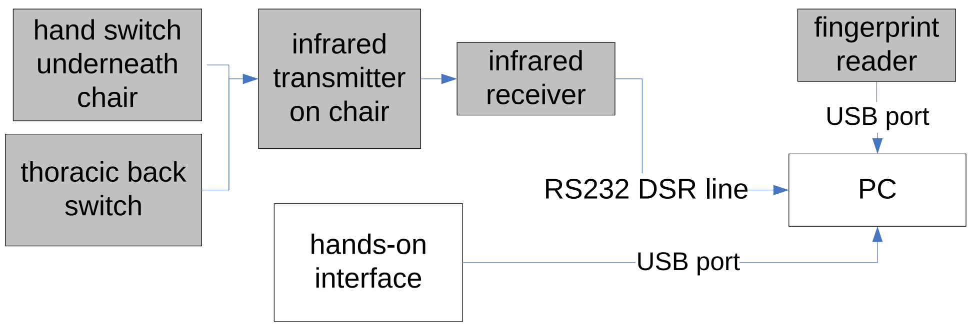

Figure 4.1: Block diagram of hands-on interface VR therapy system. The shaded boxes denote components that are also present in the PS2-E VR therapy system.

4.2. Hardware and Instrumentation

This section describes all of the hardware components that are unique to the adaptive hands-on interface system shown in Figure 4.2. Details on the fingerprint reader and chair system can be found in Chapter 3.

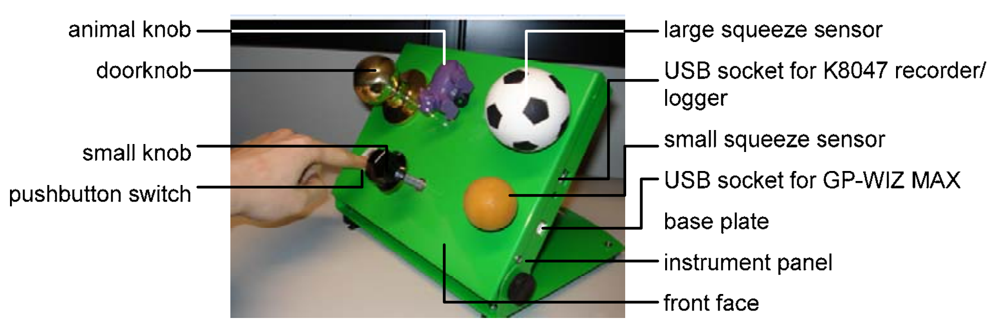

Figure 4.2: Photograph of the hands-on interface system. The user squeezes or turns one of the controls to effect actions in the games.

4.2.1. Metal Enclosure

The metal enclosure was specially manufactured for this device. Detailed measurements and specifications are available in appendix B. The enclosure has three main pieces: a front face with laser-cut holes to accommodate the physical controls that resembles a lid, an instrument panel that provides space for the electronics associated with the physical controls and data acquisition cards, and a base plate that provides stability to the device. The base plate and instrument panel are held together by screws that make the incline of the panel relative to the table surface adjustable: when the screws are loosened, the incline can vary from 0° (completely horizontal) to 90° (normal to the horizontal). Using a wrench, a therapist may adjust the incline of the front panel to promote different degrees of wrist extension for handling the controls. An additional benefit is that, if adjusted to 0°, the device can be carried conveniently with the handle on the base plate. Meanwhile, the metal shell also has generic rubber stoppers that prevent the device from moving while the user manipulates the controls on the front face.

The design allows new types or configurations of controls by replacing the front face with a different one. This feature permits different types or layouts of controls to be used or evaluated with different users to best accommodate their needs. These layouts are possible without replacing the entire device. In addition to possible individualization of the system for different users, any recommended changes to the physical layout of the controls in a future usability study can be implemented quickly.

4.2.2. Hands-on Controls

The hands-on controls are embedded on the front face of the metal enclosure. The hands-on controls are the components that the user manipulates with specific neuromotor movements. They include a doorknob, a small knob, an animal-shaped knob, a pushbutton, a large squeeze sensor, and a small squeeze sensor. Each of these components is described in turn.

Doorknob Control

This control is designed to promote the functional activity of turning a doorknob. A doorknob, such as model number 2002264,[a] is mounted flush to the surface of the front face. Any doorknob used should be spring-loaded (the knob should recoil when turned and released) and have threaded holes to allow the doorknob to be mounted to the back of the panel. Inside the shell, the doorknob is interfaced with a CT2204-ND 5K rotary linear potentiometer in its midpoint position.[b] Due to a constant voltage across the potentiometer, the signal voltage is a function of the angle that the user turns the doorknob. A doorknob can turn approximately 100° clockwise or 100° counter-clockwise; because the potentiometer has a full rotation of approximately 280°, the doorknob's angle can be monitored in both directions.

Small and Animal Knob Controls

The key difference between the doorknob and the small and animal knobs is that the potentiometer is mounted flush to the front face. One identified design problem was that children with hemiplegia might try to circumvent the system by turning this knob with a closed fist, which might be possible if the knob were sufficiently textured. Consequently, a special surplus potentiometer was used: along with a resistance that varies with the turning angle, the potentiometer also features a momentary switch that is closed when the knob slightly into its shaft. Thus, the user must simultaneously push and turn the potentiometer in order to activate it, a requirement that is relatively difficult to achieve without gripping the doorknob. Along with this instrumentation, a knob of any size that the clinician desires may be attached to the potentiometer with a set screw. The animal knob, as shown in Figure 4.2, may be a good starting activity because it has grooves that would make turning it easier. Meanwhile, behind the front face, a constant voltage is supplied to the potentiometer so that the signal voltage varies only with the rotational angle.

[a] RONA Inc., 220 chemin du Tremblay, Boucherville, QC, Canada J4B 8H7
[b] Digi-Key Corporation, 701 Brooks Avenue South, Thief River Falls, MN 56701

Pushbutton Switch

A momentary-closed pushbutton switch encourages finger individuation. The prototype used a surplus switch; however, a series 320.001 switch[c] (Digi-Key part number EG1305-ND) would be suitable. A plastic ring has been glued to the front face so that the switch can only be activated by using a single finger.

Large and Small Squeeze Controls

The squeeze controls require users to practice their grip strength. They use FlexiForce A201-25 single-element load sensors, as shown in Figure 4.4.[d] These sensors are variable resistors whose resistance is inversely proportional to the load on a circular area. Their range of load detection, according to product specifications, is 0lb to 25lb; considering that the active sensing area is 0.375'', this translates into a maximum load of 540N. The sensors are glued inside two sponge balls, one large (7 cm diameter) and one small (2.5 cm diameter), that the user squeezes.

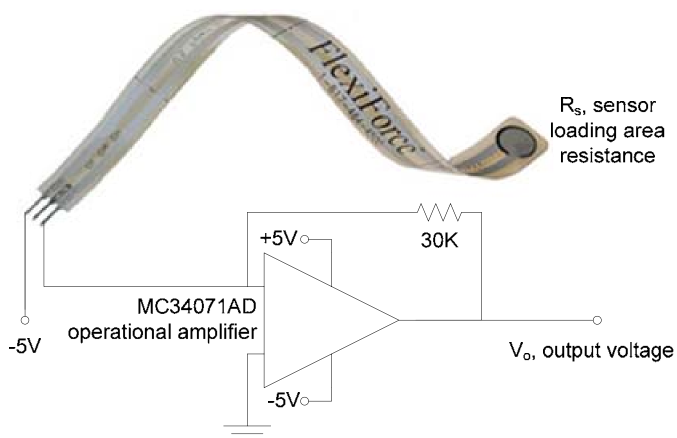

Figure 4.3: FlexiForce single-element load sensor and drive circuit. The resistance of the sensor varies with pressure on the loading area, making it useful for grip force measurements.

[c] E-Switch, Inc., 7153 Northland Drive, Minneapolis, MN 55248
[d] TekScan, Inc., 307 West First Street, South Boston, MA 02127-1309.

To convert the sensor's resistance to a useful signal voltage, an operational amplifier integrated circuit (IC) MC34071[e] is configured as an inverting negative feedback amplifier with an input voltage of -5V, a negative feedback resistance of 30 kΩ, and the sensor as the input resistor. This results in the following relationship:

$$V_o = 5\frac{30k\Omega}{R_s} \tag{4.1}$$

Because R_s is inversely proportional to the applied force, the equation results in a linear relationship between the signal voltage and the user's grip force.

4.2.3. Interfacing with PC

Along with the hands-on interface, a PC is the second main piece of equipment. Two data acquisition cards have been used to interface the PC with the hands-on controls. One of the cards also provides power and constant voltage sources to the controls. The placement of the cards in the hands-on interface can be seen in the drawings in appendix B.

Data Acquisition

The doorknob, small knob, animal knob, large squeeze sensor, and small squeeze sensor convert the user's movements into signal voltages between 0V and 5V. To digitize these four analog signals, a K8047 recorder/logger[f] was selected for its low cost and the availability of software application extensions (DLLs) configured for the device that make PC interfacing straightforward. The K8047 has four channels, meaning that four of these five controls may be connected at once. The sampling rate of 100Hz is sufficient to continuously monitor the signals from these four controls. The analog voltage data is converted to a number between 0 and 255, representing the lowest and maximum voltages that may be recorded. Because all of the data collected from the physical controls fall between 0 and 5V, the 0 to 6V setting of the controller is used. The recorder/logger plugs into a PC via a USB port.

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[e] ON Semiconductor, 5005 East McDowell Road, Phoenix, AZ 85008
[f] Velleman Inc., Legan Heirweg 33, B-9890 Gavere, Belgium

A second card is used specifically for the pushbutton switch. The GP-Wiz MAX 32 Input USB Controls Interface[g] has 32 pairs of screw-terminal input connections. The card is recognized as a human interface device (HID) by a PC. When a pair is shorted, the device sends a signal that the PC interprets as a joystick button press. For the hands-on interface, one pair of the GP-Wiz screw terminals was used for the pushbutton switch – by pressing the button, the user sends a joystick command to the PC. For future expansion involving other controls that only have on/off states, 31 other inputs are available.

Power Supply

Because the power requirements of the devices are low, drawing power from the PC's USB port is sufficient. Conveniently, the GP-WIZ has easily accessible screw terminals representing 0V and 5V. The 5V line is used for providing a reference voltage for the two potentiometers and as the positive voltage source for the grip sensors' operational amplifiers. To obtain the necessary source for the input and negative reference voltages for the grip sensors, a MAX660 inverting charge-pump IC[h] provides a -5V supply from the 5V line. The specific configuration of the application circuit using this IC can be found in appendix B. Overall, by drawing power from the USB port and providing an inverting power supply, the device avoids the need for batteries that could be inconvenient for clinicians and users, especially since the device is intended for home use.

[g] IDVT Inc., 1440 Slaterville Rd., Itacha, NY, USA 14850.
[h] Maxim Semiconductor, 120 San Gabriel Dr, Sunnyvale, CA 94086.

4.3. Software/Adaptive System

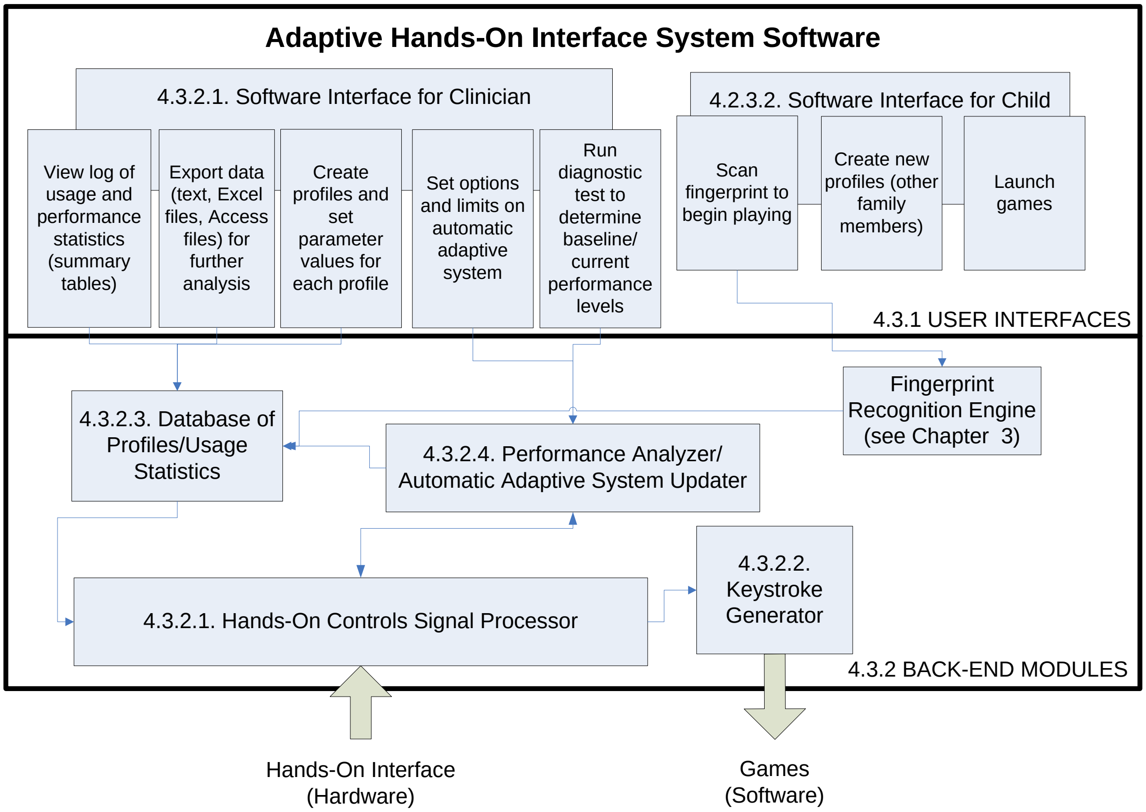

Figure 4.4: Block diagram of software for hands-on interface system. The individual subsystems have been organized into user interfaces and back-end modules.

The hardware provides the digitized voltage signals to the PC. Along with performing movements with the hands-on controls, clinicians and users also interact with software on the PC to set user parameters, play the VR games, and obtain usage data. In addition, the software must process the signals from the hardware – it must have criteria to decide whether the user has performed a targeted neuromotor movement and then effect an action in a computer game. Section 4.3.1 describes the user interfaces for the clinician (4.3.1.1) and the child (4.3.1.2) users. Then, section 4.3.2 examines the technical details and architecture of the back-end modules of the software. Specifically, the adaptive hands-on control's signal processor (4.3.2.1), user database (4.3.2.2), performance analyzer (4.3.2.3) keystroke generator (4.3.2.4) are discussed in depth.

4.3.1. User Interfaces

In explaining the user interfaces, this section offers a high-level overview of how the system software works. All of the interfaces have been written in Visual Basic 6.0 (VB6) using Visual Studio 6.0. A defining characteristic of the user interfaces is that all of the actual games that the user plays are produced by third parties – the software developed for this device processes the signals from the hands-on controls and sends keystrokes to games. This approach eliminates the development time that would otherwise be necessary to create or reinvent computer games that would interest the child. As well, because any computer game can be played, the device may appeal to a wide range of ages and interests.

4.3.1.1. Software Interface for Clinician

Clinicians can use the system to create and edit profiles for different users, set their parameters, and obtain usage data. A typical user scenario might be as follows:

1. In the main menu shown in figure 4.5, the clinician selects "Set User Parameters."

Figure 4.5: Screenshot of main menu for clinician user interface. Selecting one of the four options launches a new form.

2. The clinician launches the program and creates a new profile for a child. The screenshot in figure 4.6 shows the parameters that need to be configured for the

child. As an example, for the small knob, the clinician sets clockwise and counter-clockwise angles that the child should turn to perform activities in the games (A). The "off" or starting position of the knob must also be selected; in this case, it has been set to the "exact middle," which would allow the child to turn the knob clockwise or counter-clockwise (B). Next, the clinician must also decide whether to turn on "automatic updating" (C), in which the software will try to dynamically change the difficulty of the task while the child is playing the game based on his or her performance. If this feature is activated, then the ceiling and floor values (D) need to be set for the control; as well, the amount of playing time between attempted automatic updates (E), and the number of degrees the difficulty will be changed with each update attempt (F). If the clinician does not know the appropriate level of difficulty to set the small knob, he or she may press "Test" (G).

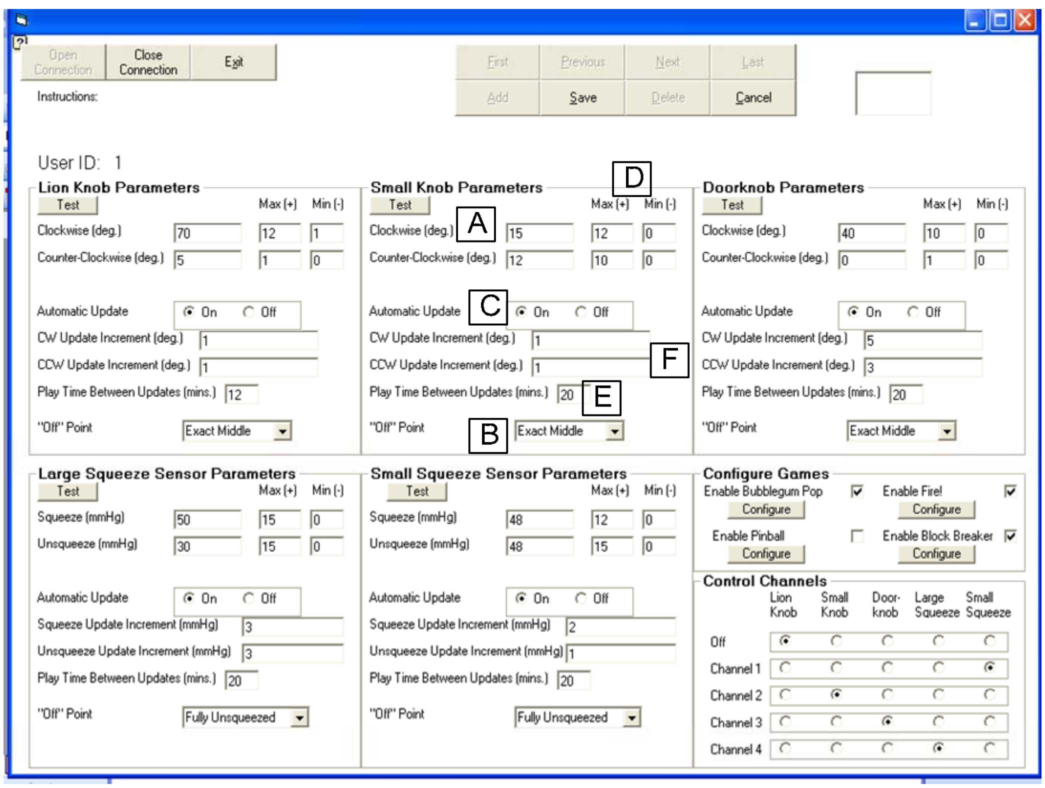

Figure 4.6: Screenshot of interface for clinician to set parameters for each control. The letter labels correspond to description in the paragraph below.

3. In the test menu screens, the software records the performance of the user in step-by-step tests. The intended way to use this feature is to have the child complete the tests while being supervised by a therapist. Continuing with the small knob example, the software will ask the child to turn the knob clockwise and counter-clockwise as far as possible with his or her hemiplegic hand. The angles will be measured by the software and be set as the parameters for the small knob in the games. A therapist may have adopt these values as the user parameters, have the child repeat the test, or overrule the angles determined by the software.

4. In addition to setting the difficulty of each control, the clinician also sets which games the child may play and the controls that are used within each game. In Figure 4.6, possible games include “Pinball,” “Bubblegum Pop,” “Fire,” and Block Breaker.” Separate menu screens appear to test out these games with the selected controls and to make any changes.

5. After the child has used the system for at least one session, the clinician may select “Usage Statistics” or “Export User Statistics” from the main screen in Figure 4.5. In the currently developed version of the software, these commands simply display or export the raw numerical data of the child’s activities with the physical controls is exported to another program. Each line of data contains the date and time, the game being played, and the particular signal voltage value at that instant. Other events that may also be viewed include fingerprint recognition, successfully generated keystrokes, or program errors.

4.3.1.2. Software Interface for Child

The child using the system in a home setting has a simplified user interface that can only launch games. Only the games that the clinician has enabled for the child are visible. The graphic associated with each game corresponds to the physical control that has been configured to play that game.

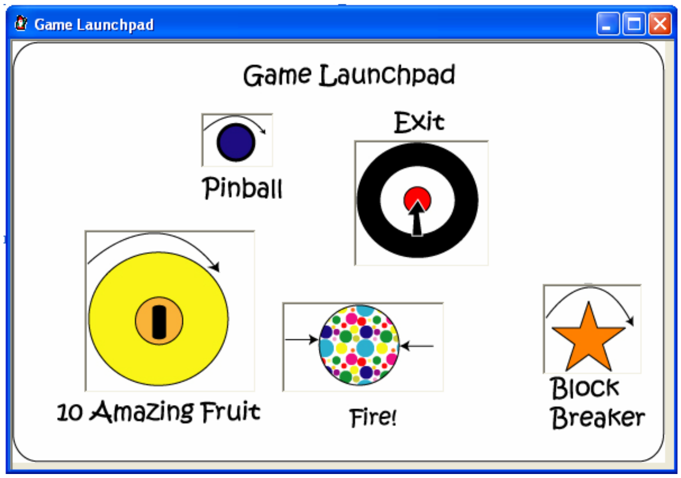

Figure 4.7: User interface for child. The only options that the child has are to start games and exit the program.

Upon selecting a game, the game launches, and the child plays by manipulating the pre-set physical control. For example, in Pinball (figure 4.8), the right paddle may be activated by turning the small knob clockwise, while the left paddle may be activated by turning it counter-clockwise.

Figure 4.8: Screenshot of Pinball. This game is among many that may be used with the hands-on interface because it typically uses keyboard inputs.

4.3.2. Back-End Modules

This section provides the technical details of how the system software works. It is intended to provide a level of understanding of the software architecture that makes it possible to debug or make future improvements to the code. The software, as shown in Figure 4.4, is divided into modules that interact with each other. They are described in order below. Once again, all of the modules have been created in VB6.

4.3.2.1. Hands-On Control Signal Processor

The signals from the K8047 recorder/logger need to be read and processed by the software. Specifically, the signal processor determines whether the signal should result in the generation of a keystroke. As well, it logs all of the input signals for later analysis by clinicians. Fundamentally, each of the controls of the hands-on interface has a small number of properties that determine how input signals are processed. First, to obtain the data, a timer control in VB6 continuously polls the appropriate channels of the recorder/logger. Then, the captured data is compared to the criteria set by the clinician.

The physical controls are represented in the software as instantiations of a VB6 class module (the VB6 equivalent of classes in object-oriented languages such as C++) called ‘Control.cls.’ For every different user, therefore, each of the grip sensors and knobs are objects of type ‘Control’. The data members of the ‘Control’ class and their meaning in the two types are controls are listed in Table 5.1. Each ‘Control’ includes a continuously monitored measurement (the incoming signal from the corresponding physical control), the thresholds for generating keystrokes that may also be subject to dynamic modification, and permissible ranges of values, frequencies, and directions of change of the parameters.

While the games are being played, the “SignalProcessor()” function continuously compares “SignalValue” to “ThresholdValueHigh” and “ThresholdValueLow” to decide whether to call the keystroke generator, which is described below. The specific relationship between “SignalValue” and the thresholds that generates a keystroke depends on the “OffPoint,” which is the value of the voltage signal of the physical control in its natural position. For example, the doorknob’s “OffPoint” is usually halfway between the “ThresholdValueHigh” and “:ThresholdValueLow.” Consequently, the

"SignalValue" should be *greater than* the "ThresholdValueHigh" and *less than* the "ThresholdValueLow" for keystrokes to be generated. In contrast, the squeeze sensor is usually set with an "OffPoint" equalling 0; thus, if the clinician wants a certain grip force to translate into one keystroke and a second, stronger force into another keystroke, then "SignalValue" should be *greater than* "ThresholdValueLow" and *greater than* "ThresholdValueHigh." These algorithms are implemented as condition statements in the "SignalProcessor()" function.

Table 4.1: Members of 'Control' class module

<table>
<tr><th>Declaration</th><th>Role</th><th colspan="2">Implementation with Knobs</th><th>Implementation with Grip Sensors</th></tr>
<tr><td>Public SignalValue As Integer</td><td>Continuously monitored measurement</td><td colspan="2">Angle of knob</td><td>Grip pressure applied on sensor</td></tr>
<tr><td>Public MidValue As Integer</td><td>Off point</td><td colspan="2">Reference zero point – exact middle, 0 or maximum voltage value</td><td>Reference zero point – usually 0</td></tr>
<tr><td>Private ThresholdLow As Integer</td><td rowspan="2">Parameters eligible for dynamic modification</td><td colspan="2">Counter-clockwise rotation angle</td><td>Primary force requirement</td></tr>
<tr><td>Private ThresholdHigh As Integer</td><td colspan="2">Clockwise rotation angle</td><td>Secondary force requirement</td></tr>
<tr><td>Public ThresholdLowKey As String</td><td rowspan="2">Action in games</td><td colspan="2">Keystroke generated with CCW rotation</td><td>Keystroke generated with primary force applied</td></tr>
<tr><td>Public ThresholdHighKey As String</td><td colspan="2">Keystroke generated with CW rotation</td><td>Keystroke generated with secondary force applied</td></tr>
<tr><td>Private ThresholdHighMinus As Integer</td><td rowspan="4">Clinician-imposed limitations on extent to which system can self-adapt</td><td colspan="2">Max. decrease of CW rotation</td><td>Max. decrease of secondary force</td></tr>
<tr><td>Private ThresholdHighPlus As Integer</td><td colspan="2">Max. increase of CW rotation</td><td>Max. increase of secondary force</td></tr>
<tr><td>Private ThresholdLowMinus As Integer</td><td colspan="2">Max. increase of CCW rotation</td><td>Max. decrease of primary force</td></tr>
<tr><td>Private ThresholdLowPlus As Integer</td><td colspan="2">Max. decrease of CCW rotation</td><td>Max. increase of primary force</td></tr>
<tr><td>Private UpdateFrequency As Integer</td><td rowspan="3">Permissible ranges of values, frequency, and magnitude and directions of changes that the system can automatically update</td><td colspan="3">Time before update is attempted</td></tr>
<tr><td>Private ThresholdHighUpdateIncrement As Integer</td><td>Change in CW rotation angle with every successful automatic update</td><td colspan="2">Change in secondary grip force with every successful automatic update</td></tr>
<tr><td>Private ThresholdLowUpdateIncrement As Integer</td><td>Change in CCW rotation angle with every successful automatic update</td><td colspan="2">Change in primary grip force with every successful automatic update</td></tr>
<tr><td>Public Channel As Integer</td><td colspan="4">Channel corresponding to control</td></tr>
<tr><td>Public EnableUpdate As Boolean</td><td colspan="4">Activation of self-adapting system</td></tr>
<tr><td>Public Sub SignalProcessor()</td><td colspan="4">Determination of whether a keystroke should be generated</td></tr>
</table>

4.3.2.2. Keystroke Generator

Closely related to the signal processor is the signal processor is the keystroke generator. The VB6 'SendKey' command is used to generate a keyboard event in the Windows environment. The function obtains the specific keys that should be activated from the "ThresholdHighKey" and "ThresholdLowKey" data members in 'Control.cls.' Then, when commanded by the signal processor, the 'SendKey' function sends a keystroke to the active window, which is the game being played by the child.

4.3.2.3. Database of Profiles/User Statistics

The user parameters and the data collected in each play session are stored in an Access[i] database. The database interfaces with the VB6 modules using ActiveX Data Objects (ADO). The database contains two tables: First, the "UserStats" table contains all of the user parameters set by clinician or changed by the self-adapting software. For the clinician, these parameters are loaded into the form in figure 4.6 for viewing and editing; for the child, they are loaded in the background at the start of each play session to serve as reference values for the signal processor. Second, an "Events" file time-stamps and logs all of the continuously monitored signal values from the hands-on controls, keystrokes that are generated, games that are selected, and fingerprint recognition events, and changes to the parameters made by the adaptive system. Because of each different type of event is given an numerical classification identifier, clinicians or researchers can make queries to the database to obtain only certain types of events depending on their needs.

4.3.2.4. Performance Analyzer/Adaptive System Updater

The performance analyzer is the decision engine for the adaptive system. As shown in figure 4.4, it takes inputs from the signal processor and the user database to decide whether the parameters that govern the difficulty level of using each control should be changed. It can potentially have access to all of the current and past usage data of the child as well as the settings made by the clinician. It is limited by the restrictions set by the clinician described in section 4.3.1.1. Changes by the adaptive system updater might occur over short or long time scales. Evidently, this module has the potential to

[i] Microsoft Corporation, 1 Microsoft Way, Redmond, WA 98052-6399.

integrate large amounts of information into decisions about changes to the difficulty level of the physical controls; it might account for fatigue, short- or long-term improvements, or any other features that can be extracted from the signals from the hands-on controls.

In the absence of literature on how to promote rehabilitation using this type of setup most effectively, however, a simple algorithm has been adopted for this initial development in consultation with clinicians. After 20 minutes of play, the adaptive system automatically tries to automatically update the parameters. In a two-minute "transient" period, the software logs the number of successful keystrokes under the new parameters. It also records the number of attempts that would have been successful under the old parameters but not the new ones. If the success rate exceeds 90%, then the new parameters become permanent; if not, then the parameters revert to their previous values. The system performs these changes without notifying the child so that he or she is less likely to circumvent this mechanism. Overall, this approach, while unproven, is a starting point that may be tested in a usability study with the device.

Chapter 5

Conclusions

This section summarizes the contributions of this thesis to the development and evaluation of a VR therapy system for children with hemiplegic cerebral palsy. Secondly, it outlines the limitations of the findings and the further work necessary to advance the work presented.

5.1 Contributions

This thesis documents the following research work completed in support of a new low-cost VR therapy system designed for home use:

1. A novel VR therapy system was designed and implemented using a PlayStation 2 with EyeToy (PS2-E) and associated electronics. Along with the video game system, a chair system to encourage the use of the hemiplegic UE and a fingerprint recognition system to monitor usage was developed and implemented.

2. The PS2-E with the chair system was shown, in tests with five children with hemiplegia, to promote targeted neuromotor movements of the proximal UE with effectiveness, efficiency, and user satisfaction. These findings have been submitted to a peer-reviewed conference and journal.

3. The hardware and software of an adaptive hands-on interface VR therapy system were designed and implemented. This system complements the PS2-E by focusing on more distal movements of the UE. The system incorporates a framework to be able to analyze the input signals from the user's performance and dynamically adjust the challenge associated with the therapy activities, with the intent of maximizing rehabilitation outcomes. It also proposes to reuse the chair and fingerprint recognition components of the PS2-E system.

5.2 Limitations and Further Work

While some contributions have been made, more work needs to be done for these devices to become useful technologies for clinicians who treat children with hemiplegia:

1. The PS2-E system needs to be further evaluated with the design changes recommended from the two rounds of testing. In particular, a different chair design may help to promote good posture while playing the games. Studies that involve using the system in actual home settings and investigating its potential to enhance specific upper extremity function are warranted.

2. Further technical development of the adaptive hands-on interface would help to improve its robustness and usability. It may be useful to characterize the precision and reliability of each of the hands-on controls for signal drift, hysteresis, and sensitivity over prolonged use to determine whether this might have any negative effect on the usability of the system. In terms of software, the signal processor and keystroke generator must be tested with any game proposed for use with the system in order to ensure that the keys are generated correctly and with sufficient speed. Meanwhile, additional features in the software, such as an easy way for clinicians to add a game to the possible choices for the child, would be desirable.

3. The adaptive hands-on interface needs to be tested for usability with children with hemiplegia. As discussed in Chapter 3, the testing of the PS2-E with the actual intended revealed numerous issues that were not previously detected. As a completely novel device not based on an off-the-shelf video game system, there may be even more issues identified by the usability testing.

4. Improvements to the adaptive system module of the hands-on interface may be driven by data collected from actual users. This is a major challenge because many factors need to be taken into account. For example, what criteria should it consider before making a change to the difficulty of the controls? How much weight should the system place on data collected very recently, and how much should it account for, or neglect, data from previous days, weeks, or months? These are not simple questions; however, clinical expertise and actual testing with patients may help to answer them. Inspiration may also be drawn from

theories and methods of nonstationary data analysis. For the type of data being collected, the detection of regime shifts (statistically significant change of model parameters) will most likely be the main approach, although other approaches can be tried. The work done on this part of the project may be applicable into other research currently being done in intelligent systems for rehabilitation.

Overall, more research remains to evaluate the usefulness of the devices developed as part this VR therapy system. This thesis has provided the technical groundwork and some evidence of usability that supports the further investigation of VR therapy for children with hemiplegic cerebral palsy.

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Appendix A

PlayStation 2 with EyeToy Documents

A.1. Circuitry for Video Switching

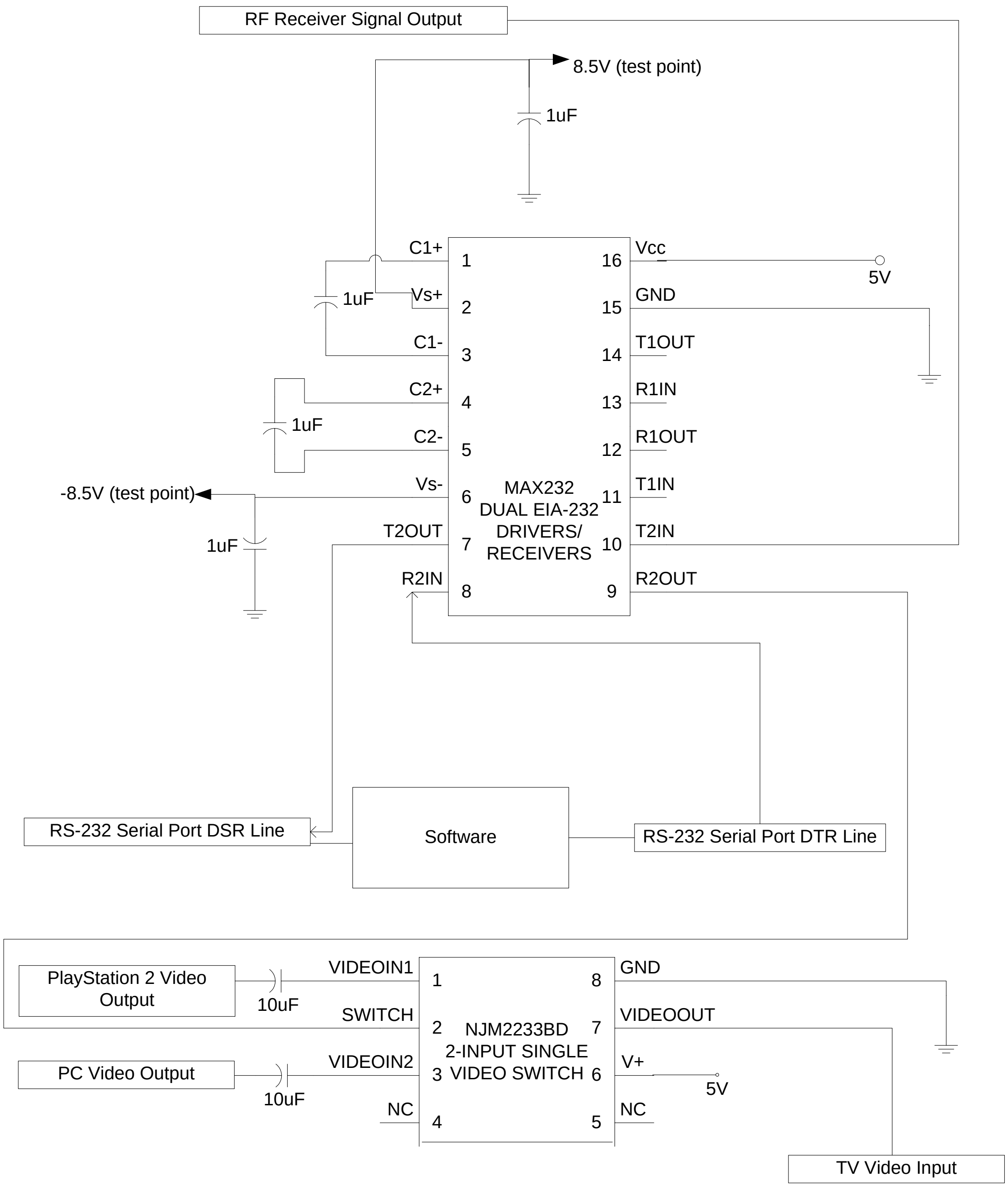


Figure A.1: Detailed circuit diagram for PS2-E VR therapy system video switching. Power and ground are supplied through the PC.

A.2. Study Forms

The following pages are the approved forms that were administered to evaluate the usability of the PS2-E VR therapy system. They include forms completed by the research occupational therapist and the caregiver and child at the usability test sessions.

CLIENT DEMOGRAPHICS FORM

Study ID No.____________ Chart No. ______________________ Phone No. ______________________

Age ____________ Gender ☐ M ☐ F

Side of Involvement _______________

Caregiver attending ☐ Mother ☐ Father ☐ Other (specify) ______________________________________

Assistive Technology used (e.g. powered wheelchair, walker) ______________________________

____

Communication ☐ Verbal ☐ Non-verbal

Method of indicating yes/no ____

Computer Use ☐ Communication Aid ☐ School ☐ Home

Previous Video Game Use ☐ PlayStation 2 ☐ Other

____

Standard Assessment Test Scores (documented previously by OT)

House Classification ____

Quality of Upper Extremity Skills Test (QUEST)____

Grip Strength ________________

Sensory Testing ____

PROM ____

AROM ____

Cooperativeness (from QUEST) ____

Medical

Primary Diagnosis ____

Vision ____

Hearing status ____

Perceptual motor status ____

Name of care providers ____

____

____

Treatment types ☐ Occupational Therapy No. times per week ___________________________

☐ Physical Therapy No. times per week ___________________________

☐ Speech Therapy No. times per week ___________________________

OBSERVATION CHECKLIST FOR TARGETED NEUROMOTOR MOVEMENTS – TO BE COMPLETED BY OCCUPATIONAL THERAPIST

Study ID No. ____

Age ____

No. of Sessions Attended __________

Overall Assessment
The child appeared engaged in the game situations.

Strongly disagree   Disagree   Neither agree or disagree   Agree   Strongly agree

Which game was most appropriate for promoting targeted neuromotor movements?

Secret Agent   Mr. Chef

What would make the setup more conducive to promoting targeted neuromotor movements for this child? (Circle all that apply)

Child closer to camera	Brighter lighting conditions
Child further from camera	Darker lighting conditions
Child higher on screen	Games easier to understand cognitively
Child lower on screen	Other ___________________________
Physically more challenging games	
Physically easier games	

Other Comments:

____

____

____

____

Setup Screens

DESIRED MOVEMENT	**OBSERVED (√ if yes)**	**<=1/2 range**	**>= 1/2 range**	**COMMENTS**
Shoulder Flexion				
Shoulder Abduction				
Shoulder Extension				
Reach Across Midline				
Elbow Extension				
Forearm Supination				
Wrist Extension				
Finger Extension				
Thumb Abduction				
Thumb Extension				
Thumb Opposition				

General Comments:

“Secret Agent”

DESIRED MOVEMENT	**OBSERVED (√ if yes)**	**<=1/2 range**	**>= 1/2 range**	**COMMENTS**
Shoulder Flexion				
Shoulder Abduction				
Shoulder Extension				
Reach Across Midline				
Elbow Extension				
Forearm Supination				
Wrist Extension				
Finger Extension				
Thumb Abduction				
Thumb Extension				
Thumb Opposition				

General Comments:

"Mr. Chef"

DESIRED MOVEMENT	**OBSERVED (√ if yes)**	**<=1/2 range**	**>= 1/2 range**	**COMMENTS**
Shoulder Flexion				
Shoulder Abduction				
Shoulder Extension				
Reach Across Midline				
Elbow Extension				
Forearm Supination				
Wrist Extension				
Finger Extension				
Thumb Abduction				
Thumb Extension				
Thumb Opposition				

General Comments:

CHILD QUESTIONNAIRE
"Virtual reality therapy"

The therapist will ask these questions orally and record the child's answers.

Study ID No. ______ No. of Sessions ________________ Date ______________

Pre-Test

Rate the following from 1 to 5, with 5 being the strongly agree and 1 being strongly disagree.

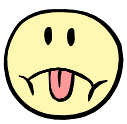
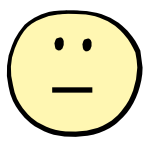
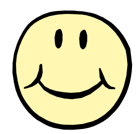
1. I play video or computer games often.

Never	Rarely	Once/week	A few times/week	Every day
1	2	3	4	5

2. I enjoy playing video or computer games.

1	2	3	4	5
Don't enjoy				Enjoy very much

Post-Test

3. I had lots of fun today.

1	2	3	4	5
No fun				Lots of fun

4. I don't feel tired.

1	2	3	4	5
Very tired				Not tired at all

5. I had fun playing "Secret Agent"

1	2	3	4	5
No fun				Lots of fun

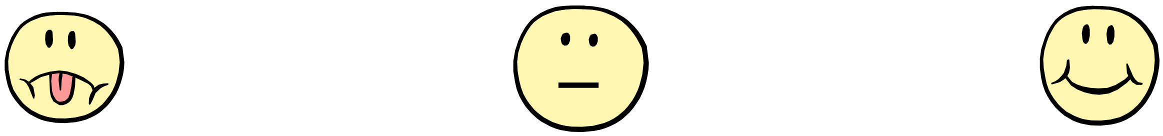
6. I had fun playing "Mr. Chef"?

1	2	3	4	5
No fun				Lots of fun

1. What did you like most about playing the games today?

2. What did you like least about playing the games today?

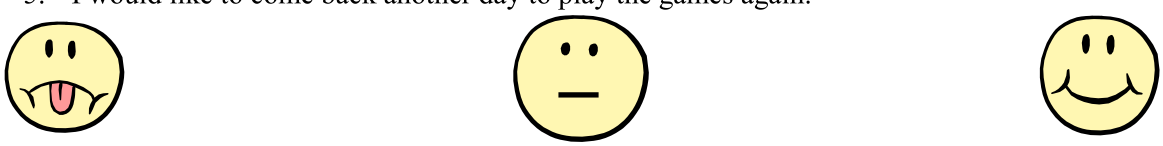
3. How hard was it to hold down the buttons on the chair?



1	2	3	4	5
Very hard	Hard	Neither easy nor hard	Easy	Very easy

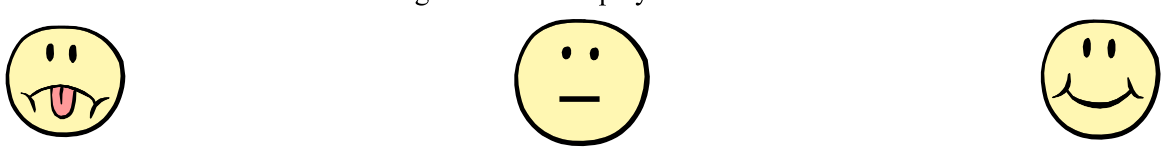
4. Was there anything you didn't understand while playing the games?

5. I would like to come back another day to play the games again.



1	2	3	4	5
Strongly disagree				Strongly agree

6. I would like to take the video games home to play.



1	2	3	4	5
Strongly disagree				Strongly agree

PARENT QUESTIONNAIRE
“Virtual reality therapy”

Study ID No. __________ No. of Sessions Attended _____________ Date _______________________

Read the statement. Circle the response that is most true for you.

1. Scanning my child’s fingerprint, putting in the disc, and turning the system on was easy.

   Strongly disagree   Disagree   Neither agree or disagree   Agree   Strongly agree

2. I would feel confident doing the setup I did today at home.

   Strongly disagree   Disagree   Neither agree or disagree   Agree   Strongly agree

3. Another family member or I would feel confident setting up the entire system (PlayStation, computer, and transmitter) out of the box.

   Strongly disagree   Disagree   Neither agree or disagree   Agree   Strongly agree

4. Do you have a computer at home?   YES   NO

5. Does your child play computer or video games at home?   YES   NO

   a. If YES, what computer/video game systems does s/he play with? Circle all that apply.

      Computer (running Windows)   Computer (MacIntosh)

      Sony PlayStation 2   Sony PlayStation 2 with EyeToy

      Sony PlayStation One   Microsoft XBox

      Nintendo GameCube   Microsoft XBox 360

      Nintendo 64   Game Boy Advance

      Super Nintendo   Game Boy DS

      Sony PSP   Sega DreamCast

      Other (please specify) ___________________________

   b. If YES, what are the names of some computer/video games he or she likes to play?

   ____

   ____

Read the statement. Circle the response that is most true for you.

1. My child would enjoy using this virtual reality therapy system at home.

Strongly disagree Disagree Neither agree or disagree Agree Strongly agree

2. Other family members at home would enjoy playing with this system for fun.

Strongly disagree Disagree Neither agree or disagree Agree Strongly agree

3. I think that my child would practice therapy activities every day with this system at home.

Strongly disagree Disagree Neither agree or disagree Agree Strongly agree

4. I would like my child to return for another session.

Strongly disagree Disagree Neither agree or disagree Agree Strongly agree

5. I would like to have this system at home.

Strongly disagree Disagree Neither agree or disagree Agree Strongly agree

6. I would allow my child to use the system daily as a therapy activity.

Strongly disagree Disagree Neither agree or disagree Agree Strongly agree

7. I would recommend this system to a friend.

Strongly disagree Disagree Neither agree or disagree Agree Strongly agree

8. I think that "Secret Agent" is an age appropriate game for my child.

Strongly disagree Disagree Neither agree or disagree Agree Strongly agree

9. I think that "Mr. Chef" is an age appropriate game for my child.

Strongly disagree Disagree Neither agree or disagree Agree Strongly agree

10. What should change about the system to make it more suitable for your child and your family?

____

____

____

____

11. Please share any other comments about the video game system.

____

____

____

VIDEO REVIEW CHECKLIST

Name of Reviewer: ______________________________ Date: ____________________

Client No.

Session (check one) ____ 1st ______ 2nd

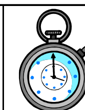
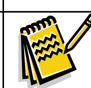
System Evaluation

Did the fingerprint recognition system work properly?	**Y** ☐ **N** ☐	
If "No," what problems occurred with the fingerprint recognition system?		
Did the wireless pushbuttons work properly?	**Y** ☐ **N** ☐	
If "No," what problems occurred with the wireless pushbuttons?		
Was the child able to "cheat" to avoid or minimize use of the hemiplegic involved side? If "Yes", what did he or she do?	**Y** ☐ **N** ☐	
How much time was required to adjust the setup for the particular child (i.e. move the chair, adjust the pushbutton switches)?		
What errors made by the caregiver were subsequently self-corrected?		

What errors made by the caregiver required external intervention to solve?		
How many times did the system need to be reset?		

Setup/Play Evaluation

1. Caregiver Setup Segment

Did the caregiver use the official Sony PlayStation 2 official manual?	**Y** ☐ **N** ☐	
How much time was spent on the setup (inserting the DVD, fingerprint registration)?		
What errors made by the caregiver were **subsequently self-corrected**?		
What errors made by the caregiver required **external intervention** to solve?		
What **positive comments** did the caregiver make about the setup process?		

What **negative comments** did the caregiver make about the setup process?		

2. Initial Instructions to Child

How much time was spent giving initial **instructions**?		

3. Guide Through Startup Segment

During the guide through setup, how many times:

does the child **intentionally** activate the system (i.e. choose the right menu option)?		
does the child **inadvertently** activate the system (i.e. choose the wrong menu option)?		
does the **system not respond** to the child's movements?		
does the child **seek interaction/guidance** from the therapist?		
does the child **need** to be given **instruction** on or reminded about how to activate the system?		

4. "Secret Agent" Segment

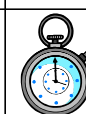
During "Secret Agent:

What **parts of the body** were used to activate the system?		
What was the **total duration** of the activity?		

How many levels did the child **complete**? 1 – “Equipment” 2 – “Rope” 3 – “Keys” 4 – “Coloured locks” 5 – “Alarm” 6 – “Disguises”		
Did the child understand that they were not allowed to move in the “hot spots” on the screen?	Y ☐ N ☐ Not sure ☐	
Was the child able to even begin playing the game?	Y ☐ N ☐	

5. “Mr. Chef” Segment

During “Mr. Chef”:

What are the **parts of the body** used to activate the system?		
What was the **total duration** of the activity?		
How many levels did the child **complete**? 1 – “2 meals done” 2 – “Milkshakes” 3 – “Cook-off #1” 4 – “6 meals done” 5 – “8 meals done” 6 – “Ice cubes” 7 – “Cook-off #2”		
Did the child **comprehend** the order-filling part of the game?	Y ☐ N ☐	
Was the child able to even begin playing the game?	Y ☐ N ☐	

6. End notes

Did the child successfully complete all the activities of the session? **Y ☐ N ☐**

Did the child voluntarily express fatigue verbally during or after the session? Y ☐ N ☐

Appendix B

Adaptive Hands-On Interface Documents

B.1. Circuitry for Negative Power Supply from PC

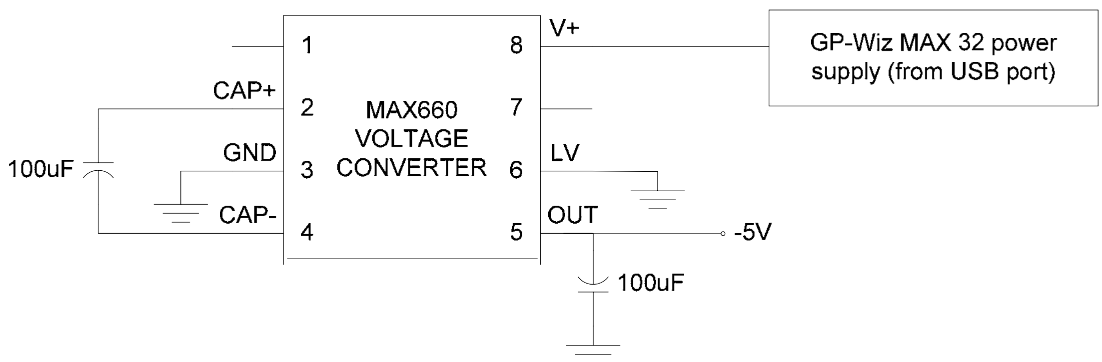


Figure B.1: Detailed circuit diagram of negative power supply for adaptive hands-on interface. The +5V from the GP-Wiz MAX 32 results in a -5V output from the MAX660.

B.2. Adaptive Hands-On Interface: CAD Drawings

The following pages feature the CAD drawings of the adaptive hands-on interface system.

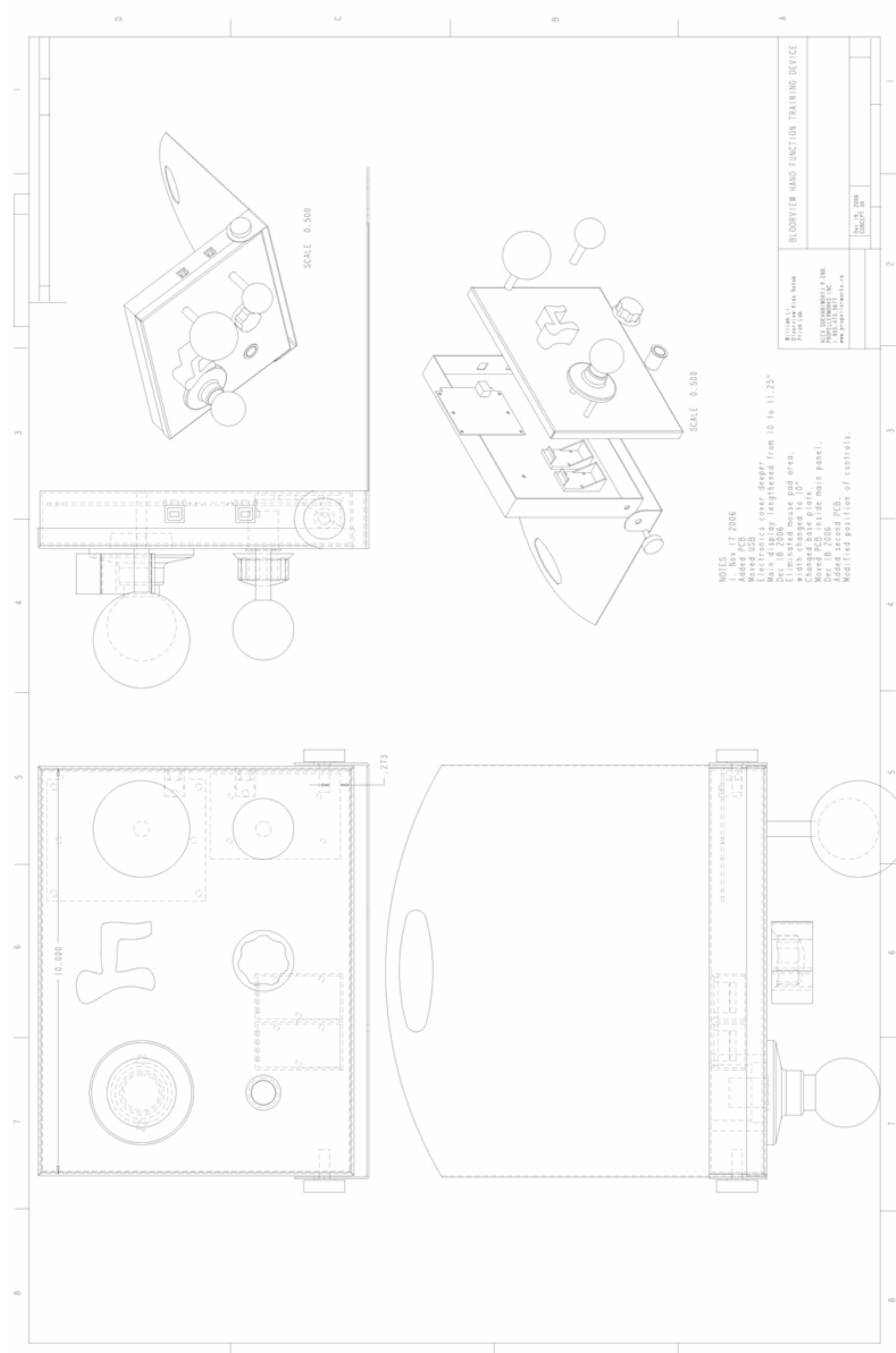


Figure B.2: CAD drawing of adaptive hands-on interface with four views. The instrument panel has space for two 9V batteries; however, these are not necessary because power is supplied from the PC.

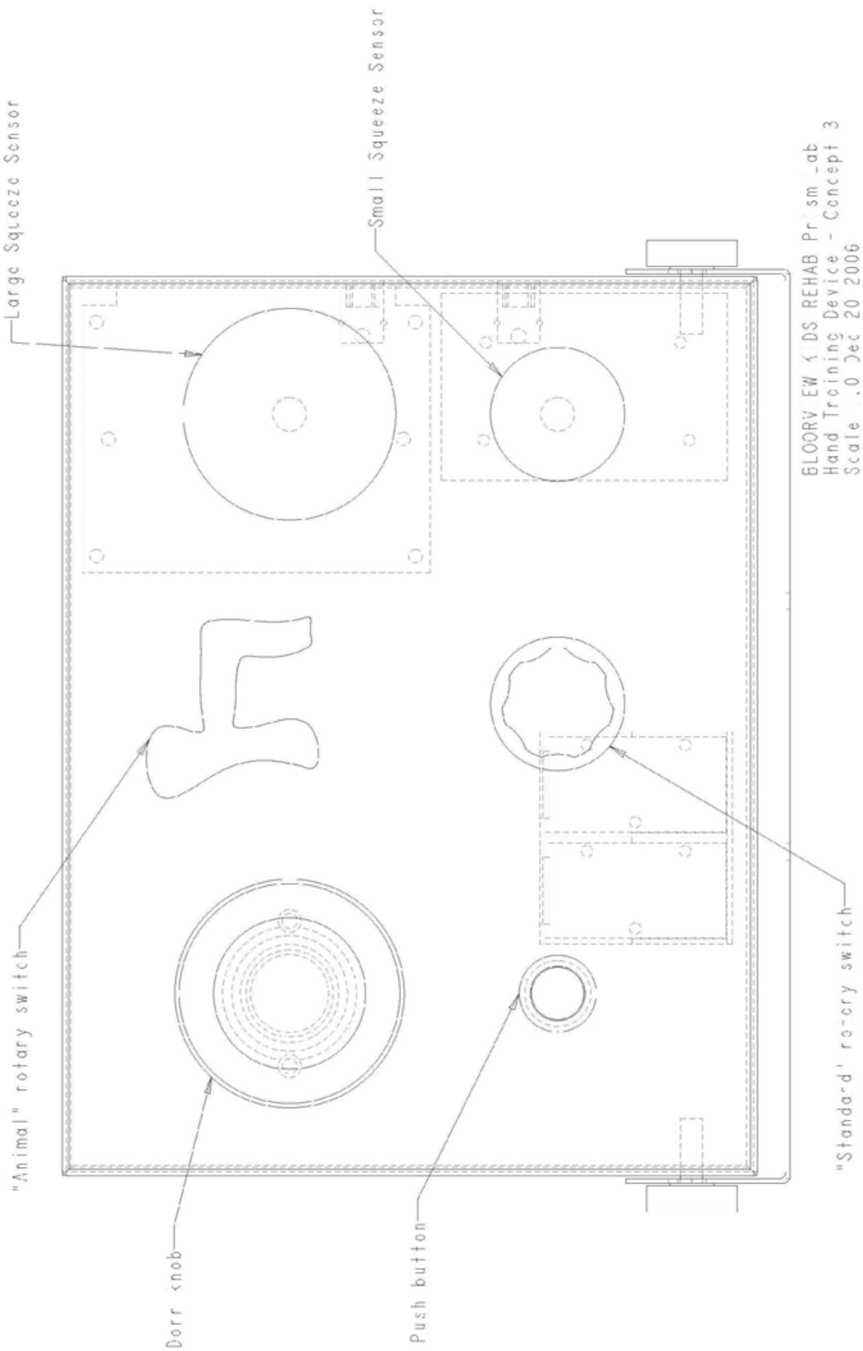


Figure B.3: Layout of physical controls on front face of adaptive hands-on interface.

Appendix C

Directory of Additional Documentation

Supporting documentation, software code, and other relevant files are located in the "VR Therapy" in the Bloorview Research Institute network directory. Access is restricted to study investigators. As of April 8, 2007, the names and organization of subdirectories was as follows:

- VR Therapy
  - Publications
    - APMR
    - CMBES
    - ICUE2007
    - AACPDM
    - BASc Thesis
  - PlayStation Study
    - Study Submissions to BRI
    - Approved Forms
    - Study Data
    - Software Code
    - Other Technical Documents
  - Adaptive Hands on Interface
    - Software Code
    - Technical Documents
  - Meetings and Minutes