ASSESSING THE POTENTIAL UTILITY OF A VIRTUAL AND MIXED/AUGMENTED REALITY SYSTEM TO ASSIST IN STROKE REHABILITATION

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Dedication

I would like to dedicate this Thesis to Dr. Jill Bolte Taylor. She is a brilliant scientist and extremely dedicated woman who has greatly contributed to the field of neuroscience and biology. She experienced a stroke and had the willpower and courage to fully recover and begin teaching again at Indiana University. Dr. Taylor's idea for this project is brilliant, and I could not have written and completed this without her perpetual support and drive. Thank you Dr. Taylor.

Acknowledgements

I would like to acknowledge Sonny Kirkley. Sonny is the co-founder and CEO of Information in Place. Besides aiding me with the technical side of this project, he played a major role in every step. I deeply appreciate what he has done for me, and hope my Thesis will help progress his internal research and company project.

Last, but certainly not least, I would like to thank Dr. Anna McDaniel, who has been with me since the commencement of my graduate program. Anna, thank you for guiding me through my graduate studies, aiding me with advice and always being available for help!

Abstract

Stroke is the number one cause of disability in the United States. This thesis summarizes current techniques and technologies for stroke rehabilitation and in addition, describes a revolutionary new concept and rehabilitation system, Visually Directed Intention (VDI), created by Dr. Jill Bolte Taylor (Indiana University). The purpose of this research is to determine the feasibility and potential of her system through comparative research and expert opinion.

Dr. Taylor's rehabilitation system harnesses several technologies such as mixed reality, biofeedback, and game-like environments. Key concepts such as visualization, intention, motivation and repetition are also pivotal to her ideology. Specifically the system uses biofeedback, viewed through a mixed reality headset to motivate a user to utilize nerves and muscles he/she may have lost through experiencing a stroke.

In order to properly identify and analyze current methods used in stroke rehabilitation, several subject matter experts (SME) at the University of Chicago's Rehabilitation Institute of Chicago (RIC) were interviewed. The SME provided useful critique on current stroke rehabilitation techniques, technologies and Dr. Taylor's innovative concept. Through a general qualitative interview, examining the SMEs research and actually experimenting with some of their technologies, meaningful insight into expert opinions on stroke rehabilitation technologies was obtained.

After several detailed interviews at the RIC, the experts agreed that VDI is noble concept and has great potential. Although they had some specific comments about how to properly utilize the technologies involved, overall they believe the system encompasses

several exciting and motivating features that will significantly improve the rehabilitation process.

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CHAPTER ONE: INTRODUCTION

Introduction to subject

Stroke is the number one cause of disability in the United States. "Each year about 750,000 people experience a new or recurrent stroke. About 500,000 of these are first attacks, and 200,000 are recurrent attacks" (AHA, 2005 p 3). Of the 750,000 strokes, 400,000 (53%) of these people survive with varying degrees of disability (Duncan, 1998).

Stroke occurs when a clogged or burst artery interrupts blood flow to the brain. This interruption of blood flow deprives the brain of needed oxygen and causes the affected brain cells to die. When brain cells die, the functions of the body parts they control are impaired or lost. A stroke can cause paralysis or muscle weakness, loss of feeling, speech and language problems, memory and reasoning problems, swallowing difficulties, problems of vision and visual perception, coma, and even death (American Speech, Language, and Hearing Association, 2005).

Because of how the nervous system is organized, an injury to one side of the brain, affects the opposite side of the body's motor and sensory abilities. Stroke survivors often have difficulties adjusting to daily tasks of living due to this situation also known as hemiparesis (partial weakness). Listed below are a few stroke statistics that give further insight into the effects and severities of a stroke.

- 10 percent of stroke survivors recover almost completely.
- 25 percent of stroke survivors recover with minor impairments.
- 40 percent of stroke survivors experience moderate to severe impairments requiring special care.
- 15 percent die shortly after the stroke
- 10 percent of stroke survivors require long term care in a nursing home or other long-term care facility.

Depending on the severity of the stroke, post-treatment options include:

- A rehabilitation unit in the hospital
- A sub acute care unit
- A rehabilitation hospital
- Home with in-home therapy
- Home with outpatient therapy
- A long-term care facility that provides therapy and skilled nursing care

(University Hospital Network 2005)

Importance of subject

The 57% of people who survive strokes have a vast need for rehabilitation. Because their need for care ranges from home to intensive hospital care it is difficult to establish a single schedule for these people.

It is important that stroke survivors participate in rehabilitation on their own schedule. Attempting to relearn how to live and complete simple daily tasks requires a great deal of concentration, willpower and energy. If a stroke survivor only has energy in the morning, then the afternoon or evening is not a good time for rehabilitation. Because of the depleted energy these survivors possess, timing for rehabilitation is crucial.

The field of stroke rehabilitation is attempting to move away from the concept of dependency in rehabilitation and move toward a more autonomous vision. Allowing the patient to rehabilitate on his/her own time and pace is more beneficial than being reliant upon others. Although patient's families share a great deal of the responsibility in the rehabilitation process, more efficient and comprehensive techniques must be created.

A major issue associated with stroke rehabilitation and disability is the cost. "Stroke rehabilitation costs our society tens of billions of dollars every year. The estimated direct and indirect cost for stroke rehabilitation in the U.S. in 2006 was $57.9 billion" (Duncan, 1998).

Knowledge Gap

In just a few years, stroke rehabilitation literature has advanced from articles that primarily described the potential benefits of using rehabilitation technology, to articles that describe the development of actual working systems, testing of prototypes and randomized clinical trials

Ongoing research in stroke rehabilitation spans from refining traditional techniques to testing new methods and technologies. New technologies employing virtual reality and sophisticated computer systems are being developed and tested in stroke rehabilitation. Understanding the potential use and anticipated problems is important in the development of innovative rehabilitation technologies.

Dr. Jill Bolte Taylor has proposed a new approach to stroke rehabilitation. Her approach involves a combination of mixed reality technology and a concept called Visually Directed Intention (VDI). Currently there is no efficacy data for VDI, so expert opinions and research on similar concepts is exhibited throughout this paper.

Dr. Taylor developed her idea for a stroke rehabilitation system based on the foundation of proven technology complemented with VDI. It is important to assess the concept of VDI as it is integrated with mixed reality, for stroke rehabilitation in order to determine its potential.

CHAPTER TWO: BACKGROUND AND LITERATURE REVIEW

History and Related Research

Brain neurons die when blood supply and oxygenation is interrupted as a result of a stroke. Neurons are the building blocks of the brain for storing and processing information. When these units (in the motor cortex) die, nerve signals that control voluntary functions are impaired and, in turn, a stroke survivor is unable to perform motor functions, such as walking, moving an arm, and wiggling a toe or turning his/her head. Because such loss of function can be debilitating for a survivor, it is crucial to rehabilitate these survivors quickly and comprehensively.

Stroke rehabilitation is a long process that for most involves both inpatient (hospital care), and outpatient (home care) after discharge. Outpatient rehabilitation is crucial in order to readjust to activities of daily living (ADL) and regain various functional levels. According to a stroke rehabilitation study, “Therapy-based rehabilitation services reduced the odds of a poor outcome and increased personal activity of daily living scores” (Outpatient Service Trialists, 2003, p. 1).

Stroke rehabilitation has been traditionally approached as an “outside-in” process. It is generally labor-intensive, usually relying on one-on-one interaction with therapists and rehabilitation specialists. Proven methods of traditional stroke rehabilitation revolve around intense physical repetition exercises, workout plans and massage therapy.

The “outside-in” rehabilitation approach sends signals (unconscious or consciously) to the brain that attempts to reestablish the neural pathways and connections with the rest of the body. Specialists aim to stimulate the brain to reacquire this connection by moving a finger, bending a leg or exercising certain muscles of a stroke survivor for that survivor.

Traditional stroke rehabilitation techniques range from stretching, massages, and assisted exercise of muscles to physical exercise (such as walking down a path or using a treadmill). These techniques are simple methods that involve assisting a patient to use a part of his/her body in order for the brain to reestablish the connection it once had with that entity. The more times the entity is exercised and moved, the stronger the identification fabric will become (neurons will rebuild their connections). Repetition will allow a survivor to "remember" consciously and unconsciously how to perform certain motor functions.

These "traditional" methods have been proven fairly effective over time, but they are not good enough. Because only ten percent of stroke survivors recover almost completely, it is crucial that faster and more effective techniques are put in place (University Hospital, 2005).

Current Stroke Rehabilitation Technology

The use of technology and innovative approaches in stroke rehabilitation has played an increasingly important role in the past decade. Some of the more recent experimental techniques involve electrical stimulation, biofeedback, virtual and augmented reality, and virtual gaming. The Spaulding Hospital and Rehabilitation Center describes several of these techniques:

Biofeedback**:** EMG (electromyography) Biofeedback has been studied and used clinically for a number of years to enhance stroke recovery. Biofeedback works using a sensor placed over a target muscle, which is of relevant importance to a specific movement or activity. “When the muscle is successfully activated, the electrical activity generated by the muscle is picked up by the sensor and used to provide feedback to the individual” (Spalding Hospital Network, 2006). This feedback is generally provided as sound or visually. The purpose of biofeedback is for the individual to become more aware of the “means” or pathway to activate the target muscle and achieve this activation more easily. Biofeedback essentially raises the patient’s self-awareness and conscious control of their unconscious physiological activities.

Electrical Stimulation***:*** Electrical stimulation, also known as Functional Electrical Stimulation (FES), involves the use of electricity to stimulate muscles weakened or paralyzed by stroke to cause them to contract. Similar to biofeedback, research on the effects of this technique has given conflicting results. FES is primarily considered to be an experimental technique for stroke rehabilitation at the present time, although many clinical sites employ the technique across the U.S. There are systems that combine FES and biofeedback, such as the commercially available Auto Move System. “In these systems, electrical stimulation is applied to a muscle once it achieves a certain threshold of activity itself. In a sense, this provides an electrical ‘assist’ to the weak muscle” (Spalding Hospital Network, 2006). While there is some preliminary evidence that these systems may be useful, further studies are needed before they are used widespread.

These methods have been utilized in the field of stroke rehabilitation, but the need for the establishment of more effective and efficient techniques is clearly evident. Technology such as robotics, virtual, augmented and mixed reality are several means that have been developed. Strong evidence suggests that these technologies are more stimulating, engaging, and produce faster rehabilitation times than traditional methods, although no large scale clinical trails have established their efficacy.

The Machines Assisting Recovery from Stroke (MARS) program at the Rehabilitation Institute of Chicago focuses on using robotics to aid in stroke rehabilitation. Their mission is “To evaluate the utility of simple robotic devices for providing rehabilitation therapy after hemispheric stroke… To develop devices that will assist the therapist in providing rationally based treatments which are intensive and long in duration” (Halper, 2002).

“Machine-assisted training can be highly accurate, can be sustained for very long periods of time, can measure progress automatically, and can produce a wide range of forces or motions”(Patton, 2005, p.368). Repetitive practice of the impaired limb has been shown to be beneficial in improving functional ability (Taub, 2000).

Strong evidence suggests that virtual reality is another effective technique that aids in stroke rehabilitation. Virtual reality “has a number of well-known assets, which make it highly suitable as a rehabilitation intervention tool” (Rizzo, 1992, p.121). These assets include the opportunity for experiential, active learning and the ability to objectively measure behavior in challenging but safe and ecologically-valid environments while maintaining strict experimental control over stimulus delivery and measurement (Rizzo, 1992).

According to Dr. Heidi Sveistrup, “VR applications present opportunities for individuals to participate in experiences, which are engaging and rewarding. In addition to the value of the rehabilitation experience for the user…therapists and users benefit from the ability to readily grade and document the therapeutic intervention using various systems" (2004, p.2). Users can engage in a controlled and monitored environment in which limits can be stretched and performance measured. Individual testing and increased standardization of assessment and training protocols becomes feasible. In addition, it is feasible to suggest that virtual reality has the capability to test certain neurological sensors.

According to Dr. Emily Keshner of the Rehabilitation Institute of Chicago (RIC), "…specific postural responses differ between paradigms where isolated individual control pathways are manipulated (i.e., visual, vestibular, somatosensory pathway) as opposed to within a functionally relevant context where information from multiple pathways is available" (2004).

Keshner states, "Mixed reality is a tool towards bringing the real world into a static environment rather than in a controlled lab" (Keshner, 2004, p.3). This is critical because it allows for multiple factors and issues to be manipulated in a controlled virtual environment. Bringing real world dynamics into this controlled environment gives the user of the system a more realistic experience and ingrains responses into the brain. This is achieved through higher stimulation and engagement levels.

Studies involving robots in collaboration with virtual environments have also been shown to enhance stroke rehabilitation (Volpe 1999). A study conducted by Jack and colleagues, using robotics and VR found that motor function of the affected arm was improved following robot-assisted sensorimotor activity. "Subjects were able to relearn patterns of shoulder and elbow coordination in order to smoothly and efficiently move the handle of a robot to acquire targets" (Jack 2000, p.309).

Augmented reality (AR) is another technology similar to VR that is being used experimentally in rehabilitation. Augmented reality is a combination of real world and computer generated data. Most AR technology uses live video imagery that is digitally processed and augmented using computer generated graphics. Digital images that overlay the real world allow for a partially submersed environment. In stroke rehabilitation, augmented reality technologies are experiencing significant growth and many research universities are assessing the usefulness and effectiveness of the technology. This technology is used in limited circumstances in terms of stroke rehabilitation, except for its use in conjunction with robotics.

The fore mentioned MARS program experiments with augmented reality using robotics. The principal investigators who assess this technology are James Patton and Derek Kamper. Their use of reality technologies stretches farther than virtual reality, embracing augmented reality. Interlacing real and virtual worlds and incorporating various robotic technologies into bodily movements gives these researchers the ability to precisely control experiments and even produce expected beneficial outcomes.

The MARS researchers at RIC can manipulate and map the user's brain activity when standing on a moving platform and wearing a mixed reality heads up display. In addition, the researchers can cause the brain to send mixed signals to the body, due to contradictory visual and physical movements. Dr. Patton states, "By completely controlling the visual input and physical environments, it is easy to recreate stroke-like conditions and learn about motor function" (Personal communication 2005).

In rehabilitation, researchers can manipulate this environment and the user can experience almost anything they choose. They can give a stroke survivor the impression they are walking, running or raising a hand in an attempt to “rewire” the brain. Because stroke survivors may lose their ability to perform activities of daily living (ADL), augmented reality shows great potential as a technology for assisting in the recovery process.

Robotics, virtual, augmented and mixed reality are all stimulating technologies that have proven to retain users’ attention and interest; however, this is not enough. In order to truly keep a person engaged, it is crucial to keep his/her attention completely diverted from the real world and immersed in the exercise.

In addition to the standard exercises associated with robotics and mixed realities, incorporating a “game” or “game-like” environment can improve the effectiveness of rehabilitation. Dr. Sung H. You of Hampton University is a leading scholar in the area of virtual reality and game-like environments. Dr. You stated (personal communication July 8th 2006) “Game-like environments have been experimented with, assessed and proven effective in maintaining high interest and retention levels among stroke survivors. The levels of fun, engagement over time, social interaction, boredom and challenge are positively affected through game play.”

Dr. You conducted a study involving VR and game-like environments. Ten patients with a hemiparetic stroke were assessed. Five patients were randomly assigned to a control group that did not receive intervention, while the other five were assigned to an experimental group that received virtual reality and rehabilitation training and exercises. The hypothesis was “Cortical reorganization and motor recovery would improve after VR intervention (You 2005).” The study aimed to re-familiarize stroke survivors with commonly used muscle movements and activities.

Three games/activities were presented; (1) A simple step-up and step-down activity; (2) A “shark bait” activity; (3) A complex snowboarding activity. The simple “stepping” activity only involved the use a patients legs, while the more complex “sharkbait” and “snowboarding” activities required the use of both the arms and legs. Users were only required to wear cyber gloves while a majority of other VR systems require headgear. A large screen was used to show the user what he/she was doing in the virtual environment, while a video camera tracked the patient’s movements.

A functional MRI (fMRI) was used to measure the neural organization before and after on both groups. This was the first study to utilize an fMRI for VR and stroke rehabilitation. The study’s hypothesis was validated, showing that patients in the experimental group, (who received VR training), displayed positive results in neural organization and motor function. In addition, the experimental group showed results in “reorganization of brain activation, or brain recovery, which is associated with improved gait function.” (You 2005). The control group remained similar to their first assessment pre-intervention.

Another recent breakthrough in technology, which follows along the lines of Dr. You’s virtual gaming research, is the use of Nintendo’s Wii gaming console for stroke rehabilitation. Nintendo’s Wii is a home video gaming console that utilizes a wireless remote control, called the Wii remote, which can be used as a handheld pointing device to detect movement in three dimensions. The wireless device can be used to simulate the movement of a myriad of objects ranging from a hand to a tennis racket or even a steering wheel. Although its efficacy is unproven, the Wii has demonstrated positive results in several stroke rehabilitation studies.

An innovative new program is being attempted at the Sister Kenny Rehabilitation Institute at Minneapolis' Abbott Northwestern Hospital. Jerry Pope, a 77 year old retired semi pro tennis player who experienced a debilitating stroke, utilized Nintendo's Wii console to regain his motor skills, coordination and balance. "Gripping the Wii's unique motion-sensing wireless controller in his right fist, Pope swung his arm as if hitting a real tennis ball. The character onscreen responded by hitting the ball to a computer-controlled player in the virtual tennis game. Pope swung his arm each time the ball returned, and his Wii avatar responded in kind." (Salas 2007) Pope stated that because of the interaction of the game, he got the physical sensation of playing tennis. "It really works. It can fool me into thinking that I'm doing what's happening on the screen." (Salas 2007)

When he first experienced the stroke in June 2007, Pope lost control of the entire right side of his body and could not stand up. Just a few days after the stroke, he began participating in traditional stroke rehabilitation techniques, but found them repetitive and boring. Matthew White, an occupational therapist at the Minneapolis institute, suggested using the Wii as he thought "the physical movements required to play games on the system would make it a good fit for rehab." (Salas 2007)

Although he has never played a video game in his life, Pope admits this particular rehabilitation technique is engaging, motivational and beneficial, and his therapists agree. He has currently regained the use of his hand and arm movement from playing the Wii's tennis video game in conjunction with traditional rehabilitation. Another example of the use of Nintendo's Wii system in rehabilitation is a case study that was conducted at the University of Medicine and Dentistry of New Jersey on a patient with Cerebral Palsy. Although the patient did not have a stroke, comparisons can be made to the improvements of motor function, levels of engagement and effectiveness of the technology to the patient. Judith E. Deutsch, PT, Ph.D., led a team of researchers in conducting this study. “Considering the cost and time delay from development to testing to implementation of virtual reality systems, Deutsch wondered if use of the Nintendo Wii, a relatively low-cost, commercially available, interactive gaming system, could provide an alternative to the high-cost, high tech virtual reality rehabilitation robotic systems.” (Deutsch, 2008, p.1196)

The patient a thirteen year old male with spastic diplegic cerebral palsy participated in eleven training sessions, ranging between sixty and ninety minutes over a four-week period, using the Wii while continuing to receive physical and occupational therapy. The Wii games he played were boxing, tennis, bowling, and golf. The results displayed that the patient utilizing the Wii console produced positive outcomes at the impairment and functional levels. Specifically, “Improvements in visual-perceptual processing, postural control, and functional mobility were measured after training” (Deutsch 2008, p.1205).

This particular case study demonstrates that the Wii gives stroke survivors additional tools to utilize during the rehabilitation process. Dr. Deutsch explains that “While the Wii complements physical therapy, it will not replace standard of care (traditional) rehabilitation techniques. We have a sense that the Wii is going to be useful even though it was not specifically designed for rehabilitation. We’re really just learning the system’s possibilities as well as its limits” (2008, p.1206).

The Nintendo Wii takes stroke rehabilitation technology to a new level where inexpensive technological hardware meets groundbreaking rehabilitation results; however experimentation is being conducted beyond this landmark. The incorporation of haptic technology, (being able to get feedback from a user's movements/actions in a virtual environment, by applying vibrations/force to the user) is currently being examined.

A research study currently being conducted by Feintuch involves incorporating haptic feedback to a user (at varying degrees of intensity), while playing either a soccer or juggling game. In the current (early) stages of testing, healthy subjects are receiving the training. The outcomes are being measured by the number of saves (soccer game), and misses (juggling game). Although this study is still in its infancy phase, the conclusions thus far suggest that "…adding haptic feedback may enhance the quality of intervention for various theoretical and empirical reasons" (Feintuch, 2006, p.129)

Although many different types of technologies have been explained and assessed in this thesis, it is important to distinguish the differences between their methods and results. It is significant to understand that virtual/mixed/ augmented reality technology breaks the boundaries of traditional rehabilitation from the "outside-in" and makes use of the "inside-out" concept that Dr. Taylor has devised. The inside-out concept is explained in the following section.

Visually Directed Intention (VDI)

Dr. Jill Bolte Taylor has developed an innovative concept derived from her own personal experience. Her idea revolves around stroke rehabilitation from the "inside-out". Her views are not meant to replace traditional rehabilitation, but to rather act in conjunction with it.

The concept of "inside-out" rehabilitation involves the brain either observing or visualizing something in order to reestablish a connection with the body and relearn various tasks. In order to work from the inside-out, a person must be able to visualize a movement, action, or path and “try” to attempt it. The visualization and “trying” are the keys to learning. Dr. Taylor states (personal communication June 15th 2006), “Neurons are living creatures who respond to all sorts of stimulation. Simply because I cannot move my finger when I want to move it, does not negate the power and reinforcement I am providing my neurons when I ‘try’ to move my finger by focusing my attention and effort and life force toward the goal. I am essentially saying to my neurons, 'hey, I value this connection' every time I consciously ‘try”.

She goes on to explain that, “I may need to try to move my arm a million times before it begins to be under voluntary control. But I must try to get it back. If I don’t try then I won't get it back (Taylor 2006).”

Valuing the body’s intricate connections, utilizing willpower and “trying” play a key role in Dr. Taylor’s concept of Visually Directed Intention (VDI). Visually Directed Intention is simply seeing then doing. Being able to visualize or virtually “see” the body and nerves inside will trigger brain activity and allow for control and directed energy to perform certain activities or movement.

Visually Directed Intention relies on a three pronged approach: (1) A person must value the connection he/she has with the body by consciously “trying” to do a task; (2) A person must have the willpower and a drive to succeed; (3) A person must have the proper visualization technology. Dr. Taylor envisioned a system that in conjunction with current practice (e.g. biofeedback, exercise, physical therapy, occupational therapy), will heal the mind and body, keep the user engaged and allow for faster and more comprehensive rehabilitation.

The System

Dr. Taylor brought her concept of a juxtaposed virtual and augmented reality system to Dr. Sonny Kirkley. Dr. Kirkley is the CEO of Information in Place, an augmented reality research and educational video game company in Bloomington, Indiana. Several brainstorming and prototype design sessions were held to produce a vision of the product.

The VDI system harnesses several technologies such as mixed reality, biofeedback, and game-like environments. Key concepts such as visualization, intention, motivation and repetition are also pivotal to the success of this rehabilitation technique. Specifically the system uses biofeedback, viewed through a mixed reality headset to motivate a patient to utilize nerves and muscles he/she may have lost through experiencing a stroke.

The envisioned system will utilize Visually Directed Intention in a controlled mixed reality environment and will keep the patient highly engaged. The end-goal is that combining techniques such as biofeedback, visualization and imagery, repetition, motivation and engagement will facilitate a more efficient and comprehensive rehabilitation process. Below is a schematic and overview of the system.

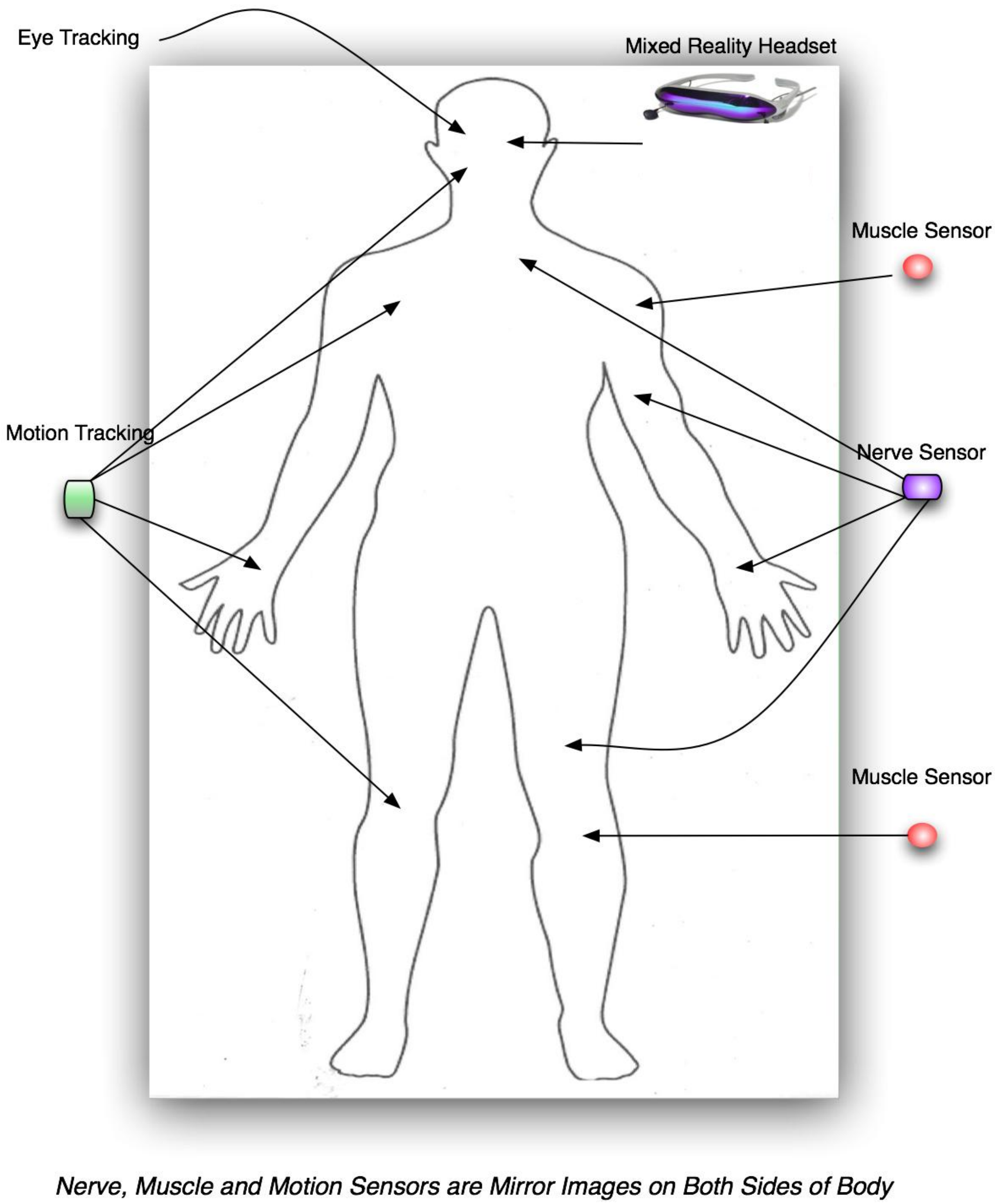

Figure 1. *Schematic of VDI system*

The system will consist of several parts; the mixed reality goggles/headset (to be worn by the user); nerve and muscle sensors, motion tracking capabilities, eye tracking capabilities; and a computer. The motion tracking device will detect a user's body movement and display it through the headset and computer screen, while the eye tracking device will display where the user is looking. Two of the key elements of the system however, are the nerve and muscle sensors.

The nerve and muscle sensors will allow the user to see what nerves/muscles are active vs. inactive (inside the user's body) and feed all of this information back to the computer. When a nerve is white, the connection is inactive, meaning the user may have little to no control over the connection. As a user values and tries to use this connection and slowly begins to reestablish it, the connection will slowly become green, until it is fully restored. If a healthy person were to use the system, the nerve and muscle sensors would display all green (healthy or active) connections, while if a patient who has just experienced a stroke were to use it, they could have an majority of white (inactive) connections.

Based upon the severity of damage experienced during a stroke, initially the patient using the system may need to harness the muscle sensor to retrieve biofeedback because of the lack of control of bodily functions he/she may have. Once the stroke survivor has gained enough control, the nerve sensor can be utilized to produce more meaningful (nerve movement vs. muscle movement) biofeedback to the user.

One of the key components involved in the success of this system is the nerve sensor. The sensor is a biofeedback tool that will be the means for detecting and displaying nerve activity throughout the body. The technology that drives the nerve sensor is currently being used in a few areas of health care, although has never been directly applied to stroke rehabilitation. Today, nerve sensors are routinely being used in medical offices to determine degrees of neuropathy in the elderly and others experiencing neuropathy in their distal extremities. The technology exists, but the realm to which it has been applied has been limited thus far.

On both the computer monitor and the VR goggles, the user of the system can manipulate the environment and decide the activity/game to be played and the level of difficulty. In order to display progress through biofeedback, the computer can display previous performance history of nerve control. In other words, the system will store previous data and results, so a user can look back at progress made. The previous history now takes on a dual purpose; storing/organizing data and facilitating better results through motivation.

Below is an example of a simple ball drop game that can be played in the VDI system. It displays what a user wearing the VR goggles would see (from the 1st person).

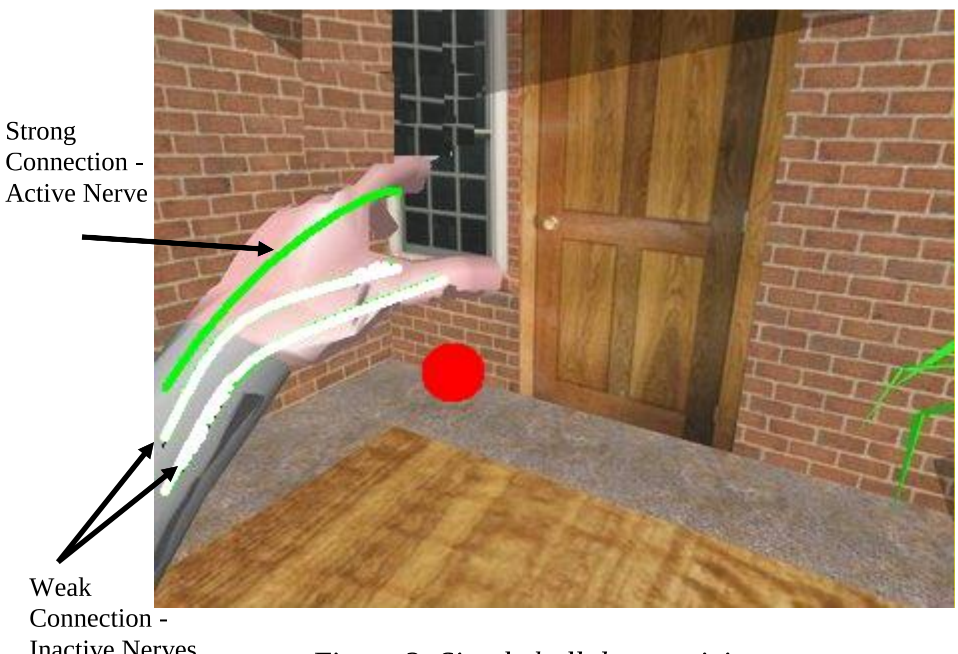

Figure 2. *Simple ball drop activity*

In this activity, the user holds onto a red ball and then drops it. This game is designed for users who have very little control over there bodily functions and will most likely be in the early stages of rehabilitation. As pointed out by the arrows on the left, two of the nerves in the arm/hand are white, (an inactive or weak nerve connections), while one nerve is green (an active and strong connection), that is allowing a few fingers to release the ball from the hand.

Hand -eye coordination plays a significant role in the user's progression and rehabilitation. The motion and eye tracking technology used in the VDI system are still being shaped, however the basic goal behind their use is clear; detect the user's movements and echo them in the virtual world.

The technology behind the motion sensors could range from using a video feed with infrared light to detect movement to physical sensors worn on the skin. The eye tracking is similar. It is critical to properly track not only body and head movement, but eye movement. A stroke survivor in a debilitating state may not be able to move her head, but still be able move her eyes. In this case, the eye movement will need to be tracked so as to properly reflect a 1st person view while in the virtual world.

In addition, in some of the more advanced activities or games that can be played in the VDI system, it is important to track where the eyes are looking. An example of where motion and eye tracking play a key role is the ping-pong game.

Watching the replay of a ping pong match in the 2nd person view

Figure 3. *Advanced game of ping pong*

The image above is a replay (in the second person view) of a patient playing a game of ping pong. Similar to the ball drop game, notice the green lines which indicate a strong connection (nerves which a patient has control over), while the white lines are nerves which are inactive (which the patient does not have control of) being displayed virtually through biofeedback to the user. He is slightly tilting and turning his head to concentrate on the ball, and clearly relying more on his right side while hitting the ball with his right hand.

On the user's right arm, half of nerve is green while the other (lower) half is white. In this case, only has partial control of that nerve, however because of the other working (green colored) connections, he is able to swing the ping pong racket. This is clearly a more advanced activity, but the importance here is the patient's engagement and motivation to play and heal themselves.

Below is another approximate representation of what a user of the VDI system would see while wearing the mixed reality headset. This view is once again from the second person so that it is easier to distinguish the active/healthy nerves and the muscles being used to open the hand right hand. It is important to understand that the user of the system will be able to see the nerves and muscles being utilized to open the hand, as this is a key component to motivation and engagement in the VDI system.

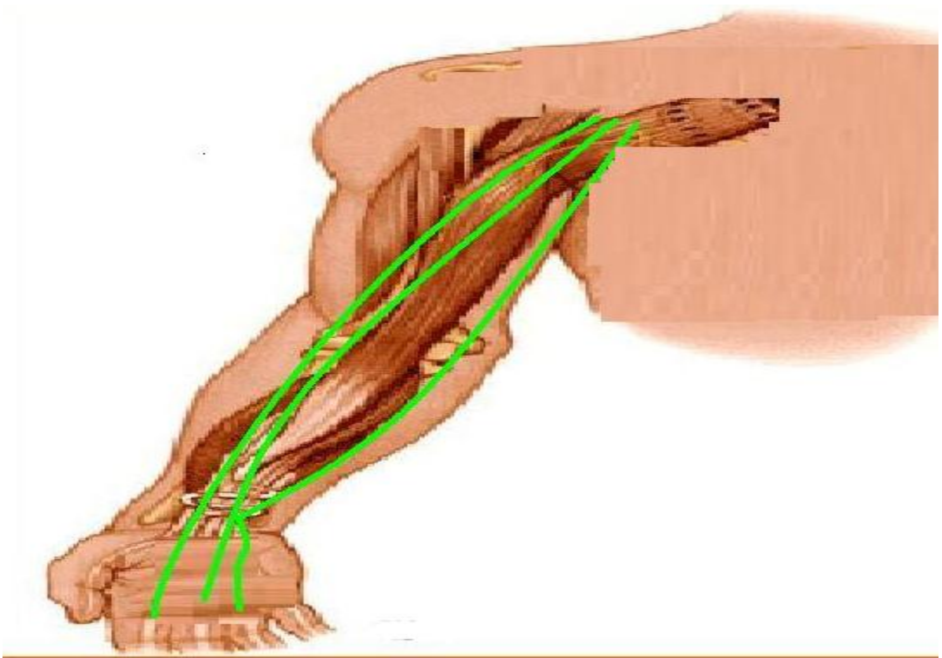

Figure 4. *Representation of muscles and nerves of the right arm in the VDI system*

Visually Directed Intention Compare/Contrast

A portion of the Visually Directed Intention system can be compared to techniques such as meditation, imagery and visualization and technologies for virtual/mixed reality and biofeedback. Although the system has its roots in the areas mentioned above, there are also many distinguishable differences.

Imagery and meditation are used (consciously and subconsciously) by everyone thousands of times a day for activities of daily living (ADL) and other complex activities, e.g., visualizing lifting an object before actually attempting to do so. Imagery and meditation are also used for more complex activities and sports, such as visualizing a golf swing or before a jump shot in basketball. Although these may just seem like common thought processes, imagery and visualization assist people subconsciously and prepare certain body muscles and nerves for activity. It is like giving your body a “heads-up” on what is to come and allowing yourself to prepare accordingly. A studied conducted by Stevens (2003) discusses the effects of using visualization and imagery. In this study, two chronic hemiparetic stroke survivors used visualization and mirrors to trick patient’s brains into thinking they were moving their arms and legs. The training continued through intense movements and mental stimulation involving object manipulation and mirrors. This process gave patients the appearance and feelings of moving their affected limbs, but did not actually contain the associated physical movements. In addition to the object manipulation, patients underwent intensive imagery and visualization in order to “retrain” their brains. The study concluded that patients who used imagery and visualization showed improvement in the motor function of the paretic limb (Stevens 2003).

Many comparisons can be drawn from the Stevens imagery and visualization study to Dr. Taylor's VDI concept. The VDI system utilizes not only visualization and imagery, but other technologies such as mixed reality, biofeedback and game-like environments. Although the systems roots are in these technologies there are fundamental differences and tweaks that make it unique.

We have already examined biofeedback in this analysis; however its use in the VDI system has presented a new opportunity for its potential. In the VDI system, biofeedback will be obtained through nerve and muscle sensors, while feeding this information back to the user. In addition, the system's use of color coding nerves will break down the biofeedback to a level of detail that has never been attempted in this area. To date, this is the first prototype that will use this level of biofeedback with mixed reality to enhance motivation to rehabilitate and user engagement.

In addition, the systems activities or games that the user can play draw many similarities to research involving game-like environments. Game-like environments are excellent methods for keeping user engagement levels high and retaining information (You, 2006). The "ping-pong" game, as described above, is an efficient method for keeping a stroke patient engaged, while continuing to reinforce concrete re-learning of body movements and ADL.

Technologies, both traditional and experimental are clearly major advancements in stroke rehabilitation. Retraining the brain to perform simple tasks is a daunting task that requires effort from not only the stroke patient, but inspiration and motivation from surrounding people. In some cases, inspiration and motivation can come from other sources (rather than people) such as games or game-like virtual environments.

Until this point, rehabilitation environments have never been able to be (widely) manipulated. Utilizing mixed reality technologies has enabled experts to gain a high level of control. Now it is possible to determine the level at which the survivor is responding and apply appropriate levels of training and motivation to enhance rehabilitation.

Although Dr. Taylor's VDI system as a whole is theoretical, the technologies that it utilizes are available, specifically, virtual/mixed/augmented reality, biofeedback and game-like environments. In other research studies, these techniques and/or platforms have shown strong evidence to hasten the rehabilitation process. However, in order to thoroughly analyze the feasibility and validity of such a system requires further insight. This can be obtained from expert opinions, literature and experimentation in the field of stroke rehabilitation.

CHAPTER THREE: METHODS

To determine the feasibility of VDI for stroke rehabilitation, a qualitative interview with experts in stroke rehabilitation technologies was conducted. The purpose of the interviews was two-fold. First, current technologies being tested at the Research Institute of Chicago were reviewed with the principal investigators. In addition, experts were queried about their opinions of the proposed VDI system.

The Institute for Stroke Rehabilitation at the University of Chicago is one of the leading medical centers in the nation. They are on the forefront of virtual and mixed reality technologies for stroke rehabilitation. Dr. Emily Keshner, Dr. Jason Leigh, Dr. Derek Kamper, and Dr. James Patton are some of the professionals paving the way experimenting with new technologies and techniques.

The subject matter experts (SMEs) involved in this research paper play a fundamental role in the assessment and analysis of current stroke rehabilitation techniques and Dr. Taylor's concept of VDI. Their role in this process is to assess Dr. Taylor's system and give further input and suggestions on viability and practicality.

Experts in stroke rehabilitation technologies were identified using online journals, knowledge bases and library resources, searching on the terms of virtual and augmented reality and robotics. Research scientists from the Machines Assisting Recovery from Stroke and the Sensory Motor Performance Program at the Research Institute of Chicago (RIC) include some of the most prominent experts in the field.

Interviews were scheduled with six investigators, although due to scheduling conflict, only four experts were available. The experts interviewed were Emily Keshner, PT EdD., W. Zev Rymer, MD PhD, Derek Kamper, PhD and James L. Patton, PhD.

Each expert is involved in a segment of mixed reality rehabilitation experimentation. Their expertise ranges from hand and other lower body motor movement to head movement and brain monitoring. It is because of this wide range of knowledge that these individuals were selected for this study.

Open-ended surveys and semi-structured questioning were used to obtain feedback about the proposed VDI system. Appendix A contains the general and technical questionnaires. Each expert received copies and completed the surveys. Following this, personal opinions on Dr. Taylor's VDI system and current stroke rehabilitation technology were elicited.

I was fortunate enough to visit several of the labs at the institute, observe several studies in progress and even use some of the technology. The specialists at RIC use the experimental labs to perform clinical trails with stroke survivors. They are one of the top tier experimental facilities in the world and are on the cutting edge of technology.

Data Analysis

Interview data from the experts at Rehabilitation Institute of Chicago were recorded on paper. In order to turn the data into meaningful results, answers were categorized and coded for analysis.

The first step in coding the results was to take the separate interview documents and combine them into a single master document. In the master document, under each interview question, a section for each expert was created. Each question therefore had four responses beneath it as shown in the Appendix C.

Next, responses were grouped within themes relevant to the answers. This categorization allowed for determination of similarities across respondents as well as recognition of unique views.

CHAPTER FOUR: RESULTS

I obtained a great deal of varying results through speaking with the experts at the RIC. Their survey and interview responses provided me with enough information to present a preliminary assessment of the feasibility for the VDI system, and a better understanding of current technologies and methods used today.

Current Technology Used by Experts

One of the labs at the RIC contains a VR system that helps researchers understand how the central nervous system calculates whole body movements when engaged in postural and orientation tasks. I was privileged to try this system and learned very quickly how the mind is separated from the body. By manipulating physical movement (standing on a sliding floorboard), and being immersed in a virtual environment (wearing a VR headset), I experienced what its like to have no control of your mind and body.

Because of the contradicting movements (of the VR headset and the sliding floorboard), the mind cannot distinguish what is visually and physically happening to the body. This experience gives researchers the ability to recreate losses of postural movement and memory from strokes.

In addition to my enthralling VR experience, Dr. Kamper allowed me to try out some of his research involving hand neuromechanics. In this scenario, I was able to experience how the hand is controlled, and how to construct a computer model of the hand for predicting the outcome of interventions. This is extremely helpful to stroke researchers, because it gives insight into what will and won't work.

General Feedback about the VDI system

Overall, the panel of experts agreed unanimously that the VDI system is a great idea with immense potential. Several of the experts drew parallels regarding the system's analogous nature to biofeedback technologies, game-like environments, motivational experiments and portions of their work.

The respondents stated that it is difficult to compare the VDI system to any commercial product or experimental project because there is truly nothing like it out there. Although this system draws roots from portions of existing and experimental technologies, nothing to date directly compares.

Advantages/ Disadvantages

What do you see as the potential advantages/disadvantages of this system?

Commonalities: If the technology itself works as Dr. Taylor describes, the experts agree in unison that this will be an efficient tool for rehabilitation. They all agree that the technology and methodology described here is experimental and even unproven in certain aspects.

Other thoughts: The construction of such a system could be potentially lengthy and costly; therefore early adopters and champions must be on board before investing time and money.

How does this prototype system compare to other augmented /virtual reality systems of which you are aware?

Commonalities: Biofeedback and virtual and augmented reality are in the early to experimental stages, and are not mainstream rehabilitation methods; therefore, it is difficult to draw comparisons to anything outside of the work being done at the RIC and other research universities.

Other thoughts: Listed are several researchers working with similar technologies; Heidi Sviestrup (VR and AR technologies), Jennifer Stevens (Imagery) Pablo Celnick (Imagery), Sheng Li (increasing reflex time and size), Carol Richardson (altering visual environments affects locomotion), Leon Cohen (Transcrainial magnetic stimulation), Mindy Levin (Immersed vs. Non Immersed VR/AR technologies) and Dr. Sung Yu (Game like environments and interaction in VR).

What do you see as the one potential fatal flaw of a system like this?

Commonalities: The nerve sensor is not only an unproven technology, but will be extremely difficult to create. To obtain the similar results, a proven technology (muscle sensor), is a more practical and cost viable solution.

Other thoughts: Visually Directed Intention is an unproven method and may not bring about the expected results.

Potential Fatal Flaws

The survey respondents all agreed on the one potential fatal flaw of the VDI system; the nerve impulse sensor. The surveyors not only questioned the internal workings of the sensor, but the feasibility and validity of it.

The respondents stated, “How would it work? Wouldn’t it be easier to detect muscle movements (an existing technology) and release biofeedback to the user? It will be too tough to sense the nerves. One can accomplish essentially the same thing by detecting and displaying muscle movements. Why go through the trouble of creating a new, expensive and time consuming tool, when you can accomplish your goal in a similar manner with existing technology?”

The respondents also seemed to agree that another potential fatal flaw is the validity of Visually Directed Intention. The experts understand the concept and did make the comparison to visualization techniques, but were not familiar with any studies directly involving VDI in dealing with stroke rehabilitation.

CHAPTER FIVE: DISCUSSION

Through expert opinions, survey results, and a thorough literature review, I am concluding that Dr. Taylor's rehabilitation system is feasible and should be prototyped and tested (perhaps in a doctoral dissertation).

As this survey was conducted three years ago, several advancements have been made in technology and this presents a counterpoint to some of the answers given by the experts at the RIC. The experts reached an overwhelming consensus regarding the availability and cost of the nerve sensor used for biofeedback in the system.

As mentioned early, nerve sensors are commonly used in medical offices to determine degrees of neuropathy in the elderly and others experiencing neuropathy in their distal extremities. Because the technology has not been applied to the field of stroke rehabilitation, it is difficult to make an assumption on the effectiveness of this technology. The nerve sensor that will be used in the VDI system, will be similar to the example mentioned above, however the final decision on the technology has not been decided on.

The nerve sensor should be used in conjunction with a muscle sensor, for patients who are on different stages of rehabilitation. An example would be a patient who has recently experienced a stroke may have very little control over their nerves, but may have just enough capability to twitch or move a muscle slightly. The biofeedback obtained from a muscle sensor would be beneficial in the early stages of rehabilitation.

A muscle sensor would be able to display which muscles are active and which are inactive; therefore, identifying which nerves are responding and which are not. All the experts agreed that a muscle sensor can substitute for and produce similar results to a nerve sensor.

Because no technology like this has been used in stroke rehabilitation, it is difficult to make assumptions on the outcome of the system. The VDI system is a juxtaposition of several existing technologies (mixed reality, biofeedback, game-like environments) and several rehabilitation methods (physical exercise, repetition and VDI).

One important point to grasp is that although the success of this system relies on some "experimental" technology and methodology, the rest of the system is composed of innovative and cutting edge technology that has great potential. Experts at the RIC agreed that this system should be a great success and add yet another novel and ground-breaking methodology/technology to the field of stroke rehabilitation.

Implications for further research

- Using virtual reality and interactive systems in stroke rehabilitation have been proven effective. In addition utilizing visualization and imagery, a technique for improving neuron stimulation and improving motor functions, has also been successful. Therefore a mixed reality system using a combination of this type of technology and visualization and imagery will be an effective technique for faster and more efficient rehabilitation.
- The system will allow for independence and autonomy in stroke rehabilitation and will cut the time required for full rehabilitation significantly.

- The stroke survivor will rehabilitate to a fuller extent than by solely using traditional rehabilitation techniques.
- There will be a significant improvement to the quality of life of stroke survivors after using this rehabilitation product.

CHAPTER SIX: CONCLUSION

Further research must be conducted to determine effectiveness and efficiency of such a system. In addition, a working prototype would have been a tremendous aid in conveying technological and methodological workings to outsiders of this project.

I would have liked to conduct further analysis regarding the cost of such a system. It is critical to gain a better idea of what a system would cost to manufacture and purchase/maintain (for the user), in order to compare it to current rehabilitation costs. I believe all of these analyses are crucial to be performed after a working prototype is created.

VDI is a method that should not be restricted to the area of stroke rehabilitation. Because of its applicability, VDI can be used in several other areas of healthcare and mental health, such as; basic neurological rehabilitation, counter degenerative neuropathy in the elderly, military injuries (Veteran's Administration clinics/hospitals), professional athletic focus and visualization exercises before games etc… The potential is unlimited.

It is very important to note that since the commencement of this project, there have been a few modifications to Dr. Taylor's VDI system. Her system has evolved in a way that will not only help lower the costs but solve a technology gap. The original idea of using a nerve sensor has been modified. The system will utilize both a nerve and muscle sensor (depending on the severity of damage from the stroke) to give biofeedback to the user. The muscle sensor will achieve a similar goal to the nerve sensor in processing biofeedback, but also cost a great deal less. The experts at the Rehabilitation Institute of Chicago stated that using the nerve sensor was the one potential fatal flaw of the VDI system. They all recommended a similar both sensors, the potential for the creation of and use for this system has no barriers.

The VDI system's use should not be limited to the field of stroke rehabilitation. As a part of the system is rooted in imagery and visualization, this tool could be used with the elderly population who suffer from neuropathy in their extremities. The same concept applies, as the patient (in this case an elderly person with neuropathy) is trying to regain better control of their nerves and muscles. VDI can be applied to almost any example of where a person needs to regain bodily control, retrain their brains or strengthen connections with nerves or muscles.

The system could even be applied to professional sports, in allowing athletes to strengthen their muscles, nerves and reaction times through imagery and visualization in order to be more prepared for a game.

The research presented in this thesis contains strong evidence that Dr. Taylor's VDI system is a feasible idea and will help stroke patients with rehabilitation. With strong roots in mixed reality technology, biofeedback and game-like environments, users of the system will have a nice compliment to traditional rehabilitation methods. The VDI system promises great potential for its users, and the data supports the assembly of a prototype and commencement of a detailed study with stroke survivors.

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Appendix A: General Questionnaire

Interview Structure

1. *Tell me about your current research using technology for stroke rehabilitation*
    a. *Have you tested the system on patients?*
    b. *What results have you obtained?*

2. *Show mock-ups of the VDI system and explain functioning*
    a. *What is your opinion about a system like this*

3. *What do you see as the potential advantages and disadvantages of a system like this?*

4. *How does this prototype system compare to other augmented /virtual reality systems of which you are aware?*

5. *What do you see as the one potential fatal flaw of a system like this?*

Appendix B: Technical Questionnaire

School of Informatics Indiana University Student Thesis

Research Questionnaire

1. *Project Name:*
2. *Investigators:*
3. *Purpose / Overview/User Experience:*
4. *Status:*
5. *Technologies used: (Brand and Model of Devices and Software)*
6. *Software (custom, open source, purchased)*
    - i. *Screen Shot:*
7. *Devices:*
    - i. *Sensor (Nerves and Muscles)*
    - ii. *Sensor (Head tracker)*
    - iii. *Input (How is a users input affecting the system)*
    - iv. *Output (What is displayed to the 5 senses)*
    - v. *Details*
        1. *Version*
        2. *Accuracy*
        3. *Resolution*
        4. *Issues and Problems*

Appendix C: Methods Section Unformatted Responses

(Due to privacy regulations expert's names will not be listed)

What do you see as the one potential fatal flaw of a system like this?

Expert 1: “The nerve sensor may be difficult to create.”

Expert 2: “I think one is, can Visually Directed Intention actually work? The nerve sensor may be too difficult to design. A higher level muscle sensor will produce similar biofeedback and results to the end-user.”

Expert 3: “I would say it would be the nerve-muscle sensor”

Expert 4: “The only one I can think of would be the nerve sensor. How would you sense the nerves? I think you would be able to get similar results using a higher level sensor, perhaps sensing through the muscles.”

Appendix D: Results Section Formatted Responses

What do you see as the one potential fatal flaw of a system like this?

Commonalities: The nerve sensor is not only an unproven technology, but will be extremely difficult to create. To obtain the similar results, a proven technology (muscle sensor), is a more practical and cost viable solution.

Other thoughts: Visually Directed Intention is an unproven method and may not bring about the expected results.

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