IMMERSIVE VIRTUAL REALITY SIMULATIONS FOR INVESTIGATING PHYSICAL ACTIVITY AND HUMAN INTERACTIONS WITH TECHNOLOGY IN YOUNGER, OLDER, AND PATIENT POPULATIONS

By

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Dedications

This thesis is dedicated to my grandmother, who has raised me and hoped that I will become a "Doctor"; and my mother, who has supported me whenever and wherever.

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Abstract

This thesis investigates how immersive virtual reality (VR) simulations can utilize exertions, movements, and physical activities for human performance evaluation or physical training.

Two initial studies were conducted in this thesis with the purpose to understand human performance in VR. Generally speaking, there were human performance differences and similarities in VR and the physical environment. Human inaccuracy (i.e. error) when locating virtual targets was 1.64 times greater (p<.001) than locating physical targets, and participants spent 1.49 times more time (p=.01) to locate virtual targets than physical targets. When participants were asked to exert forces against virtual objects using virtual exertions (i.e. mapping of human-generated forceful actions, postures, and movements that are generally used to manipulate physical objects, against projections of objects in the hands as an interface into the virtual environment), muscle activity was generally greater than when exerting forces against physical objects of the same weight. Some similarities between VR and physical environment were also observed. Biceps muscle activity was positively related to the weight of both virtual and physical objects (p<.001), which suggested that human muscle activities may respond to the weight of virtual objects similar to how they would with the weight of physical objects.

Two additional studies demonstrated the use of VR for practical applications. One study examined driver functional range of motion during a blind spot checking task. Using virtual targets in VR as visual stimuli, drivers indicated when they were detected in the driver blind spot. The results indicated that functional range of motion was 15.6 degrees greater (p<.001) than conventional neck range of motion. The other study investigated how patients perform neck exercises directed by visual stimuli in VR. It was observed that patients performed neck rotation exercises approximately 2 degrees greater than what they initially indicated their neck rotation capacity to be (p=.005).

In conclusion, virtual reality was demonstrated as a flexible environment where visual stimuli can be programmed for various evoking physical actions and sensations. Research including, but not limited to

human-VR interactions, human performance and behavior, and physical training and exercise can be conducted in VR.

1. Introduction

1.1 Thesis statement

This thesis investigates how immersive virtual reality (VR) simulations can utilize exertions, movements, and physical activities for human performance evaluation or physical training. Several VR vehicles including a CAVE or Cave Automatic Virtual Environment, and a head-mounted display (HMD) were utilized to compare human performance in VR and the physical environment, investigate how humans to interact with virtual objects, study how humans perform exercises and movements in VR, and evaluate the use of VR for physical therapy and patient rehabilitation. The results from this thesis will provide information on human-computer interaction mechanisms and simulations in VR, human performance in both VR and the physical environment, evaluation of biomechanical characteristics of different age groups, conducting physical training and exercise, and applications in physical therapy and home health care.

1.2 Research Motivation

Virtual reality (VR) is an environment generated by computers with three dimensional graphics, where users typically interact with virtual objects and a graphical environment that is usually customized to the user's perspective. Recent innovations have made VR technology portable, inexpensive, and widely available. Programmable VR systems also make studies or prototyping in VR cost-effective, and it is inherently safe for simulating hazardous tasks or for training because VR constitutes graphics and the users are not exposed to physical dangers. Research on VR and its applications has been conducted, including education (Dalgarno & Lee, 2010; E. A.-L. Lee & Wong, 2008), training (Dugdale, Pavard, Pallamin, el Jed, & Maugan, 2004; Lange, Indelicato, & Rosen, 2000), rehabilitation (Holden, 2001), and measurement (Pontonnier, Samani, Badawi, Madeleine, & Dumont, 2013; Sarig-Bahat, Weiss, & Laufer, 2009). Improvements in VR present a new research paradigm and offers potential solutions to the challenges posed by traditional research technology. A series of research studies in this thesis were conducted to investigate how humans perform and carry out activities in VR.

Comparison of the how individuals perform in the physical and virtual environments was the initial step to evaluate and understand the differences between the two environments. Previous studies have generally indicated individuals tended to underestimate distance in VR (Alexandrova et al., 2010; Thompson et al., 2004; Willemsen & Gooch, 2002; Witmer & Kline, 1998). Other performance measures, such as target aiming and grasping and movement time in VR, were also found to be different from the physical environment (Liu, van Liere, Nieuwenhuizen, & Martens, 2009; Magdalon, Michaelsen, Quevedo, & Levin, 2011). Yet, the estimation of the walking distance in VR and the physical environment was found to be similar (Plumert, Kearney, Cremer, & Recker, 2005). The varying findings in different studies could be related to different VR systems that were used (Lampton, McDonald, Singer, & Bliss, 1995).

An understanding of performance in a six-sided fully immersive CAVE was considered, due to the opportunities it offers for accommodating whole-body movements in a fully immersive virtual environment, while not only depending on kinesthetic feedback but full visual feedback of body movements relative to the projected environment. The first study in this thesis was to examine possible differences between how users physically reach for and locate virtual objects in a CAVE.

Upon understanding human performance in locating and reaching for virtual and physical objects, the next step was to investigate human performance and physiological differences (i.e. muscle activity) in both the virtual and the physical environments. A novel concept called Virtual Exertions was studied, which utilized muscle contraction and biofeedback from electromyograms (EMG) as well as gestures and movements for interacting with virtual objects in VR. Studying the difference in muscle activity patterns could provide more information on how individuals evoke senses of exertion in response to virtual objects, which may lead to improved experiences in VR simulations that involve physically demanding activities. Moreover, Virtual Exertions provided an alternative way for individuals to interact with the VR system. Using muscle activity as an input to control virtual objects could potentially replace hand-operated controller or a "wand" in the CAVE. This was a two-fold study: investigation of a novel human-

computer interface, and the examination of evoking the sense of exertions by contracting agonistic-antagonistic muscle pairs.

In addition to muscle activities, other biomechanical characteristics could be studied in VR, such as measuring movement capabilities while interacting with virtual objects. A study was conducted using a very simple driving scenario in VR to evaluate the functional range of motion of older and younger drivers during a blind spot checking task. This study was motivated by the increasing number of older drivers (>65 years of age) and neck rotation has been identified as a risk factor in older drivers (Isler, Parsonson, & Hansson, 1997; Marottoli et al., 1998; Sivak & Schoettle, 2012; Stav, Justiss, McCarthy, Mann, & Lanford, 2008) and the need to evaluate driving performance decrements in aging without the risk of actual driving. Previous research has shown that conventional neck rotation range of motion measures did not demonstrate a positive association with motor vehicle crashes or poor driving performance (Ball et al., 2006; Molnar et al., 2007; Stav et al., 2008), and some studies have inferred that trunk rotation exercises improved driver performance in older adults (Ashman, Bishu, Foster, & McCoy, 1994; Marottoli et al., 2007; Ostrow, Shaffron, & McPherson, 1992). It is possible that drivers utilize more complex motions other than neck rotation when performing various driving tasks. This study provided information on driver biomechanical characteristics, and also demonstrated the potential of VR as a measurement and evaluation instrument.

Neck movements and range of motion are important for not just driving but also activities of daily living as well as occupational tasks. Approximately 14% of the adult population in the US has pain in the neck region (National Center for Health Statistics, 2015). This not only indicates the large number of individuals suffering from health conditions and not being able to work, but it also imposes a cost on their health, wealth and wellbeing. Being able to provide more accessible and cost-effective health care to individuals is also of high importance. A portable VR rehabilitation system was developed and explored for home exercises, which is more accessible to patients in the rural area than the conventional clinical rehabilitation. The innovation for developing a VR rehabilitation system is altered visual feedback, which

was hypothesized to mitigate the fear of movement in neck pain for individuals who are kinesiophobic, which is an irrational, weakening and devastating fear of movement and activity stemming from the belief of fragility and susceptibility to injury (Kori et al., 1990). Altered visual feedback was achieved in VR by altering control-display (C-D) gain.

Control-display gain is a mismatch between user input and visual feedback. An example is when a user physically controls the position of a computer mouse (i.e. user input), the displacement of the cursor on a computer screen (i.e. visual feedback) can be greater than the displacement of the physical mouse on the table. Altered visual feedback in VR may potentially mitigate the fear of the individuals with neck pain in performing functional movement patterns, since visual feedback with C-D gain may suggest to kinesiophobic patients that they are exercising within their easy range of motion while they are physically moving greater than that range of motion. An extensive literature review on VR has demonstrated successful desensitization of fear of individuals with specific phobia, which suggested the possibility in using altered visual feedback to desensitize fear of. Through fear desensitization, individuals with neck and shoulder pain will be able to perform therapeutic exercises differently.

1.3 Research Objectives and Specific Aims

Below are the specific aims for the research objectives of this thesis:

AIM 1. ASSESS THE ACCURACY, TIME, AND APPROACH OF INDIVIDUALS INTERACTING WITH PHYSICAL AND VIRTUAL OBJECTS. In order to use VR to study physical human performance in a CAVE, the first step is to understand if there are any differences between how individuals locate and approach physical and virtual objects. To accomplish this, the accuracy, time, and approach of individuals locate physical and virtual objects were compared.

AIM 2. ASSESS MUSCLE ACTIVITY PATTERNS IN PHYSICAL AND VIRTUAL ENVIRONMENTS. A novel method of humans-computer (VR) interaction was implemented to

understand if individuals could evoke a sense of exertion in VR when interacted with virtual weights that lacked mass.

AIM 3. EVALUATE NECK AND TRUNK ROTATION MOVEMENTS OF YOUNG AND OLDER ADULTS. As the number of drivers over 65 years of age continues to increase, it becomes important to understand the biomechanical characteristics that may be related to aging. The neck and trunk rotation movements were evaluated using VR and active motion tracking technologies. Older and younger driver performance were evaluated in immersive virtual reality simulated dynamic driving blind spot target detection task.

AIM 4. DETERMINE THE JUST NOTICEABLE DIFFERENCE OF CONTROL-DISPLAY GAIN IN A VIRTUAL REALITY SYSTEM. A control-display gain algorithm responsible for altering visual feedback was created. Movement (i.e. control) of a user that was captured by the VR system was processed through a series of gain equations to produce amplified or attenuated visual feedback (i.e. display), and therefore the visual feedback is governed by the C-D gain (Poupyrev et al., 1999). It is hypothesized that there exists a range of just noticeable C-D gains such that patients with the chronic neck would not notice, such that the altered perception and the altered visual feedback would dominate proprioception.

AIM 5. EVALUATE VR EXERCISE SYSTEM ALTERING THE PERFORMANCE OF INDIVIDUALS WITH CHRONIC NECK AND SHOULDER PAIN DURING NECK AND SHOULDER MOVEMENTS. The range of C-D gains for each patient will be determined individually as described in Aim 4. The just noticeable C-D gain value below unity gain (i.e. gain=1) will be used to alter the visual feedback in VR. Chronic neck and shoulder pain patients were recruited. Baseline neck and shoulder range of motion without altered visual feedback was recorded, and then compared to the performance under C-D gains in VR.

By completing studies with these objectives we will be able to learn and gain more insights on human performance in VR, older and younger adult biomechanical characteristics, and better understand how we could utilize VR to conduct research or activities that enable humans to carry out similar tasks as in the physical environment.

1.4 Thesis Organization

This thesis starts by exploring the differences and similarities of human performance in the physical environment and the virtual environment. A simple target-aiming task was performed and the accuracy of aiming the target was quantified in terms of distance to the physical and virtual targets. The next chapter also looked at human performance in both the physical and virtual environments, but it further investigated the possibility of humans interacting with the virtual environment through the use of muscle activity. The different approach to interact with virtual objects permitted the possibility of conducting physical activities in virtual reality. The following chapter discusses the use VR to assess human movements and activities in an everyday situation. The last chapter evaluated the use of VR in not only assessing human movements but also explored the possibility of VR in exercising and rehabilitation.

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2. Background and Literature Review

2.1 Virtual reality

Virtual reality (VR) uses computers and human-computer interfaces to generate effects in the three dimensional (3D) space and its users can interact with virtual objects (Bryson, 1996). Some argue that VR is an effect created by computers and not an illusion, and some consider it is an illusion (Bryson, 1996; Ellis, 1994). The VR environment could also be considered the opposite end to the real environment on a reality-virtuality environment continuum (Ohta & Tamura, 1999). If the real environment is identified as an unmodeled physical world then the VR environment would be in a world that is completely modeled by computer graphics (Figure 2.1).

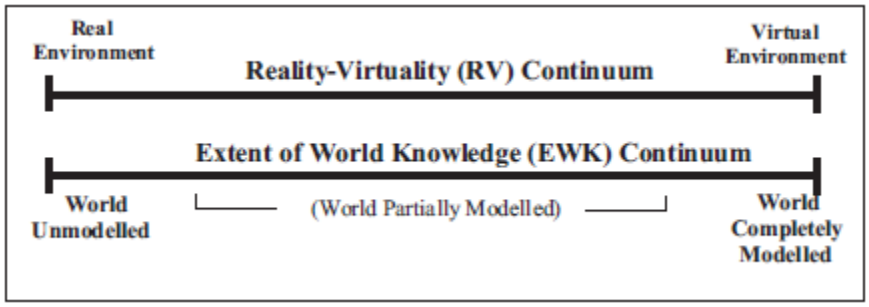

Figure 2.1. Reality-virtuality continuum proposed by Milgram & Colquhoun (1999).

Mixed reality is the area that lies in the middle of the real-virtual continuum where the environment has both visuals from the physical world and generated by computer. Within mixed reality there is augmented reality and augmented virtuality as suggested by Figure 2.2 (Milgram & Colquhoun, 1999; Pan, Cheok, Yang, Zhu, & Shi, 2006). Augmented reality is the modeled environment created through superimposition of computer generated visuals onto physical world scenes (Blade & Padgett, 2002; Pan et al., 2006). Augmented virtuality lies on the continuum between mixed reality and the VR environment, which the computer modeled environment has some elements from the physical world.

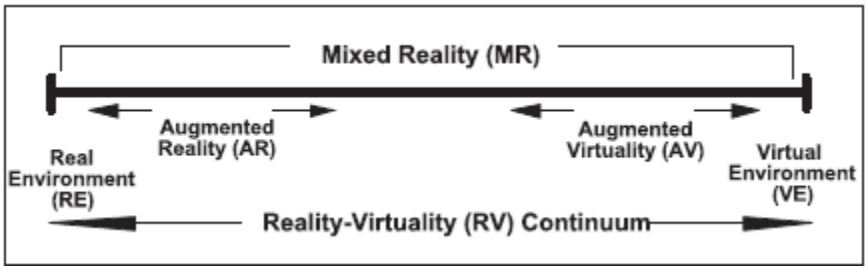

Figure 2.2. Mixed reality continuum Milgram & Colquhoun (1999).

2.1.1 User experience

Virtual reality environment lies on the opposite end of the real environment and it is an environment that is generated by computer graphics. It becomes important that users in the VR are convinced that they are at a truly at a location created by computer effects rather than where they physically are as it may affect their sense of presence (Slater & Usoh, 1993; Wilson, 1996). Virtual reality should make a user believe that the virtual environment is almost non-distinguishable from the physical world and users in an effective VR should suspend disbelief (Bates, 1992; Franchi, 1994).

2.1.1.1 Presence

Presence is the sense of being in an environment and it is often referred to the sense of being at a remote location created by VR visuals (Hendrix & Barfield, 1995; Steuer, Biocca, & Levy, 1995). Hardware, software, and the human-computer interaction features of the VR environment are the factors that could determine the extent of and affect the sense of presence (Loomis, 1992; Sheridan, 1992; Slater & Usoh, 1993). Altogether the level of technological equipment and the sense of presence could then impact user performance in VR (Bystrom, Barfield, & Hendrix, 1999; Slater, Linakis, Usoh, & Kooper, 1996). Greater the degree of presence the likelihood of the users in VR behaving naturally as the physical world is higher (Slater et al., 1996). It becomes important to understand the characteristics of the factors affecting presence because they could potentially influence the outcomes of experimental results involving human participants.

Since presence is not a quantifiable measure (Steuer et al., 1995). It is usually evaluated using self-reported subjective measures and user feedback (Hendrix & Barfield, 1995; Slater & Usoh, 1993). Based on user subjective ratings, Hendrix & Barfield (1995) suggested that larger field of view and stereoscopy technology enhanced presence. Moreover, users pointed out that "things don't behave naturally (law of physics)" and "body doesn't behave naturally" all decreased the sense of presence (Slater & Usoh, 1993). Studies also indicated that location tracking of the user provided the ability to view VR images from a first-person's perspective increased the sense of presence (Hendrix & Barfield, 1995; Slater & Usoh, 1993). Additionally, Slater & Usoh (1993) discovered that with greater proportions of visual predicates and references, the users had greater sense of presence. They identified that the proportion of kinesthetic references was able to achieve a higher sense of presence in the case where users had a virtual body in the VR compared to not having a virtual body. Additionally, increased amount of body movement was reported to have a positive association with presence (Slater, McCarthy, & Maringelli, 1998).

Attempts to provide a better measure of presence, Witmer & Singer (1998) have proposed and assessed the reliability of a self-developed presence questionnaire as to evaluate the effectiveness of VR. However, it had a slight variation in the definition of presence and was not recommended by others in the field of VR (Slater, 1999). An alternative indicator such as physiological change (e.g. varying heart rate) was identified as a measure for an effective sense of presence (A. Van Dam, Laidlaw, & Simpson, 2002).

2.1.1.2 Immersion

As opposed to a psychological sensation of presence, immersion is another characteristic of VR that is a measureable quality of the VR technology (Slater, Usoh, & Steed, 1995). Immersion of a VR system depends on computer graphics, sound, haptics, system that senses human state and emotion, and advanced user interfaces (Zyda, 2005). This proposed research follows the definition of Slater and colleagues such that criteria for immersive displays are "extensive, surrounding, inclusive, vivid and matching" (Slater et al., 1996). More sensory feedback that a VR system accommodates, the more extensive it is. The more natural a user receives the sensory feedback it has a greater level of surrounding as it could be perceived

from any direction. It is inclusive if all external environmental cues are obstructed. The VR system is more vivid as its feedback quality is richer, higher in resolution, and better in information content. The matching between the user proprioception and display on the feedback is also a criterion for immersiveness. It is important to identify good quality immersive technology and the necessary components to enhance user presence in the VR in order to study natural user interaction with virtual objects in VR, yet the extent of the sense of presence varies by individual (Slater et al., 1995).

2.1.2 Applications of VR technology

Virtual reality technology has numerous practical applications and is high in research value as it allows users to be immersed in an environment and potentially have a sense of presence. Users inside VR can be placed in environments that they usually do not go to, are impossible to visit, perform activities that are dangerous to conduct in the physical world, and can provide users different ways to visualize entities from new perspectives (Rose, Brooks, & Rizzo, 2005; Wilson, 1996). Its wide application could be seen in research, gaming, industry, art and display, education and training, and medically related fields (Rickel & Johnson, 1999a; Wilson, 1996). Examples of industrial usage of VR are planning, plant layout, product design, and job training (Wilson, 1996). Besides the cool factor in VR and innovating, VR has the potential in manipulating the users' perception of the environment, and research has shown that it was capable in enhancing the effectiveness of learning and rehabilitation.

Research on user performance in VR has been studied and it is often compared to human performance in the physical world. It was generally agreed that humans tend to underestimate distances in VR compared to the physical world and it was less efficient in performing tasks, indicated by longer task time (Alexandrova et al., 2010; Interrante, Ries, & Anderson, 2006; Liu, van Liere, Nieuwenhuizen, & Martens, 2009; Bob G Witmer & Kline, 1998). Yet, humans are generally poor at assessing distances and there were errors in distance estimation in the physical world as well. Task performance efficiency was observed to be lower in VR also (Liu et al., 2009). Another research related application of VR is scientific visualization, which is using images created by computer graphics to enhance the understanding

of more complex and massive information (Bryson, 1996). Visualizing data in VR has the advantage over non-immersive displays because VR provides spatial and depth cues, and the peripheral vision aids in viewing in 3D (Bryson, 1996; A. Van Dam et al., 2002). One VR visualization application is design, including architectural and landscape planning (A. Van Dam et al., 2002). On the other hand, excavation sites have been reconstructed in CAVEs for studying archaeology and visualizing data (Acevedo, Vote, Laidlaw, & Joukowsky, 2001). In addition to static visually mediated objects viewed in 3D, researchers also have visualized the dynamics of geophysical interactions as well as biodynamics of blood flow and cellular visualization, and users reported positively about the usage of 3D visualization for understanding their field of interest (Camp, Cameron, Blezek, & Robb, 1998; Forsberg et al., 2000; Ohno, Kageyama, & Kusano, 2006; A. Van Dam et al., 2002).

Since VR is a computer generated environment with visually mediated objects it allows people to perform activities in a safe and controlled conditions and therefore it makes VR a good tool for training (Grady, 2003). Numerous practical applications in VR have been explored. Some VR training systems provide a trainer to guide the trainee through the drills and some allows the user to practice with the visually mediated tools (Rickel & Johnson, 1999a, 1999b). There are many training and teaching applications of VR and the following section describes a few of them. Surgical training using computer simulations or VR systems is one application of training as it is not acceptable to practice on patients (Taffiner, Sutton, Fishwick, McManus, & Darzi, 1998). Arthroscopic and laparoscopic surgical simulations were used to train surgeons (Hamilton et al., 2002; Seymour et al., 2002; Taffiner et al., 1998; Zhang, Zhao, & Xu, 2003). Based on the definition of VR the two training simulations above do not qualify as a VR training tool as it did not permit the trainees to view in stereo but the images were displayed in 3D on a computer screen to simulate the patients wound. The Virtual Intracranial Visualization and Navigation system allows users to interact with 3D objects and conduct surgical training procedures in stereo (Kockro et al., 2000; Spicer & Apuzzo, 2003). Vehicle operations including airplanes, automobiles, and industrial vehicles (e.g. cranes) also have been trained using stereoscopic VR (Grady, 2003; Xu, 2006).

Furthermore, military training using stereo VR are often accompanied by flight simulation and team training (Moshell, 1993). Team training or collaborative work allows users to work together using VR so that they could train teamwork skills or remotely work together, yet delays may lead to real-time collaboration disruption (Fraser et al., 2000).

Medical applications involving VR technology is not a new concept as it has been used to treat numerous health related problems, including stress, phobias, pain management, psychological dysfunction, and rehabilitation (Riener & Harders, 2012; Schultheis & Rizzo, 2001). Previous studies have shown promise in VR for treatment related purposes (Schultheis & Rizzo, 2001). The ability to tailor the treatment for individual needs and provide repeated rehabilitative training in an ecologically valid environment generated by VR are the advantages for using VR in medically related fields (Riener & Harders, 2012; Rose et al., 2005; Schultheis & Rizzo, 2001).

Besides serving as a medical treatment device, the possibility of VR as a cognitive and physiological assessment device was also examined (McGeorge et al., 2001; Rose et al., 2005; Sarig-Bahat, Weiss, & Laufer, 2009). Traumatic brain injury (TBI) patients performed a series of cognitive based tasks in a VR kitchen environment and their performance examined was by computers (Christiansen et al., 1998). The authors reported that VR was a relatively reliable tool for assessing cognitive function and it would have greater reliability if the tasks were more cognitively demanding. Cervical spine range of motion (ROM) was measured in asymptomatic patients; it was reported that the ROM assessment performed in VR was more precise than the conventional method and participants' ROM increased after assessment in VR (Sarig-Bahat et al., 2009). Additionally, chronic neck pain patients' cervical spine ROM was measured to be greater in VR than in conventional measurement setting, which suggested that VR may be able to distract patients from their pain and help overcoming kinesiophobia (Bahat, Weiss, & Laufer, 2010; Sarig-Bahat, Weiss, & Laufer, 2010). Moreover, VR has been used to distract user attention from pain during wound care or chemotherapy to manage patient anxiety (Gold, Kim, Kant, Joseph, & Rizzo, 2006; Hoffman, Doctor, Patterson, Carrougher, & Furness III, 2000; Morris, Louw, & Grimmer-Somers, 2009).

In addition VR has shown success in distracting induced pain (Hoffman, Garcia-Palacios, Kapa, Beecher, & Sharar, 2003). Hoffman et al. (2000) suggested that stereoscopic VR was more effective than non-stereoscopic gaming distractor. Gordon and colleagues demonstrated that users' pain distraction using HMD was not different from using a large projection screen; however the distractor game scenario was not displayed in stereo (Gordon, Merchant, Zanbaka, Hodges, & Goolkasian, 2011). Various VR rehabilitation and medically related applications are further discussed in later sections.

2.1.3 Human factors in VR

Although VR is large in potential for various applications there exist some concerns regarding this technology. Symptoms of discomfort such as eye strain, head ache, blurred vision, disorientation, diplopia, nausea, and vomiting have been reported after experiencing VR or performing visual scanning tasks in VR (LaViola Jr, 2000; Mon-Williams, Warm, & Rushton, 1993). Wilson (1996) has identified four issues; visual and musculoskeletal ergonomics, and disorientation were two physiological issues, and the two other issues are behavioral changes and VR dependency, i.e. addiction. Users have different levels of susceptibility due to differences amongst individuals, which means not everyone will experience these problems. Below reviews these concerns and it is separated into two discussions that one examines the physical ergonomics aspects and the other is related to cognitive human factors.

2.1.3.1 Physical Ergonomics

Items in VR are visually mediated objects and users heavily rely on their visual sensory to perceive the information. Stereoscopic images enhance the sensor of depth perception in VR but it has been labeled as an ergonomic issue (Bolas, 1994). In the physical world, the eyes focus (i.e. accommodate) on a given target as they converge together and the accommodation and convergence distances are the same (Wilson, 1996). However in VR, eyes try to converge on a visually mediated object generated by the system in which the image is not necessarily at a distance to focus. This is because the generated image might not be on the screen and therefore there exists a mismatch between accommodation and convergence. This poses strain on the eyes and results in "eyeache" and headache (Wilson, 1996). Moreover, stereoscopy in

VR is generated through displaying two images – one image to each eye of the user with minor differences. This creates a sense of visual disparity similar to the physical world as two eyes have binocular disparity because the two eyes perceive different spatial distribution of light, which provides depth perception (Foley, 1967). Each of the two VR images displayed to the user should be collinear to each eye of the user otherwise the users would see the VR image from an off-center portion (Howarth, 1999). However each user has different distances between the two eyes, or interpupillary distance (IPD), and it would be problematic as the distance between the VR images delivered to the eyes are not customized for each individual and also affects the ability for users to converge on an image and then in turn lead to eye strain.

Users in VR have reported experiencing feelings of discomfort and develop symptoms similar to motion sickness that people may experience in the physical world (Cobb, Nichols, Ramsey, & Wilson, 1999; LaViola Jr, 2000; So, Lo, & Ho, 2001). Researchers distinguish the sense of irritation in VR from motion sickness in the physical world, and it is referred to as cybersickness as it is not a result from actual physical motion but rather the discomfort that has developed from the sense of motion suggested by the visuals in VR (LaViola Jr, 2000; So et al., 2001). Stanney and colleagues have further asserted that cybersickness is different from simulator sickness such that the severity of sickness is three times greater in cybersickness (Stanney, Kennedy, & Drexler, 1997). It was suggested that the users experiencing cybersickness are more disoriented, followed by nauseous, and then oculomotor-related disturbance (e.g. eye strain). The most commonly accepted theory to cybersickness is the sensory conflict theory (Cobb et al., 1999; LaViola Jr, 2000; Regan, 1995). The visual display from VR suggests the user that motion is occurring but actually the vestibular system does not perceive the same sensory feedback and therefore induces an impression of self-motion, or vection (LaViola Jr, 2000; McCauley & Sharkey, 1992; So et al., 2001). When users in VR receive sensory information from the system that is not expected by the user based on experience, a conflict arises. Another factor that may lead to sensory conflict is the lag of the VR system in which the delay in displaying the appropriate visual feedback has reported performance

problems and discomfort (Wilson, 1996). Research has shown that increased movement of objects in VR has significantly increased the level of nauseous and higher simulator sickness questionnaire scores (So & Lo, 1999).

These physiological effects on the user may impact user task performance and reduce the sense of presence (Lewis & Griffin, 1997). As a result this may alter data collection in a research study. Potential concerns may arise in the proposed study since we are trying to impose mismatch between user visual feedback and proprioception. However it is expected that cybersickness is relatively unlikely to occur as the users will be not be performing locomotion, which will less likely to introduce discrepancies between the visual and vestibular systems and then less likely to induce vection.

2.1.3.2 Cognitive human factors

On the other hand VR may pose potential cognitive effects on the users.

Users in a VR system with high levels of fidelity and sensory feedback may be at risk of information overload (Behr, Nosper, Klimmt, & Hartmann, 2005). Output from the VR system is intended to provide information to the user such that they may have a greater sense of presence and therefore the output device may be very obtrusive (Behr et al., 2005). As a result the user may not be able to selectively filter the desired information and potentially be presented with the problem of overloaded information.

Moreover, the reconstructed environment in VR may lead to the intensification of user experience and impact the user mental state and cognition (Behr et al., 2005). Users may be exposed to certain stimuli in VR and then lead to emotional arousal, such as fear or stress, which further intensifies users' emotions and then may limit the users' coping abilities. Suppose this was a research experiment, the unintentional effects on the user may be a confounding variable, and it negatively affect the user's well-being (Behr et al., 2005).

The users' cognitive state may need to readapt to the physical world after exiting the VR system (Behr et al., 2005). Researchers may be concerned about users' initial performance when participants just entered the VR system, and the users may spend some time to adapt to VR. However, researchers may overlook the potential need of users readapting to the actual world after experiencing VR. It is probable that users may face some difficulties transitioning back to the physical world (Behr et al., 2005). Users may experience cognitive disturbances as they do not distinguish between the information they acquired in VR and attempt to apply that to the physical world (Behr et al., 2005). Yet this may be an advantage for VR training purposes.

Extending the transferal of knowledge back the physical world, there could be the potential of negative skill transfer from VR back to the physical world (Lewis & Griffin, 1997). Users may have strategically developed a set of behaviors just for performing tasks in VR and these behaviors do not represent the natural behaviors they exhibit in the physical world. Though users have acquired new skills sets through training in VR they may not be able to perform them in the physical world.

2.2 Virtual reality system components

There are three components of a VR system: processing units such as computers, sensors that allow user control input, and effectors also output feedback; the latter two serve as the interface between the user and the computer (Grady, 2003; Steuer et al., 1995; Wilson, 1996). Arguably, the user him/herself is another component of a VR system (Grady, 2003). High-performance computer graphics system renders the visual effects of VR and the user receives the output from a head-tracked stereoscopic display (effector), while allowing inputs from the user to the VR system (Bryson, 1996; Ellis, 1991, 1994). In addition to visual effects, auditory and tactile feedback may also be generated by the computer, which may affect user experience in VR (Grady, 2003). Below describes some of the effectors, including VR display system, tracking equipment that recognizes the location and movement of the user with respect to the VR

objects, equipment allowing input and interaction between the user and VR, and potentially equipment that provides sensory feedback in addition to visual displays.

2.2.1 Visual display systems

Visual effects in VR are rendered by computers, which are generated images that rapidly change to reflect the users' actions (Grady, 2003). Various devices were used to display visual effects to the users. They vary in sizes and also have different levels of immersion. In the past VR systems have been categorized into four main areas, including cathode ray tube (CRT) based monitor, head mounted display (HMD), binocular omni-oriented monitor (BOOM), and Cave Automatic Virtual Environment (CAVE).

2.2.1.1 Monitor VR

In this proposal the usage of single monitor or multiple monitors are categorized as monitor VR. Single CRT based monitor or window system generally refers to visual display systems using monitors (desktop computer or television) and it is generally considered non-immersive (Sharples, Cobb, Moody, & Wilson, 2008; Slater et al., 1996). Sharple and colleagues further asserted that visual displays from standard computer monitors were often not considered as true VR (Sharples et al., 2008). The field of view (FOV) is limited to approximately 45 degrees makes this type of display system not immersive (Cruz-Neira, Sandin, & DeFanti, 1993; Cruz-Neira, Sandin, DeFanti, Kenyon, & Hart, 1992). Also, considering the characteristics of monitor display systems this proposed research classifies visual display systems that do not completely obstruct external physical environmental cues as non-immersive visual display system. Fish Tank VR is one type of single CRT monitor based visual display system (Ware, Arthur, & Booth, 1993). The images of a Fish Tank VR are three dimensional stereoscopic and the visuals are displayed with respect to the user as the head position of the user is coupled to the monitor. The stereo images are created by wearing shutter glasses.

The advancement in technology enabled research to incorporate more complex display system that involves multiple liquid-crystal display (LCD) monitors. The Leeds Powerwall at the University of Leeds

at the United Kingdom has developed two visualization systems that are both tiled display systems (Hodrien, Wood, & Ruddle, 2007). The larger system consists of 28 vertical panels with a combined resolution of 53 megapixels and the smaller system with 23 megapixels combined from 12 horizontal panels that is referred to as the Powertable (Hodrien et al., 2007; Ruddle et al., 2013). Tiled display system has been used for applications such as flight simulation (Le Ngoc & Kalawsky, 2013). The advantage of having multiple monitors tiled together to form a display system is potentially increasing the quantity and the ability to display the fine details and it was reported that users were less likely to identify same target twice with more monitors (Ball & North, 2005b). However the tiled monitor display systems have seams between the monitors and disrupt the continuity of the display system, which is referred to as the interior bezel issue (Ball & North, 2005a; Bi, Bae, & Balakrishnan, 2010). Ball and North suggested that the bezel could potentially help users to organize their viewing items (Ball & North, 2005a). McNammara and colleagues stated that user performance on navigation tasks was not influenced by display discontinuity and Bi and colleagues also reported that user target search performance was not affected by interior bezel but accuracy was negatively impacted (Bi et al., 2010; McNamara, Parke, & Sanford, 2011). These tiled display systems described above did not identify them as stereoscopic.

However one could occlude the external visual cues by looking through two modified eye holes similar to binoculars and view displays two cathode ray tube (CRT) monitors while tracking the user head location. This is called a Binocular Omni-Oriented Monitor (BOOM) that was developed by Fake Space Labs (Bryson, 1996; Cruz-Neira et al., 1992; Strickland, Patel, Stovall, Palmer, & McAllister, 1994). The viewing directions of a BOOM are adjusted by the user. The BOOM would be considered as an immersive VR display system (Bolas, 1994).

2.2.1.2 Screen projection VR

The mirror, vehicle-based, and CAVE systems utilize projections onto screens to display VR visual effects. A mirror system operates on the idea that the users see their own image projections superimposed in the visual display on a screen that is recorded by the system's videoing equipment, i.e. the

VIDEOPLACE system and the ALIVE system (Grady, 2003; Krueger, Gionfriddo, & Hinrichsen, 1985; Maes, Darrell, Blumberg, & Pentland, 1995). Vehicle-based system allows users to be physically situated inside a vehicle and then operate the vehicle in stationary while the visual displays that are projected onto a screen move with respect to the movement of the vehicle (W.-S. Lee, Kim, & Cho, 1998). The CAVE is a confined cubic space with rear projections on all six screens of the cube and it was first introduced by Cruz-Neira et al. (1992). It is "real-time viewer-centered head-tracking perspective with large angle of view, interactive control, and binocular display" (Cruz-Neira et al., 1993). Users inside a CAVE views the stereoscopic display through shutter glasses that creates binocular disparity while the user location is tracked, and the user interacts with virtual objects using a controller called wand (Bowman, Datey, Ryu, Farooq, & Vasnaik, 2002; Ni et al., 2006). Tracking allows the system to render images based on the use location so that as the user traverses in the CAVE the viewpoint updates accordingly (Bowman et al., 2002). There are variants of the CAVE that may have fewer projection screens, for instance the Hanover Immersive Virtual Environment that has three screens and the users wear shutter glasses and the PC-based distributed CAVE (Cliburn & Stormer, 2005; Li, Chang, Hsu, Kuo, & Way, 2001).

Big advantages of a CAVE are that it has at least 180 degrees to full FOV of a human, relatively low tendency of experiencing motion sickness compared to other VR systems, and high level of immersion (Bowman et al., 2002; Cruz-Neira et al., 1992; Cruz-Neira et al., 1993). However the high cost of constructing a CAVE and the fragility of the screen surfaces are its limitations. One other advantage of projection-based VR is the elimination of the bezel effect as there is no monitor frames (Ni et al., 2006).

There are also VR systems that are composed by multiple screens. Hereld, Judson, and Stevens referred to those systems also as tiled display systems and they are semi-immersive (Hereld, Judson, & Stevens, 2000). The ActiveMural is a rear-projected tiled display system that utilizes four screens aligned adjacent to one another with a combined resolution of 5120*2304 pixels from 15 projectors (Figure 2.3) (Hereld, Judson, Paris, & Stevens, 2000; Hereld, Judson, & Stevens, 2000). Users do not view the display in stereo.

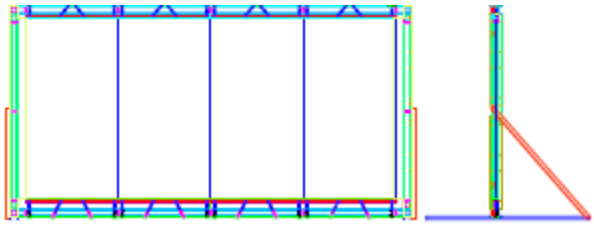

Figure 2.3. Schematic diagram of the ActiveMural system with four screens adjacent to one another (Hereld, Judson, Paris, et al., 2000).

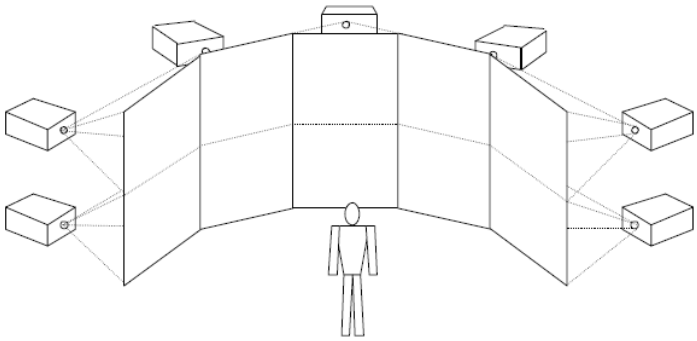

Figure 2.4. PowerWall ™ layout at the University of Minnesota (Elder et al., 2000).

The InTENsity PowerWall™ system at the University of Minnesota is also another variant of the screen projection VR system, where fives screens are oriented radially around the user who stands in the center of the screen (Elder et al., 2000). This system also uses the rear-projection that uses 10 projectors, with a combine resolution 6400*2048 for the entire PowerWall (Figure 2.4).

2.2.1.3 Head-mounted display VR

A head-mounted display (HMD) is a displaying device that is worn on the head of the user with small CRT of liquid-crystal display (LCD) located in front of each eye (Grady, 2003; Shibata, 2002). An HMD that completely obstructs the visual cues from the physical environment creates an immersive VR system while an HMD that allows partial see-through with the ability to superimpose VR visual effects onto the physical environment scenes is an augmented reality system (Maimone et al., 2013; Shibata, 2002). Typically the images displayed by an HMD are in stereoscopy because it is capable presenting individual images to each eye and therefore creating binocular disparity (Shibata, 2002). The stereoscopic images

are presented to the user based on the user posture and motion detected by the location tracking system accompanied with that HMD.

Since HMD is a display device worn on the head of the user it may have some ergonomic concerns and it may drive the specifications for an HMD used for various applications. Firstly, the weight of the HMD is situated anterior to the head since bulk of the HMD weight comes from the displays that are located in front of the eyes (Knight & Baber, 2004; Wilson, 1996). This may affect the user's ability to perform natural head movements. Moreover head load could cause pain and discomfort as it has significant effects on the musculoskeletal system of the head and neck region (Knight & Baber, 2004, 2007). It could potentially exacerbate the symptoms in the chronic neck and shoulder pain patients as perceived pain was significantly higher when users wore helmets weighed 1.3kg compared to not wearing (Knight & Baber, 2004). These would impact the data collection results and therefore the weight of the HMD should be carefully chosen for this proposed experiment.

The FOV and display resolution are also related to user performance when wearing an HMD or a helmet-mounted display and therefore these should be taken into design consideration (Arthur, 1996; Rash, McLean, Mora, Ledford, & Mozo, 1998; Schiefele, Albert, Doerr, Kelz, & Schmidt-Winkel, 1999). Narrow FOV negatively affected user performance as target recognition ability decreases and head motion increase which leads to head and neck muscle fatigue (Arthur, 1996; Rash et al., 1998; Wells & Venturino, 1990). However there is a tradeoff between FOV and display resolution as larger FOV results in the spreading of pixels and lead to image distortion (Bowman et al., 2002). The effect of display resolution on user performance was found in other display systems and the general consensus is that lower resolution negatively impacts user performance (Ziefle, 1998).

2.2.2 User input and tracking

Various input devices have been used to control or interact with items in VR, including computer mouse, joystick, gloves, or even tracked stylus (Grady, 2003.; Liu et al., 2009). Users in a vehicle-based system

usually use the lever or the steering wheel to control and interact with the VR system. Sutcliffe and colleagues studied user interaction with virtual chess using hands with pinch gloves in a CAVE based on the collision of the user's hand and the chess pieces (Sutcliffe, Gault, Fernando, & Tan, 2006). Another study explored human interactions with a ball in the "Virtual Catch Ball" large scale multi-projector system using strings (Jeong, Hashimoto, & Makoto, 2004).

Another method of user input is through direct user gesture or movement tracking and the VR system determines if the user location intercepts the location of the VR object. Although this was not performed in VR, Takahashi & Kishino (1991) used a hand gesture detection device for recognizing 46 manual Japanese alphabets and the gesture interface was able to recognize 30 joint angles and movements. Recent development of the Microsoft Kinect, which is a motion sensing device with a depth sensor, a color camera, a four-microphone array for full-body 3D motion capture, facial and voice recognition (Zhang, 2012). The location of the user is sensed by the depth sensor, in which utilizes infrared (IR) projection and receiver to reconstruct the tracked user location. The ability of the Kinect to track user postural changes and movements has been validated and its functions are comparable to a three-dimensional camera tracking system with anatomical markers (Clark et al., 2012). Ultrasonic wave is also used as a method of tracking and InterSense, Inc. has been developing various input devices that were tracked using ultrasound that is being used by various VR systems worldwide (Wormell & Foxlin, 2003). Ultrasonic system enables 6-degrees-of-freedom tracking in larger areas (Wormell & Foxlin, 2003). For instance, the CAVE utilizes ultrasound as a method of user location tracking. Ultrasonic wave emitters are places along the edges of the CAVE cubic walls and the emitted waves are received by the location tracker worn by the user. Through the location tracking of the user the display system generates images that are based on the specific user's perspective. Moreover, the wand, or the input controller of the CAVE, is also equipped with ultrasonic sensors that allow the user to interact with the virtual objects.

On the other hand, instead of using waves to locate users Fitzgerald and colleagues developed a motion capture suit that was used for rehabilitation in athletes (Fitzgerald et al., 2007). As the athletes perform the instructed exercises from the computer, the suit was tracked and analyzed. Moreover, some have explored user inputs using physical items. For instance, users touched a physical object and the movement of the physical object was tracked by sensors and in return controlled the movement of the same virtual object seen in the HMD (Hoffman, 1998). This required an actual physical item in VR, and it would not be practical to have physical objects in VR for all items that needed to be interactive.

Despite of most existing research tries to make the simulation in VR resembles the physical world as closely as possible (e.g. using pinch gloves to capture finger motion) some research investigates the potential using bio-signals as an input method to control virtual objects. Using bio-signals as an input to control VR objects requires the calibration of the VR system to adapt its parameters to the current user of the VR system (Lécuyer et al., 2008). Brain signals in the form of electroencephalogram (EEG) individuals' mental processes may be identified and then be used as the input interface for computer systems (Bayliss & Ballard, 2000; Berg, Junker, Rothman, & Leininger, 1999; Friedman et al., 2004, 2007; Leeb, Scherer, Lee, Bischof, & Pfurtscheller, 2004). In addition to EEG, forehead EMG was also used with EEG to operate flight simulations and user performance improved over time (Nelson et al., 1997). Doherty and colleagues applied the CyberLink as an assistive technology for computer input interface for individuals with mental and physical disabilities but only one out of their ten participants demonstrated high input accuracy (Doherty, Cockton, Bloor, & Benigno, 2001). EEG user input to control movements of avatars (virtual persons) was investigated and the results indicated that users were able to rotate and translate their avatars in a four-sided CAVE (Friedman et al., 2004, 2007) and wearing HMD (Leeb et al., 2004). Additionally, Leeb and colleagues demonstrated successful control of avatar translation through feet movement imagery with EEG in a case study of a wheelchair patient who had a spinal cord injury (Leeb et al., 2007). It was subjectively commented that EEG control of avatar was natural (Friedman et al., 2007).

2.2.3 Output and sensory feedback

It is generally suggested that human proprioception of a three dimensional (3D) environment involves vision, auditory, and touch (Grady, 2003). Out of the five senses vision is the most greatly used one, followed by auditory and then touch. VR provides visual feedback using its visual display system and some research has explored the option of including haptic feedback in VR as they are important for immersion in VR.

Force feedback has been incorporated to virtual reality training, such as the Personal Haptic iNTerface Mechanism (PHANToM) and the Cyberglove. The PHANToM is a force feedback device that has 6 degrees of freedom. The instrument has a stand and an arm connected to it, and a pen-like device attached to the arm. The user grips the pen and the location of the user fingertip is measured, and the device exerts a force vector on the fingertip of the user (Sallnas 2000). The user grips the pen and interacts with an object on a screen. If the position of the hand gripping the PHANToM pen intercepts the location of the virtual object on the screen (and protrudes the object), the PHANToM sends a resistive force to the pen and pushes the tip of the pen to return to the surface of the object. The Cyberglove is a light-weight sensing glove that measures finger grasping and abduction/adduction motions, and it can provide resistive forces up to 16N per fingertip. It relies on pneumatic actuators that are low-friction glass-graphite pistons (Burdea, Popescu, Hentz, & Colbert, 2000; Popescu, Burdea, Bouzit, & Hentz, 2000). Connelly and colleagues developed an air pressure controlled pneumatic glove for VR hand rehabilitation that provided haptic feedback, which was used together with HMD visual feedback (Connelly et al., 2010). Additionally, the study done by Jeong et al. (2004) demonstrated the ability to use hands to catch a moving ball that was thrown by a virtual avatar, and force feedback to the user's movement was provided by a string-based haptic interface.

2.3 Electromyography control and algorithm

Virtual reality objects are computer generated visually mediated items. Unlike physical items these VR objects lack tactile features and physical resistance. Typically users would rely on a controller for inputting commands interact with VR objects instead of directly moving VR objects with hands. To be able to perform functional movement patterns in VR that is comparable to traditional rehabilitation in the physical world, it becomes important to overcome the challenges of absence of tactility and resistance, and indirect interaction with VR objects.

In the physical world, muscles are recruited when humans move physical items and action potentials are evoked. The action potentials are recorded as electromyography (EMG), which are waves of nerve impulses fired to signal muscle contraction during an event of object manipulation. Electromyography signals and other bio-signals such as EEG and EOG have been implemented in prosthetics, robotics, and wheelchair control and device activation (Hashimoto, Takahashi, & Shimada, 2009; McMillan, 1998; Tsui, Jia, Gan, Hu, & Yuan, 2007). It has been proposed in as early as 1947 by Norbert Weiner (Bottomley, 1965). Battye and colleague were the first to successfully control the movement of hand prosthesis, controlled by EMG, to grasp and hold a pencil (Battye, Nightingale, & Whillis, 1955). Bottomley (1965) has described the early hand prosthesis control mechanism as the activation of a pair of agonistic and antagonistic muscles. It required the EMG signal of the flexors to activate the closing movement of the hand, and then it was necessary for the activation of the extensor EMG signal to relax the grasping movement. More complex EMG controlled prosthetic movements could be made possible with the additional EMG inputs of additional numbers of muscles to achieve the multiple degrees of freedom that a physiological hand has (R. F. Weir, Troyk, DeMichele, & Kerns, 2006). Although EMG signals are capable in controlling prosthetics, there exist challenges such as skin and tissue impedance, noise and interference from the environment (Lai, Schoen, Gracia, Naidu, & Leung, 2007). Additionally, EMG signal characteristics vary according to the state of the muscles, such as muscle fatigue, and therefore results in a shift of EMG frequencies that might influence the identification of desired EMG

signal for prosthetic activation. Later it has been identified that EMG could be used as signals for controlling virtual arm movements displayed on computer screens for studying motor control, and even injuries (Manal & Buchanan, 2005; Manal, Gonzalez, Lloyd, & Buchanan, 2002).

Relationship between EMG and muscle force exertions has also been studied and experimentally determined. It was found that rectified surface EMG could approximate linear relationship with tension produced by muscles during isometric contraction (De Jong & Freund, 1967; Lippold, 1952; Moritani & DeVries, 1978). Muscle torque and integrated EMG signals were generally linear in the forearm flexors, and better linearity was exhibited in the leg extensors (J. P. Weir, Wagner, & Housh, 1992). However, some studies have shown that summation of motor unit EMG potentials is non-linear at high tension levels, or a general non-linear relationship between EMG and muscle tension was identified (Milner-Brown & Stein, 1975; Zuniga & Simons, 1969). There is not a definite EMG-tension relationship that could be generalized to all muscle groups. For instance, the four muscle groups of the quadriceps exhibited varying EMG-tension relationships during one isometric contraction, such that one of the three superficial groups of the quadriceps exhibited linear EMG-tension relationship and two groups were non-linear (Alkner, Tesch, & Berg, 2000). These findings suggested relationships between EMG and muscle tension, which makes it feasible for us to impart physical characteristics to the virtual objects, and then allow the manipulation of VR objects based on the monitored EMG values.

There are multiple factors that influence muscle tension production, including the size of the muscle such as physiological cross-sectional area (PCSA) and its length, muscle mass, and how quickly the contraction is happening (Winter, 2009) The PCSA is usually constant however muscle length varies at different joint angles. Typically muscle force production decreases as muscle fiber lengthens or shortens relative to the resting length, which is described as the force-length relationship. On the other hand, the force-velocity relationship suggests that as velocity of the muscle contraction increases, the amount of force produced decreases. A biomechanical model that consists of mass, spring, and damper could link the relationship between the possible physiological factors and muscle force production (Buchanan,

Lloyd, Manal, & Besier, 2004; Winter, 2009). The Hill-Type model (Equation 2.1) is a commonly used biomechanical model that estimates muscle force production from contractile elements of the muscle fiber (Buchanan et al., 2004).

$$F^m(t) = f(v)f(l)a(t)F_o^m \qquad \text{(Equation 2.1)}$$

Fm(*t*) represents muscle force production varying over time, f(*v*) is the normalized velocity dependent fiber force, f(*l*) is the normalized length dependent fiber force, a(*t*) is the time varying muscle activation, and F^m_o is the maximum isometric muscle fiber force. This will help to determine the force production of desired muscles when lifting an object for a given weight. The determined muscle forces could then be mapped onto the experimentally derived EMG-tension relationship to estimate the magnitude of the EMG signal that would be measured when operating an object with a set weight.

2.4 Neck and shoulder pain

Pain of the neck and shoulder region has been receiving a lot of attention because of its impact on patient's activities of daily living and musculoskeletal function (Falla & Farina, 2007). In a sampled adult (age 18 and above) population in the United States in 2014, 35.2% reported shoulder pain in the past 30 days and 16% reported neck pain in the past 3 months (NCHS, 2015). Moreover, it is a costly problem for medical resources, from the work aspect, and personal suffering and disability (Ferrari & Russell, 2003). The most common causes of neck pain are muscle strain and ligament sprain characterized by stiffness and/or pain (Ferrari & Russell, 2003; Meleger & Krivickas, 2007). Muscle strain is from a single event where a large amount of force is posed on the anatomical structure and ligament sprain is a result of stretching of the ligamentous structure beyond the physiological range of motion (ROM) (Meleger & Krivickas, 2007). Neck pain resulting from the mechanical disruption of the tissues is classified as musculoskeletal injury and the majority (95%) of the neck pain patients is diagnosed with a problem of a musculoskeletal origin (Ferrari & Russell, 2003; Kumar, 2001).

2.4.1 Musculoskeletal injury and musculoskeletal disorder

It is important to make the distinction between musculoskeletal injury (MSI) and musculoskeletal disorder (MSD) as they have different clinical meanings. The onset of a MSI is sudden and it involves mechanical impact to the musculoskeletal structure but a MSD can result without a mechanical impact and MSD can occur gradually (Kumar, 2001). Musculoskeletal injuries that occur repetitively, involve forceful motions, or awkward postures may lead to repetitive strain injuries, which is a collective term referring to MSD (Yassi, 1997).

Musculoskeletal disorders (MSDs) are inflammatory or degenerative conditions that affect the physiological or anatomical characteristics of the tendon, muscle, nerve, vascular, bursa, and bone or cartilage (Freivalds, 2011; Punnett & Wegman, 2004). Activities that involve high force demands, high rates of repetition, awkward postures, and are long in duration are considered having the risk factors for MSD (Gallagher & Heberger, 2013). Additionally, physiological or psychosocial factors, diseases, and personal factors are related to MSD.

MSDs that occur at different anatomical structures are characterized by different symptoms. The characteristic features of MSDs of tendons are inflammation, swelling, and localized pain (Freivalds, 2011; Punnett & Wegman, 2004). Over usage of tendons can result in degeneration to tendon structures and result in micro tears. Disorders of the muscles start with simple muscle soreness or pain from microstrains, and progression to inflammation of muscles and surrounding fibrous tissue, cramping, and limited motion (Freivalds, 2011). Nervous structure MSDs are typically from nerve entrapment that results in tingling and pain, and compression of spinal nerve roots. Low in blood supply that leads to tingling, numbness, and loss of fine control are characteristics of vascular MSDs. Inflammation and thickening of synovial tissues and thinning (degenerative) of cartilage are characteristics of joint MSDs.

2.4.2 Significance

Musculoskeletal disorder has been leading causes of disabilities during working years and they are negative health outcomes of population health (Kindig & Stoddart, 2003; Larsson, Søgaard, & Rosendal, 2007; Punnett & Wegman, 2004; Snook & Webster, 1987). Research has shown the relationship between MSD and aging, sports, and diseases such as diabetes (Arkkila & Gautier, 2003; Badley & Crotty, 1995; Vingård, Sandmark, & Alfredsson, 1995). Work-related musculoskeletal disorder (WMSD) has been used to identify the type of MSD associated with work (Grieco, Molteni, Vito, & Sias, 1998). Armstrong and colleagues have explicitly categorized MSD as a work-related disease as opposed to an occupational disease since work-related diseases are multifactorial and many factors contribute to the occurrence of a particular MSD (Armstrong et al., 1993). The conditions of WMSD typically result in pain and functional impairment of the affected region (Buckle & Devereux, 2002). It is one of the primary causes of loss of days from work in the industry and it accounts for 33 percent of all workplace injuries and illnesses (Gallagher & Heberger, 2013; U.S. Bureau of Labor Statistics, 2012). The result of days away from work affects not only the loss of the company's production but also the cost associated with the medical treatment and rehabilitation, worker's compensation, and also workers suffering from the repetitive injury (Arnetz, Sjögren, Rydéhn, & Meisel, 2003). It has been reported that on average MSD can cost up to ten times more than other workplace injuries (Arnetz et al., 2003). In general, both days away from work and the cost associated with MSD are relatively higher than other workplace injuries.

2.4.3 Causations of musculoskeletal injury

There are various causes of MSI; Kumar has categorized the causations and suggested four MSI causation theories (Kumar, 2001). Causation one is the multivariate interaction theory where many factors, including genetic, morphological and psychosocial characteristics, and occupational stressors combined all together that lead to the development of musculoskeletal injuries. Differential fatigue theory is the second suggested causation, which unbalanced and asymmetric work and daily-life activities create differential loading and fatigue on the body and its components leading to injury. Third proposed

causation theory is the cumulative loading model with a multivariate threshold of force loading, motion range, and repetition, and exceeds the bearable level and results in tissue degradation and injury development. The fourth suggested causation theory is the overexertion model is an acute incident of the third theory (Freivalds, 2011).

2.4.4 Neck injury and disorder, and chronic pain

Neck injuries, neck disorders, and pain are commonly reported and they are frequent causes for sick leaves and disability, and it is the second most common MSD reported (Borenstein, 2007; Ferrari & Russell, 2003; Jensen & Harms-Ringdahl, 2007). A new conceptual model of neck pain described that neck pain is multifactorial and it has six premises (Guzman et al., 2008). Chronic neck pain is related to various problems of mechanical and non-mechanical origins (Borenstein, 2007). Mechanical neck pain could limit a patient's ability to move the cervical spine and negatively affect their daily living activities and work and therefore chronic neck pain is of high importance (Borenstein, 2007). Decreased mobility in C7-T1 and T1-T2 regions have been demonstrated as good predictor and indicator of neck and shoulder pain (Norlander, Aste-Norlander, Nordgren, & Sahlstedt, 1996; Norlander & Nordgren, 1998). Preventive strategies for chronic neck pain suggested by Borenstein include workplace ergonomic modification, take short breaks during work time, and perform ROM exercise for the neck (Borenstein, 2007).

There exist several risk factors and potential causes of neck pain. Research has identified specific work-related risk factors for neck pain, including high force demands, posture, vibration, and computer-related work (Larsson et al., 2007). Non-work related factors is the female gender, which has been recognized as a factor for chronic musculoskeletal pain in general, as well as neck pain and upper extremity (Gran, 2003; Larsson et al., 2007). Whiplash trauma is a specific mechanical neck injury mechanism such that the sudden high acceleration or deceleration is posed to the head and the head is quickly forced backwards, forwards, or laterally, and it accounts for most chronic neck pain (Ferrari & Russell, 2003; Nederhand, Hermens, IJzerman, Turk, & Zilvold, 2003; Nijs, Van Oosterwijck, & De Hertogh, 2009;

Robinson, Theodore, Dansie, Wilson, & Turk, 2013). It is characterized by limited neck mobility and patient's range of motion is moderately correlated with patients' self-perceived disability rating from Neck Disability Index, but less physical signs of injury (Nijs et al., 2009; Robinson et al., 2013; Sarig-Bahat et al., 2010; Vernon, Guerriero, Kavanaugh, Soave, & Puhl, 2013).

2.4.5 Source of neck pain

Neck pain is defined as the pain that perceived of a region that is bounded by the superior nuchal line from the superior, an imaginary transverse line through the T1 spinous process from the inferior, and the lateral margins of the neck (Bogduk, 2011). It is considered as neck pain as long as the pain is sensed from the region described above though the cause of the pain may not be from that region (Bogduk, 2011).The potential source of pain, or the anatomical location of pain, has been experimentally stimulated. It was demonstrated that in addition to the production of pain in the cervical vertebrae, the stimulation of the upper cervical segments (occiput, C1, and C2) also produced referred pain into the head and stimulation of lower cervical segments produced referred pain into the shoulder and upper limb (Bogduk, 2011). Often pain from the nerve innervation from the C2-C3 source is accompanied with headache(Bogduk, 2011). Cervical vertebrae receive innervation from multiple sources and therefore the muscles, synovial joints, and intervertebral disks at the neck region all are potential sources of neck pain (Bogduk, 2011). It was also suggested that pain of muscles around the neck region innervated by a given cervical zygapophysial joint could result in distributed pain spreading to other regions (Figure 2.5).

Moreover, disorders of the cervical vertebrae could produce additional symptoms in other nearby regions, such as headache and pain in the upper limb (Bogduk, 2011). It is often difficult to locate the most painful disk. Maintaining balance is also a challenge in some individuals with neck pain (McPartland, Brodeur, & Hallgren, 1997).

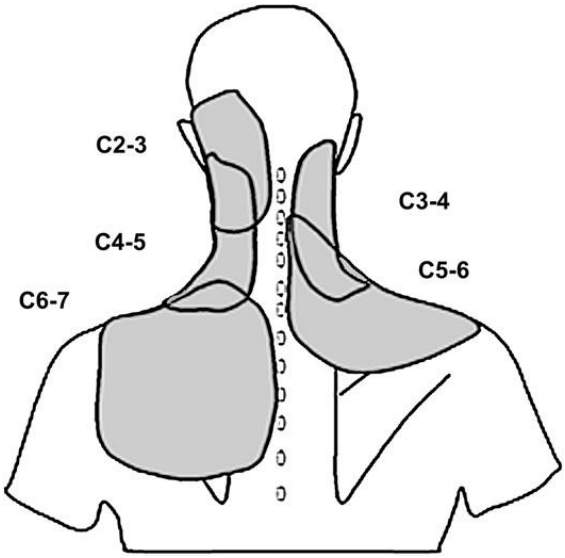

Figure 2.5. Distribution of pain after stimulation of the indicated cervical zygapophysial joints (Bogduk, 2011).

2.4.6 Existing neck pain treatment

Various treatments for chronic neck pain are used in the clinic and numerous randomized controlled trials (RCT) were conducted to better understand the efficacy of those treatments. Typically their outcome measures are neck disability index (NDI) to measure the level of neck functionality, visual analog scale (VAS) to measure patient's perceived pain, Tampa Scale of Kinesiophobia (TSK) to examine whether patients exhibit avoidance behavior because of fear of pain, SF-36 to measure quality of life, and global perceived effect to understand patients' general health perception. The lengths of RCTs varied from right after treatment to 6 years of follow up, with mostly 2 to 3 years out from initial treatment (Hurwitz et al., 2009). Moreover the definition of chronic neck pain was operationally defined differently for different studies, where some defined chronic as more than one month and some defined as at least three months (Hurwitz et al., 2009). Treatments range from non-drug based, medicinal and injection, and some studies have applied a combination of therapies that are categorized as multimodal therapy (Borenstein, 2007; Graham, Gross, Goldsmith, & Klaber Moffett, 2007; Kay et al., 2012; Kroeling et al., 2013; Vernon, Humphreys, & Hagino, 2007). Usually these treatments aimed to reduce pain intensity in patients, improvement in musculoskeletal function, improvement quality of life, and sometimes to increase patient subjective satisfaction.

Manual therapy, traction, exercise, electrotherapy, acupuncture, and ultrasound are the non-drug based therapies (Borenstein, 2007). Manual therapy is a collective term referring to types of therapies performed by hand, such as manipulation of the cervical spine (i.e. low magnitude but high velocity forces directed at cervical joint segments), mobilization of the cervical spine (i.e. low or high magnitude but low velocity force movements to the cervical spine that remain within the range of motion of the patient), and massage therapy (Gross et al., 2004; Vernon et al., 2007). In general patients with mechanical chronic neck pain have demonstrated improvements in levels of pain intensity measured by a visual analog scale (VAS) after receiving manual therapy, and manipulation and/or mobilization therapies in conjunction with exercise have shown promise in reducing pain and improvement of functionality (Gross et al., 2004; Hurwitz et al., 2009; Vernon et al., 2007; Walker et al., 2008). Tractive forces could also be applied to the neck region as treatment and it could be done mechanically or manually; it was found that patients did not benefit from traction applied continuously but intermittent traction was moderately beneficial (Graham et al., 2007). Overall, exercises that involve specific neck stretching and strengthening were beneficial for improving chronic neck pain symptoms and functionality however general exercises involving the upper extremity were not shown useful in improving neck pain symptoms (Kay et al., 2012). Although electrotherapy has been shown to temporarily reduce neck pain symptoms resulted from MSD its long term effect in chronic neck pain patients still remain debatable (Kroeling et al., 2013; Maayah & Al-Jarrah, 2010). In general acupuncture was reported to temporarily alleviate pain in patients with chronic neck pain (Trinh et al., 2006). Ultrasound therapy has been used to treat MSDs but it was not found to be effective (van der Windt et al., 2000).

Medicinal and injection therapies involve medication being administered internally to the patient via oral consumption or venous injection. Content of the therapeutic injections vary from corticosteroid, morphine, botulinum toxin, and lidocaine (Borenstein, 2007). Injection could be delivered into the muscles located at the posterior side of the neck or into the outermost area of the spinal canal called epidural injection. Results from RCTs suggested that lidocaine, methylprednisolone, corticosteroid, or

combinations of those were able to reduce chronic pain in the short term (Benyamin et al., 2009; Peloso et al., 2007). Botulinum toxin did not reduce pain in the patients (Padberg, de Bruijn, & Tavy, 2007; Wheeler, Goolkasian, & Gretz, 2001). Some evidence showed that there was a prolonging effect of epidural injection in chronic pain reduction after 1 year than injection into the muscles (Benyamin et al., 2009; Peloso et al., 2007).

Multimodal therapy can be different possible combinations of the interventions, with the commonly seeing combinations including patient education and exercise, or manual therapy and exercise. There was not a difference in the effectiveness of education and advice compared to education, advice and active exercise therapy (Scholten-Peeters et al., 2006). Similar findings in another multimodal therapies such that active exercise and behavioral support with a therapist is not different in effectiveness than performing prescribed exercise at home, but those two therapies were better than education alone (Taimela, Takala, Asklöf, Seppälä, & Parviainen, 2000). Insufficient evidence existed that would support the effectiveness of biopsychosocial rehabilitation (Karjalainen et al., 2003). Of many multimodal therapies, most experimental results and reviews supported the combination of manual therapy and exercise as it demonstrated higher effectiveness in improving pain and functionality in patients with neck pain (Hurwitz et al., 2009; Miller et al., 2010)

2.5 Pain, fear, and avoidance behavior

Individuals with neck pain may be reluctant in performing certain movement patterns during physical therapy or during performing daily activities as they are fearful of experiencing pain while performing these tasks, and therefore tend to avoid performing these activities (Picavet, Vlaeyen, & Schouten, 2002). In this case fear avoidance refers to the avoidance of movements or activities due to fear, and the term kinesiophobia refers to the behavior of fear of movement (Vlaeyen & Linton, 2000). Musculoskeletal pain intensity was found to be correlated with the level of kinesiophobia (Branstrom & Fahlstrom, 2008).

In the past fear avoidance and pain have been viewed as a sensation of pain that led to the avoidance behavior, and it was until later in the 1960s that linkages between pain, fear, anxiety, and other emotions have been studied (Vlaeyen & Linton, 2000). Lethem and colleagues have indicated two components of pain perception in the Fear-Avoidance Model of Exaggerated Pain Perception, which were the emotional reaction and the sensory component (Lethem, Slade, Troup, & Bentley, 1983). The emotional reaction component was considered to contribute to pain experience and behaviors related to pain. This becomes the basis of the fear avoidance model that will be described below. In addition to the emotional reaction, there is some cognitive behavioral characteristic in avoidance behavior as individuals with chronic pain have gradually learned to avoid pain provoking situations (Fordyce, Shelton, & Dundore, 1982; Leeuw et al., 2007).

2.5.1 Pain initiation

By definition, human pain experience is "an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage" (Merskey & Bogduk, 1994). This definition suggests that there may be tissue damage involved when pain occurs and it is accompanied by unpleasant emotional experiences. As indicated by the definition as there may be the involvement of potential tissue damage, pain serves as a warning device to alert an animal from being injured (Price, 1988). The role of pain is further suggested to promote recuperation after tissue damage has occurred (Price, 1988; Wall, Melzack, & Bonica, 1994).

2.5.2 Pain-related avoidance behaviors

In the specific case of musculoskeletal pain avoidance, Vlaeyen and Linton have suggested (1) activity and (2) fear avoidance models (Vlaeyen & Linton, 2000). The activity (movement) avoidance model described where an individual has learned to predict and react against neutral stimuli that contained negative significance to the individual. As an individual started to associate a stimulus to painful experiences, it would lead to prediction of pain and trigger fear and anxiety and then avoidance learning would begin. Vlaeyen and colleagues have also suggested that avoiding movement was associated with

the fear of reinjury (Vlaeyen, Kole-Snijders, Boeren, & Van Eek, 1995). Subjectively speaking individuals with back pain usually feel that increased physical activities could lead to more pain and suffering (Al-Obaidi, Nelson, Al-Awadhi, & Al-Shuwaie, 2000). Chronic musculoskeletal pain patients tend to attend more of their attention to pain related as indicated by their increased attention to pain-related word (Dehghani, Sharpe, & Nicholas, 2003).

The fear avoidance model contained greater cognitive aspects and it had closer connections with the development of musculoskeletal pain problems (Vlaeyen & Linton, 2000). This model (Figure 2.6) has hypothesized two behavioral responses; the confrontational behavior suggested that an individual who did not exhibit fearful responses when experienced pain after an injury would go through the confrontation stage and recover from the injury; the avoidance behavior suggested that an individual who developed pain-related fear would lead fear avoidance, and may result in disability, depression, and disuse in the long term (Smeets, van Geel, & Verbunt, 2009; Vlaeyen & Linton, 2000). Lower activities of daily living were observed in the population that had high fear avoidance beliefs and studies have reported supporting results such that trunk muscle weakening is related to disuse because of fear of pain (Al-Obaidi et al., 2000; Buer & Linton, 2002). Poor behavioral performance was observed in the population with pain-related fear (Crombez, Vlaeyen, Heuts, & Lysens, 1999). Waddell et al. (1993) asserted that the individuals' reaction towards the fear of pain may be more disabling than pain itself. Confronting fearful memories was used one of the earlier stages in trauma treatment in VR (Gerardi, Rothbaum, Ressler, Heekin, & Rizzo, 2008). Activity and fear avoidances were often characteristics of individuals with chronic pain because it was suggested that high levels of pain or kinesiophobia increased the risks of chronic low back pain and disability (Lethem et al., 1983; Picavet et al., 2002). Fear of pain and kinesiophobia are identified as mediating factors of pain, disability, daily living activity, and ROM (Jensen & Harms-Ringdahl, 2007; Robinson et al., 2013; Vernon et al., 2013).

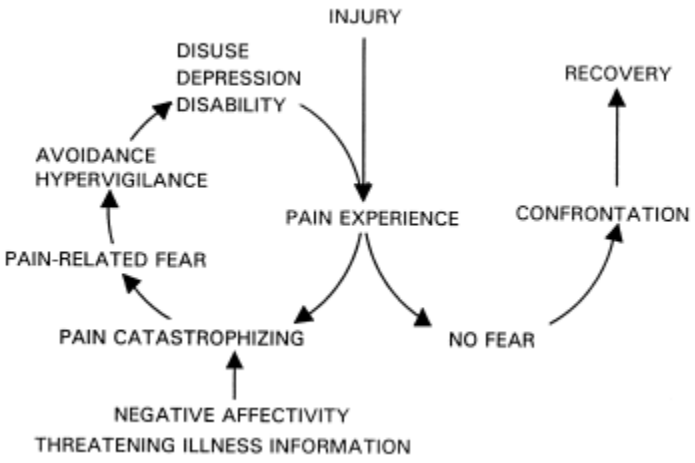

Figure 2.6. Fear avoidance model (Vlaeyen & Linton, 2000).

Various interventions and treatments for musculoskeletal pain have been studied. Treatments include cognitive behavioral programs and patient education and therapeutic exercises (Al-Obaidi et al., 2000; George, Fritz, Bialosky, & Donald, 2003; Leeuw et al., 2007). A decrease on fear avoidance beliefs was demonstrated in patients who received educational booklets (Burton, Waddell, Tillotson, & Summerton, 1999). It appeared that patients with high fear avoidance benefitted more from therapeutic exercises than individuals with lower fear avoidance (George et al., 2003; Moffett, Carr, & Howarth, 2004). Yet generally speaking the fear avoidance beliefs of the patients impeded them from achieving therapeutic results of the exercises or the efficacy of practitioner care (Al-Obaidi, Beattie, Al-Zoabi, & Al-Wekeel, 2005). Moreover, patients developed fear avoidance due to work-related injuries affect their fear avoidance belief about work which is related to work-loss or work-related compensation, and returning to work (Al-Obaidi et al., 2000; Jensen & Harms-Ringdahl, 2007). Overall, activity and fear avoidances of patients with injuries negatively impact their daily living, functional performance, recovery ability, and work. It is important to design and develop interventions that could desensitize patients' fear during therapy.

Researchers have been trying to apply the fear avoidance and kinesiophobic model to patients with chronic neck pain. Nederhand et al. (2003) proposed that individuals at the acute pain stage undergo

reorganization of neck and shoulder muscle activation as an inverse relationship was observed between EMG and neck pain disability. Nieto, Miró, and Huguet (2009) reported supporting results that kinesiophobia is a mediator of the level of disability in sub-acute whiplash injury. Most studies support the relationship between fear and level of chronic neck symptom severity (Robinson et al., 2013). However the score from a validated questionnaire of fear avoidance, the Tampa Scale of Kinesiophobia, was not found to be correlated with the range of motion of chronic whiplash patients as the range of motion is an indicator of their level of neck pain (Vernon et al., 2013).

2.6 Physical therapy and therapeutic exercises

Physical therapy (PT) is type of rehabilitation received by individuals with MSDs that aim to restore the functionality of the musculoskeletal system. It is considered a preferred management strategy for lower back pain and aim to relieve symptoms and musculoskeletal pain and reduce inflammation, restoring muscle force, length, and control at the painful shoulder (Ginn, Herbert, Khouw, & Lee, 1997; Jette & Delitto, 1997; McNeely, Olivo, & Magee, 2006; Novak, 2004). As there are many aspects in PT and it is the therapeutic exercise that has been demonstrated to be the foundation in improving function and disability (Jette & Delitto, 1997). Therapeutic exercise is considered a core elemental in most PT care plans (Hall, 2005). These therapeutic exercises primarily consist of repetition and training of specific body segments. It includes flexibility exercises that involved stretching of muscle groups, strengthening activities where the patients worked against reaction forces such as pulling elastic bands, body mechanics such as daily sitting and standing, and baseline walking distance evaluation (Means, Rodell, & O'Sullivan, 2005).

Patients are prescribed with a series of therapeutic exercises, or functional movement patterns, to be performed that aim to restore the function of the region with the disorder. Studies have looked at therapeutic exercises alone as a treatment alone and some have created rehabilitation programs that consisted of patient education and therapeutic exercises to help treating patients with MSDs (Feuerstein et

al., 1993). The selection to which functional movement patterns are prescribed to the individuals is essential to make improvements to their functional performance and disability (Hall, 2005). Different functional movement patterns are designed for different regions of MSDs.

Positive effects of rehabilitation were demonstrated in interventions for chronic neck pain involving of strengthening, proprioceptive, and personalized home exercises (Jensen & Harms-Ringdahl, 2007). Range of motion exercise was most effective for acute neck pain patients (Jensen & Harms-Ringdahl, 2007).

2.7 Therapies in virtual reality

One attractive feature of VR rehabilitation is that therapies are no longer restricted in clinics as VR provides the opportunity for tele-rehabilitation at patients' homes (Burdea et al., 2000). This potentially resolves the challenges that patients reside in remote areas face – lack of easy commute – accessibility to clinic, timeliness to treatment, and length of rehabilitation (Burdea et al., 2000). The effectiveness of rehabilitation may be affected if the duration of the therapy is reduced and these impairments could become permanent (Hilton, Cobb, Pridmore, & Gladman, 2002). This may be a cost-effective method to do therapy and saves traveling time for the patients. Moreover, VR rehabilitation could be tailored to match the training level needed by individual patients through easy software programming, and it could be gradually increased to match the patients' capacity overtime (Chen et al., 2007). The increasing level of difficulty would help improving their functional abilities (Rizzo, Buckwalter, Neumann, Kesselman, & Thiebaux, 1998). Another advantage is ecological validity since VR could be designed to match the meaningful daily activities and environment that the patients' daily activity takes place (Hilton et al., 2002; Rose et al., 2005). VR treatment setting is a controlled environment with the physical danger removed to enhance the safety of the rehabilitation environment (Hilton et al., 2002; Lewis & Griffin, 1997). Furthermore, it also has been shown effective for rehabilitation in chronic patients (Boian, Lee, Deutsch, Burdea, & Lewis, 2002). Rehabilitation in virtual reality could be designed to have

characteristics of games that may help patients to stay engaged through the exercise and achieve the training duration with less boredom (Dukes, Hayes, Hodges, & Woodbury, 2013; Jack et al., 2001).

Although VR has been described as an environment with stereoscopic visually mediated objects, many existing rehabilitation were conducted with 3D objects displayed on a flat monitor or screen (non-stereoscopic). Studies have revealed positive outcome with non-stereoscopic flat monitor simulation therapy and they are valuable information. The review below contains a mixture rehabilitation performed in both stereoscopic and non-stereoscopic environments, and the stereoscopic VR environments are specified.

This section further categorizes into two general areas of therapy: physical and cognitive; it then introduces the concept of VR as a potential tool for psychophysical treatments. This new concept was enlightened by the suggestive needs of chronic neck pain patients with fear avoidance behavior who experience challenges performing therapeutic exercises.

2.7.1 Rehabilitation

Rehabilitation aims to minimize symptoms and disability, to restore lost functionality of the movement, and to acquire compensatory skills (Riener & Harders, 2012; Stucki, Ewert, & Cieza, 2002). These aims are achieved through repetition of movements, active participation, and performance feedback (Riener & Harders, 2012). Virtual reality allows individuals to perform training movement repetitions and provide performance feedback, and it also motivates patient active participation. It has been used as a tool to improve patient ROM, motor learning, and for orthopedic rehabilitation (Holden, 2005). These characteristics and advantages of VR potentially make it a beneficial rehabilitative device.

Various physical disability types have been therapeutically treated using VR rehabilitation. VR was identified as a method of allowing brainstem or spinal cord injured patients to control the surrounding because VR lacks physical barriers (Myers & Laenger, 1998). Other application includes training for children with cerebral palsy about the surrounding and using wheelchairs, orthopedic patients after

surgery or accident, and rehabilitation for stroke patients (Aisen, Krebs, Hogan, McDowell, & Volpe, 1997; Bergmann, Krewer, Muller, Koenig, & Riener, 2011; Chen et al., 2007; M. Dam et al., 1993; Deutsch, Latonio, Burdea, & Boian, 2001; Foreman, Wilson, & Stanton, 1997; Inman, Peaks, Loge, & Chen, 1994).

Research on patients with spinal cord injury (SCI) or TBI receiving VR rehabilitative exercises has been reported. In addition to retraining the functional movements of patients with TBI, VR was identified system for retraining cognitive performance of individuals with brain damage because both physical and cognitive impairments may result from TBI (Christiansen et al., 1998; Rose et al., 2005). Thornton et al. (2005) compared functional mobility and balance of TBI patients who received VR exercises in stereoscopic to patients who received traditional activity-based therapy and they indicated positive qualitative outcomes. Stereoscopic VR rehabilitation that targeted improvement in activities of daily living was also investigated although it did not show statistically significant improvement (J. H. Lee et al., 2003). Still many reported patient enjoyment during VR rehabilitation, including both stereoscopic and non-stereoscopic VR environments (Meldrum, Glennon, Herdman, Murray, & McConn-Walsh, 2012; Thornton et al., 2005).

Physical rehabilitation in VR for children with cerebral palsy (CP) is another area of interest. Cerebral palsy is a non-progressive disorder that is a result of premature brain development in young infants and it is usually treated at younger ages (Bryanton et al., 2006). Both upper extremities reaching (Chen et al., 2007) and lower extremity movements (Brien & Sveistrup, 2011; Bryanton et al., 2006) have been examined in children with CP using non-stereoscopic or stereoscopic VR rehabilitation. Improvement in reaching was reported and the positive effects were retained (Brien & Sveistrup, 2011; Chen et al., 2007) and children demonstrated greater engagement in the rehabilitation process compared to traditional therapy (Bryanton et al., 2006; Saposnik & Levin, 2011). Children with Down syndrome underwent game-based treatment using Wii and the patients demonstrated greater gross motor functionality (Wuang, Chiang, Su, & Wang, 2011).

Improvements in upper and lower extremities functionality in stroke patients have been widely studied (Jack et al., 2001). Holden and colleagues asserted that they were the first to report the successful usage of VR to retrain movements of stroke patients through imitation of movements and achieved positive results (Holden, Dyar, Schwamm, & Bizzi, 2005; Holden, 2001). This was performed on computer monitor in a non-stereoscopic environment. The patients followed the pre-recorded movements of a "virtual teacher" in the scenarios. Movements of the patients were tracked using an electromagnetic motion tracking system which identified the movements of the patients to match the movements of the virtual teacher. Burdea et al. (2000) reported a case study of a single stroke patient who performed hand VR rehabilitation with a force feedback Cyberglove (Rutgers Master – I, or RM-I) that monitored the hand position for the upper extremity training. They established exercise routines that aimed to train the range of motion, speed, fractionation (independent finger motion), and strength. Patients followed instructions on a computer screen in non-stereoscopic that displayed a virtual hand, which outline the motion that the patient's hand has moved. This group later improved the existing system, RM-II, which shared a common control interface for rehabilitative devices for other body segments, including the elbow and the ankle. RM-II was also able to provide force feedback and trained hand motion and the authors demonstrated the potential in improving hand function in chronic stroke patients (Adamovich et al., 2005). Both RM-I and RM-II were developed for home rehabilitation. Many others also have reported positive training results in stroke patients, including patients in the chronic phase of stroke (Merians et al., 2002), but there is also evidence that upper extremity activity level was not different between chronic stroke patients who received VR or traditional rehabilitation (Crosbie, Lennon, McGoldrick, McNeill, & McDonough, 2012). Dukes et al. (2013) implemented a gaming system as part of the rehabilitation routine where the post-stroke patients aimed for and punched cartoon ducks on a large display. Patients were incentivized inside the game-like scenario and they demonstrated less abnormal trunk movements after five therapeutic sessions.

Popescu et al. (2000) have incorporated physical therapy and function rehabilitation, where the former one used force feedback to retrain motor skills and the latter one was designed to regain lost skills that were required in daily activities. This training was designed for whole-hand grasping, two-finger grasping, item selecting, and releasing of the object. The disadvantages of this training was due to the item used in training would stick to the patients and did not quite follow the laws of physics.

Lower extremity mobility and balance rehabilitation of stroke patients was studied with different VR and computer simulation technology, and they all yielded positive results as indicated by improved patient performance (Bergmann et al., 2011; Boian et al., 2002; Deutsch et al., 2001; Jaffe, Brown, Pierson-Carey, Buckley, & Lew, 2004; Yang et al., 2011). Some researchers have utilized treadmill in conjunction with visual display feedback during stroke patient lower extremity function restoration and one included body harness for safety (Bergmann et al., 2011; Boian et al., 2002; Deutsch et al., 2001; Jaffe et al., 2004; Yang et al., 2011). Alternatively Boian et al. (2002) and Deutsche et al. (2001) retrained patient ankle movement in seated posture. For instance, researchers designed VR simulation for patient ankle exercise that involved maneuvering of airplanes or boats with feet to produce repetition of ankle movement (Boian et al., 2002). Deutsch et al. (2001)reported improvement in strength and endurance of the foot after six treatment sessions of a single stroke patient case study.

Although clinic evidence shows promise of VR rehab, clinical acceptance is the first challenge faced by virtual rehabilitation as the medical efficacy needs to be proven (Burdea, 2002). Another challenge would be the attitude of the therapist towards virtual rehabilitation and it should be addressed as an additional tool to enhance the usefulness of rehabilitation. Virtual reality interface has been considered as another challenge since in some studies the equipment required to be sterilized and it was difficult to do so. Additionally, most virtual rehabilitation equipment was made for adults, and people with smaller or larger anatomy may not be able to fit well in the equipment. The weight of the equipment, limited range of trackers, and other equipment constraints would be potential factors that limit the natural movements of the patients during exercise. Communication between the patient end and the clinician was

problematic due to the poor network traffic in the past. Cost of the equipment may be a concern. Also patient safety was a concern since the force feedback equipment used may apply large forces and potentially reinjure the patient.

2.7.2 Psychological therapy

Psychological related treatments in VR have been investigated in group experiments or as single case studies. VR has been studied as a treatment or desensitization tool for fearful behavior or irrational fear in the presence of anticipation of an object, or specific phobia characterized by immediate anxiety response (Lewis & Griffin, 1997; Linares et al., 2012). These treatments rely on the potential of VR being able to overcome challenges posed by the tradition treatments, such as participants who are too fearful of undergoing phobic treatment in the physical world (Lewis & Griffin, 1997). Different types of phobia categorized as animal phobia (e.g. spiders), natural environment (e.g. height), situational (e.g. confined space, flying), or fearful behaviors were reported to be significantly reduced after exposure to VR treatment (Carlin, Hoffman, & Weghorst, 1997; Choy, Fyer, & Lipsitz, 2007; Rothbaum et al., 1995, 2006). Garcia-Palacios and colleagues reported the first controlled study with objective and subjective outcome measures supporting the effectiveness of VR exposure in treating fear of height (Garcia-Palacios, Hoffman, Carlin, Furness, & Botella, 2002).

Stress and anxiety related psychological therapies were also explored using VR. Post-traumatic stress disorder (PTSD) from various incidences have been treated using immersive VR (Reger & Gahm, 2008). The types of trauma range from soldiers returning from war, survivors from catastrophes such as September 11, individuals who have suffered through disasters, and many other psychological suffering conditions (Gerardi et al., 2008). Social anxiety or phobia are conditions where individuals who exhibit difficulties in social life (Wallach, Safir, & Bar-Zvi, 2009). Treating social anxiety using VR have been explored; some researchers reported reduction in anxiety measures from questionnaires and but not all had strong supporting data (Choy et al., 2007; Krijn, Emmelkamp, Olafsson, & Biemond, 2004; Wallach,

Safir, & Bar-Zvi, 2009). Generally the usage of VR as a tool for cognitive and psychological related therapies has demonstrated successful treatment.

2.7.3 VR as a potential psychophysical rehabilitation tool

Fear and pain avoidance behavior exhibited by patients with neck and shoulder pain would be possibly be considered as a more complex condition than just individuals with only physical functional difficulties or phobic characteristics. The improvement on neck pain patients with fear avoidance behavior initiated as the level of fear was reduced (Robinson et al., 2013). This suggested that therapy for chronic neck pain patients is possibly a two-fold process; the psychological fear avoidance attitude first needs to be mitigated and then apply the therapeutic exercises. The psychology of the patients is likely to impact the outcome of rehabilitation (Riener & Harders, 2012). As previous experiments have indicated successful management of fear related behaviors as well as improvement in functional abilities in VR, which are suggestive of capabilities of VR for psychophysical rehabilitation.

2.8 Visual perception and proprioception

Virtual reality is an environment generated by computer rendered visually mediated objects and therefore the fear avoidance desensitization strategies are all visually based. The proposed visual desensitization approach should not only be a psychological desensitization procedure but it should also influence the proprioception of the user so that there would not be anticipated pain while performing therapeutic functional movement patterns. This section describes the basics of visual perception and its relationship with proprioception, and how visual may override proprioceptive feedback.

2.8.1 Visual perception

Eye is visual sensory organ. It allows light rays to enter through and then help focus the light rays on the retina. The light receptors, or photoreceptors, located on the retina become activated. The photoreceptors synapse with the bipolar and ganglionic neurons, which conduct the nerve impulses via the optic nerve to the visual cortex. Visual cortex is a region located in the occipital lobe of the cerebrum that is responsible

for visual information processing. The formation of the visual image occurs in the brain and then the visual information becomes acknowledged by the person. Human have two eyes and therefore light rays arrive at two retinas there are each located in separate eyes. The two eyes adjust medially, or converge, to allow the eyes focus on objects. The eyes need to have greater convergence for close objects in order to have binocular vision. Binocular disparity arises from the different light rays arriving at the two retinas and gives human the ability to see objects in stereo, or three dimensions, and enhances depth and distance perception (Foley, 1967).

2.8.2 Proprioception and interaction with visual perception

Human proprioception is often dominated by visual feedback under visual-proprioception mismatch conditions as visual could bias proprioception (Burns et al., 2006; Gibson, 1966; Guerraz et al., 2012; Rock & Victor, 1964). Though vision could bias proprioception, Guerraz et al. (2012) indicated that the visual-proprioceptive mismatch in experimental conditions and the sensory preferences of individuals could lead to different levels of visual domination. Users tended to over-correct for spatial distortion during head movements when they were asked to adjust the distortion back to normal as the real world based on visual feedback (Jaekl et al., 2002). This suggested that there is a level of tolerance between head movements and visual feedback and the mismatch between proprioception and vision was not necessarily noticeable.

2.8.3 Perception alteration under visual feedback domination

Perception alteration is the experience of mismatch between proprioception and visual feedback. For instance, a person turns the head 30 degrees but the viewpoint does not change 30 degrees. Instead of perceiving the viewpoint of 30 degrees, the person receives visual feedback from the viewpoint less than 30 degrees will be operationally referred to as visual feedback attenuation; the visual feedback from the viewpoint greater than 30 degrees will be operationally referred to as visual feedback amplification. A complete match between proprioception and visual feedback is referred to as one-to-one mapping, where the eyes receive the correct spatial relationship in accordance with the head movement. Different visual

feedback could be generated in VR since VR is created using computer-generated visually mediated objects.

The mismatch between movement and visual feedback is created using computer algorithms based on the concept of control-display (C-D) gain. Generally, user physical movement is tracked by motion sensors and then visual feedback received by the user is based on the physical movement processed by the C-D gain algorithm. Poupyrev, Weghorst, Otsuka, & Ichikawa (1999) utilized quaternion to compute the desired amount of amplified rotation in 3D space. A quaternion, *q*, is four-dimensional vector with a vector **v** with 3 components and 1 scalar w (Equation 2.2).

$$q = (\boldsymbol{v}, w) \qquad \text{(Equation 2.2)}$$

Suppose the input control is q_c, the location is indicated in Equation 2.3, where θ_c represents the rotation angle, $\mathbf{u}_c$ is the instantaneous axis of rotation.

$$q_c = \left(\sin\frac{\theta_c}{2}\boldsymbol{u}_c, \cos\frac{\theta_c}{2}\right) = e^{\frac{\theta_c}{2}\boldsymbol{u}_c} \qquad \text{(Equation 2.3)}$$

The zero-order C-D gain spatial rotation equation that links the physical rotation input control to the visual display rotation is indicated in Equation 2.4. The C-D gain is the constant multiplier, *k*.

$$q_d = \left(\sin\frac{k\theta_c}{2}\boldsymbol{u}_c, \cos\frac{k\theta_c}{2}\right) = e^{\frac{k\theta_c}{2}\boldsymbol{u}_c} = q_c^k \qquad \text{(Equation 2.4)}$$

Lin and colleagues examined the effects of C-D gain on user performance with a head-controlled input device with the visual feedback of a mouse cursor and targets displayed on a computer screen, and their method of C-D gain computation was based on the scalar ratio of the head rotation or extension/flexion angle (Lin, Radwin, & Vanderheiden, 1992). This method of visual amplification or attenuation is more feasible for visual feedback on flat two-dimensional screen.

Altered perception using VR has been applied in various experimental settings for diverse purposes and different terminologies were introduced to refer to the non-one-to-one mapping of visual feedback that

corresponded to the intended function of perception alteration. Motivation of the earlier studies that applied visual amplification in VR was to overcome the insufficient field of view (FOV) in certain VR displays since narrow FOV weakens users' ability to move in an environment (Arthur, 1996; Jay & Hubbold, 2003; Kopper, Stinson, & Bowman, 2011; Le Ngoc & Kalawsky, 2013). The goal of these studies was to amplify the effects of head movement so that less head movement was necessary to perceive visual feedback from a wider viewpoint. Some advantages were discovered during visual amplification, such as decreased in user fatigue due to less head movement and faster performance (Jay & Hubbold, 2003). User performance did not decrease with head movement amplification; however it was suggested that the effect of user performance improvement would be greater in a VR with narrower FOV (Kopper et al., 2011). On the other hand, visual feedback attenuation was rarely applied to accommodate narrow FOV of VR devices. In general, users were able to perceive a greater and wider field of view from less head movement through visual amplification.

In addition to FOV compensation using visual amplification in VR, other studies have expanded the non-one-to-one mapping to other applications to understand the ability of human to discriminate the visual-proprioception mismatch. Instead of simple head rotation movements, studies examined larger scale movements called redirected walking (Razzaque, Kohn, & Whitton, 2001; Steinicke, Bruder, Jerald, Frenz, & Lappe, 2008, 2010). Users walked back and forth in a room that was relatively smaller than the represented space in VR and reported to experience the VR space larger than the physical room (Razzaque et al., 2001). The effect of redirected walking was similar to the amplification of head movements, such that the motions of the users were scaled (Steinicke et al., 2008). For redirected walking tasks, users were not able to distinguish 90 degrees of rotation in virtual and real conditions ranging from 81 to 152 degrees, but they were able to discriminate walking distances from virtual and real conditions (Steinicke et al., 2008). Redirected touching was studied by Kohli and colleagues, which examined performance of users in a mixed reality environment such that users touched a touch screen panel oriented 0 degrees from the user yet the VR visual displayed the panel that was rotated at 18

degrees (Kohli, Whitton, & Brooks, 2012). Although users did report some mismatching sensations users adapted after a few repetitions, user performance was not significantly different from the one-to-one mapping conditions.

Visual feedback amplification and perception alteration are introduced for virtual therapeutic exercise in this proposed study to utilize manipulated visual feedback to mitigate the fear of movement and pain of the patients with chronic neck and shoulder pain. Individuals with chronic neck pain are fearful of performing certain head movements because they have learned from previous experiences that head turning movements beyond a particular range would cause pain. As a result these individuals were not able to perform the necessary therapeutic exercises since they involve head movements. However, individuals under perception alteration receiving amplified or attenuated visual feedback may be able to overcome their fear of performing head movements since their proprioception is dominated by visual feedback.

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3. Manually Locating Physical and Virtual Reality Objects

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Objective: In this study, we compared how users locate physical and equivalent three-dimensional images of virtual objects in a cave automatic virtual environment (CAVE) using the hand to examine how human performance (accuracy, time, and approach) is affected by object size, location, and distance.

Background: Virtual reality (VR) offers the promise to flexibly simulate arbitrary environments for studying human performance. Previously, VR researchers primarily considered differences between virtual and physical distance estimation rather than reaching for close-up objects.

Method: Fourteen participants completed manual targeting tasks that involved reaching for corners on equivalent physical and virtual boxes of three different sizes. Predicted errors were calculated from a geometric model based on user interpupillary distance, eye location, distance from the eyes to the projector screen, and object.

Results: Users were 1.64 times less accurate (p <.001) and spent 1.49 times more time (p =.01) targeting virtual versus physical box corners using the hands. Predicted virtual targeting errors were on average 1.53 times (p < .05) greater than the observed errors for farther virtual targets but not significantly different for close-up virtual targets.

Conclusion: Target size, location, and distance, in addition to binocular disparity, affected virtual object targeting inaccuracy. Observed virtual box inaccuracy was less than predicted for farther locations, suggesting possible influence of cues other than binocular vision.

Application: Human physical interaction with objects in VR for simulation, training, and prototyping involving reaching and manually handling virtual objects in a CAVE are more accurate than predicted when locating farther objects.

Keywords: virtual reality, physical interface, simulation, CAVE

3.1 Introduction

The motivation for this research is the prospect of simulating natural interactions with objects in the physical environment (PE), such as reaching for, acquiring, and handling objects with the hands, by using visually mediated virtual objects in a three-dimensional (3-D) virtual reality (VR) environment. In this study, we examine possible differences between how users physically reach for and locate virtual objects. Observing and comparing user performance in the PE and VR may help better understand how to best use VR simulation technology for prototyping new products and devices and for studying human interactions and behaviors in living environments.

The present study was conducted in a commercially built CAVE (Cave Automatic Virtual Environment), which is a projection-based VR first introduced for scientific visualization (Cruz-Neira, Sandin, & DeFanti, 1993; Cruz-Neira, Sandin, DeFanti, Kenyon, & Hart, 1992). In general, projection-based VR is advantageous for studying natural physical interactions with virtual objects because it allows users to see their own hands relative to the virtual objects, and user performance was found to be less awkward than in other VR environments (Havig, McIntire, & Geiselman, 2011; Sander, Roberts, Smith, Otto,& Wolff, 2006; Sutcliffe, Gault, Fernando, & Tan, 2006).

We are ultimately interested in creating more natural VR interactions in which users' hands physically touch, grasp, and handle virtual objects. We wish to first comprehend user accuracy of manually targeting

virtual objects in various locations in the 3-D space in accordance with the graphics software and apply those findings to enhance natural interactions with virtual objects so that collisions with visually mediated objects and user movements in the CAVE are accurately detected and displayed. Since 3-D vision in a CAVE creates the perception that the virtual objects observed are located in 3-D space, the coordinates where users perceive and physically locate those images may not perfectly coincide with the coordinates of the object created by the CAVE software. Even small differences between the perceived and actual locations may prevent users from efficiently completing manual tasks. In this study, we investigate the magnitude of such differences and rationalize factors that might affect them.

Authors of human perception research in VR space have previously looked at distance approximation. Generally, researchers have reported distance underestimation in VR (Thompson et al., 2004; Witmer & Kline, 1998) relative to PE (Alexandrova et al., 2010; Willemsen & Gooch, 2002). However, distance estimation through walking in large screen VR and in PE was similar in adults and children (Plumert, Kearney, Cremer, & Recker, 2005). It was also suggested that distance estimation in different VR simulation technologies had varying degrees of accuracy, and simulations displayed on computer monitors had the lowest accuracy (Lampton, McDonald, Singer, & Bliss, 1995). Although there is a general consensus on distance underestimation in VR, the magnitude of error during target reach and location in a CAVE is still unclear.

Others have tried to understand differences in user performance between VR and PE through target aiming (Liu, van Liere, Nieuwenhuizen,& Martens, 2009) and object grasping (Magdalon, Michaelsen, Quevedo, & Levin, 2011). Task performance and movement time were longer in VR for both head-mounted display and single desktop 20-inch stereo monitor (Liu et al., 2009; Magdalon et al., 2011). Additionally, users who wore pinch gloves to intercept virtual and physical objects in a CAVE spent significantly longer time to complete virtual object movement tasks (Sutcliffe et al., 2006). Generally, there are performance differences between PE and VR for those studied tasks.

Human performance is also affected by various depth perception cues and individual factors as well as by objects and screen distance from the eyes (Bajcsy & Lieberman, 1976; Mather, 1996; O'Shea, Blackburn, & Ono, 1994; Walk & Gibson, 1961). Binocular disparity is one of the cues, and its association with interpupillary distance (IPD; Wann, Rushton, & Mon-Williams, 1995), an individual factor, has been mathematically demonstrated (Ogle, 1953). Accurately perceiving stereoscopic objects has been suggested to be related to binocular disparity, which is associated with IPD (Patterson, 1997). However, binocular disparity alone may be insufficient to provide accurate depth perception (Hibbard & Bradshaw, 2003), and motion parallax was another cue that was identified to aid in the understanding of user depth perception (Bradshaw, Parton, & Glennerster, 2000). Users would strategically utilize different cues under different tasks and constraints, yet seldom were binocular disparity and motion parallax cues incorporated while performing their given tasks (Bradshaw et al., 2000).

Recently, a geometric model developed by Ponto, Gleicher, Radwin, and Shin (2013) demonstrated a relationship between user VR binocular perception and a CAVE binocular disparity setting. In their geometric model, participant IPD, eye location, and distances from eye to the projector screen (DS) and from eye to the perceived location of the object projection (DP) are considered for calculating binocular disparity targeting error in a CAVE (Figure 3.1). The geometry based on the distances and locations of the points is outlined in Equation 3.1, and these equations are combined and rear ranged to solve for DP in Equation 3.2. The difference between distance to virtual point (DV) and DP is the calculated binocular disparity error, which suggested the importance to investigate the influence of binocular disparity in relation to user performance.

$$\frac{CAVE\ BD}{DV} = \frac{Disp}{DS - DV}$$

$$\frac{IPD}{DP} = \frac{Disp}{DS - DP} \qquad \text{(Equation 3.1)}$$

$$\frac{IPD}{DP} = \frac{CAVE\ BD\ \times (DS - DV)}{DV \times (DS - DP)}$$

$$DP = \frac{IPD \times DV \times DS}{CAVE\ BD \times DS - CAVE\ BD\ \times DV\ + IPD \times DV} \qquad \text{(Equation 3.2)}$$

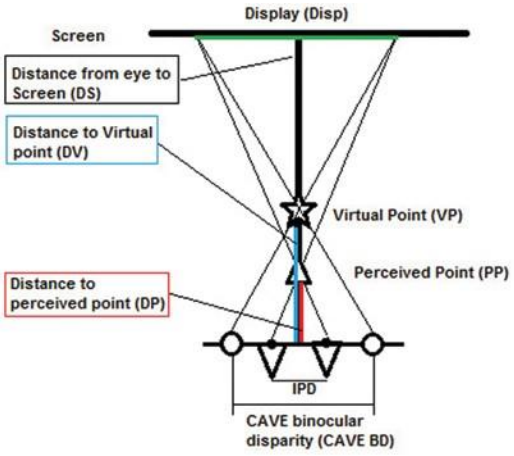

Figure 3.1. Geometric model of a user's line of sight to a virtual target (indicated as a single point, depicted by the star symbol). CAVE binocular disparity (CAVE BD) is the distance between the CAVE virtual cameras. The location of the projected image by the cameras is labeled as the virtual point (VP), depicted by the star (*), and its distance to the viewer is labeled as DV. Interpupillary distance (IPD) is the distance between the two eyes for each subject. Distance from the eyes to the perceived point (PP) is indicated as DP. Display (Disp) is the distance between the two points of the line of sight from both the cameras and the user that landed on the screen.

In the current study, we compared human reach and localization of visually mediated virtual objects in a CAVE against equivalent physical objects located at arm-length distances. It was hypothesized that human performance in the virtual condition was not equivalent to the physical condition. Participants were asked to reach for the four corners on the upper face of three physical boxes and three equivalent virtual boxes projected in a CAVE. The localization of a box corner represented the perceived location of

the box corner. We compare the perceived location of virtual against the physical box corners and then assess the extent of the contribution of external and internal factors to user performance in VR.

3.2 Method

3.2.1 Participants

Sixteen students were recruited with informed consent from the University of Wisconsin–Madison campus and Table 3.1 lists their self-reported demographics. Inclusion criteria were self-reported normal or corrected-to-normal vision and the ability to stand for at least 20 minutes. Exclusion criteria included reported history of epileptic seizures or blackouts, tendency for motion sickness when experiencing visual motion conflicts, neuromotor impairments, Lasik eye surgery, perception-altering medication, claustrophobia in 3 m × 3 m × 3 m square room, or sensitivity to flashing lights. Two participants were excluded due to Lasik eye surgery or forgotten eyeglasses.

Table 3.1. Demographics and Characteristics of the Analyzed Participants

Gender	3 females, 11 males
Age (SD)	22.7 (2.6)
Height in cm (SD)	176.1 (7.5)
Interpupillary distance in cm (SD)	6.18 (0.26)
Handedness	2 left-handed
	12 right-handed
Vision correction	10 with correction
	4 without correction

3.2.2 Procedure

Stature and arm length were measured using an anthropometric caliper, and IPD was measured using a digital pupilometer (Digital PD ruler PM-100, Luxvision, www.luxvsion. net). Participants were instructed to stand in the CAVE in their stocking feet (wearing only socks or booties) and performed targeting tasks.

3.2.3 Instrumentation

The VR was created in a 2.93 m × 2.93 m × 2.93 m rear-projected six-faced CAVE consisting of four walls, one ceiling, and one solid acrylic floor. Two 3-D projectors (Titan model 1080p 3D, Digital Projection, Inc., Kennesaw, GA, USA) with maximum brightness of 4,500 lumens per projector, total 1,920 × 1,920 pixels combined, and 70 Hz of update rate per eye projected images onto each surface of the CAVE. Immersive 3-D scenarios were implemented using the VirtualLab software package (Virtual CAVELib API, Mechdyne, Marshalltown, IA, USA), and four workstations (2 × Quad-Core Intel Xeon) generated displayed graphics. Audio was generated by a 5.1 surround sound audio system.

The data acquisition system consisted of an ultrasonic tracker set (VETracker Processor model IS-900, InterSense, Inc., Billerica, MA, USA), including a handheld wand (MicroTrax model 100-91000-EWWD, InterSense, Inc.) and head trackers (MicroTrax model 100-91300- AWHT, InterSense, Inc.) that sampled at 60 Hz. Twelve ultrasonic emitters evenly placed along the upper (two per edge) and vertical (three per edge) edges of the CAVE allowed full 6 degrees of freedom wand and head tracking. Shutter glasses (CrystalEyes 4 model 100103-04, RealD, Beverly Hills, CA, USA) with head trackers mounted on the top rim created stereoscopic images from the user's viewpoint.

3.2.4 Experimental task

The task was to locate labeled box corners corner (x, y, z). Errors along each orthogonal (Figure 3.2 to 3.4) in random order, and each corner location action represented one trial. Participants were instructed to stand in the "ready position" (hands pointing down and palms inward while standing erect) over the footprint image projected on the floor in the center of the CAVE throughout the experiment (Figures 3.2 and 3.3).

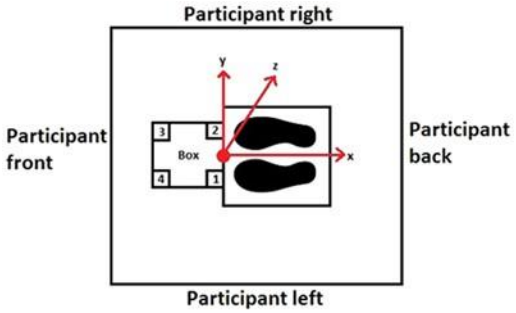

Figure 3.2. Relative locations of the box, corners, and the participant. Corners of the boxes were labeled 1 through 4; Corners 1 and 2 were the closer left and right corners, and 3 and 4 were the farther right and left corners, respectively. The red dot indicates the midpoint between Corners 1 and 2, which also represents the origin of the coordinate system when measured from the floor. The positive x-axis was toward the posterior, the positive y-axis was to the right, and the positive z-axis was toward the superior direction.

A physical box was situated, or a virtual box was projected, at the same location while participants turned their head to their right side and looked at a bull's-eye target projection on the wall (Figure 3.3). Participants were asked to face and observe the box for 3 s and then return to ready position before locating any corner. They were then instructed to locate a corner using the protruding midpoint of the wand and to squeeze a trigger when the wand was at the location they perceived was the corner. All wand-triggered click events were recorded. No auditory, visual, or tactile feedback was provided to indicate location accuracy to prevent possible ordering effects in a limited repeated-measures experiment.

The same box was used for two consecutive trials before it was swapped for the next box. Participants were instructed to locate the corner for both box types, but they were further instructed to reach as close to the corner as possible without actually touching the physical box.

Each participant completed 48 trials, two replications for each of the four corners for three physical and three virtual boxes. The physical boxes sizes were chosen based on convenience and availability (Figure 3.4), and the images of the virtual boxes were then photographed and constructed to match the dimensions of the physical boxes. No practice was provided.

3.2.5 Variables and data Analysis

Independent variables were box size (three levels), corner (four levels), and box type (two levels: physical and virtual), and they all varied within subjects. Dependent variables were accuracy (overall error and

error along the x-axis, y-axis, and z-axis), approach toward corners (wand rotation angle), and efficiency (task time). Overall error was the calculated Euclidean distance (Equation 3.3) between the coordinates of the tip of the wand (x_w, y_w, z_w) and the corner (x_C, y_C, z_C). Errors along each orthogonal axis were the absolute difference between the components of that axis (Equation 3.4). The relationships of errors and the independent variables were analyzed with repeated-measures ANOVA with $\alpha = .05$. The designated corner labels and the coordinate system are illustrated in Figure 3.2. The origin was located along the adjacent edge of the box and the projected footprints, and (0, 0, 0) was defined as midpoint between the participant's toes (Figure 3.3).

$$\text{Overall error} = \sqrt{(x_W - x_C)^2 + (y_W - y_C)^2 + (z_W - z_C)^2} \qquad \text{(Equation 3.3)}$$

$$\text{x-error} = |\, x_W - x_C|$$

$$\text{y-error} = |\, y_W - y_C| \qquad \text{(Equation 3.4)}$$

$$\text{z-error} = |\, z_W - z_C|$$

Three distinctive wand rotation angles were measured with respect to the three orthogonal axes. Wand rotation about the x-axis was roll, the y-axis was elevation, and the z-axis was azimuth (Figure 3.5). Rotation about each axis was indicated by the angle magnitude and a positive or negative sign, in which the positive rotation direction was determined by pointing the right- hand thumb to the positive direction of axis of interest and curling the fingers toward the palm (right-hand rule).

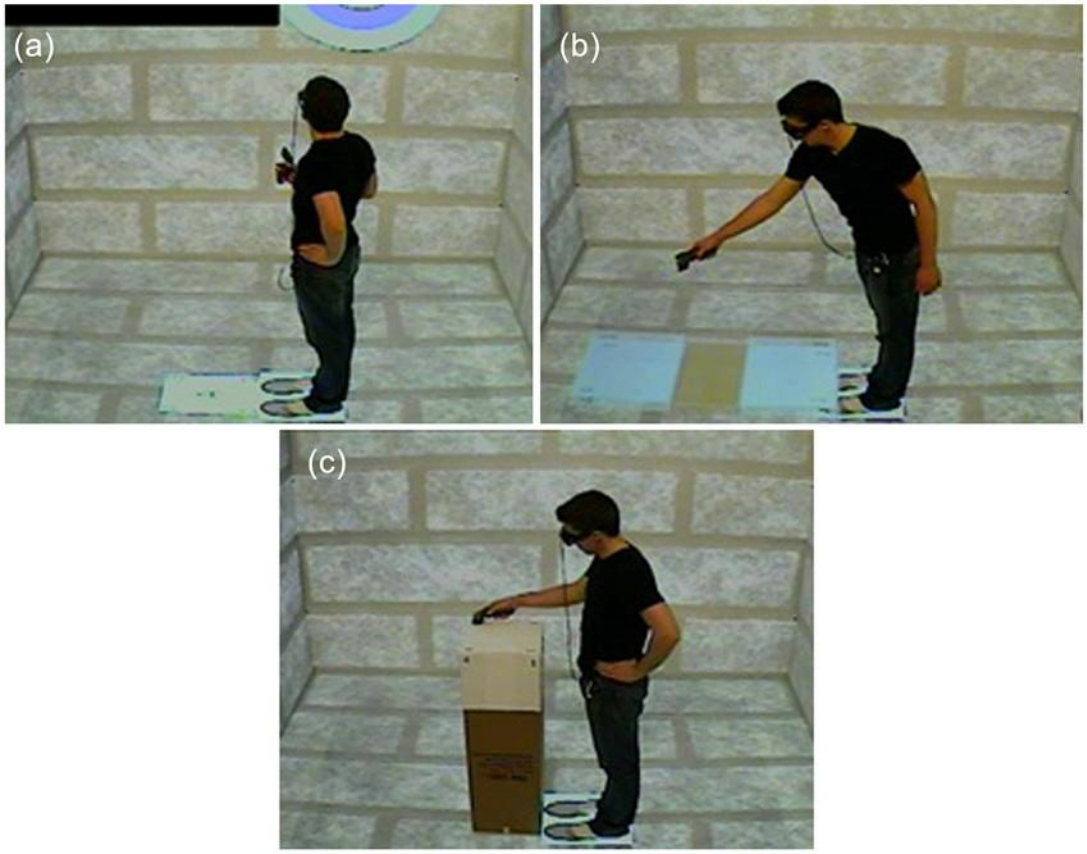

Figure 3.3. A participant inside the cave automatic virtual environment (CAVE), standing on footprint images projected on the CAVE floor while performing indicated tasks: (a) turning to the right and looking at the projected bull's-eye, (b) pointing to a corner of a virtual box while standing on the projected footprints, and (c) pointing to a corner of a physical box while standing on the projected footprints.

Binocular disparity error was predicted using the geometric model demonstrated by Ponto et al. (2013). Figure 3.6 shows an example of the relationship between the calculated binocular disparity errors using the geometric model, based on IPD values and the mean population standing eye height (156.9 cm) from the U.S. anthropometric survey (Gordon et al., 1989). No systematic relationship was observed between binocular disparity error and distance from the eyes to the target corner.

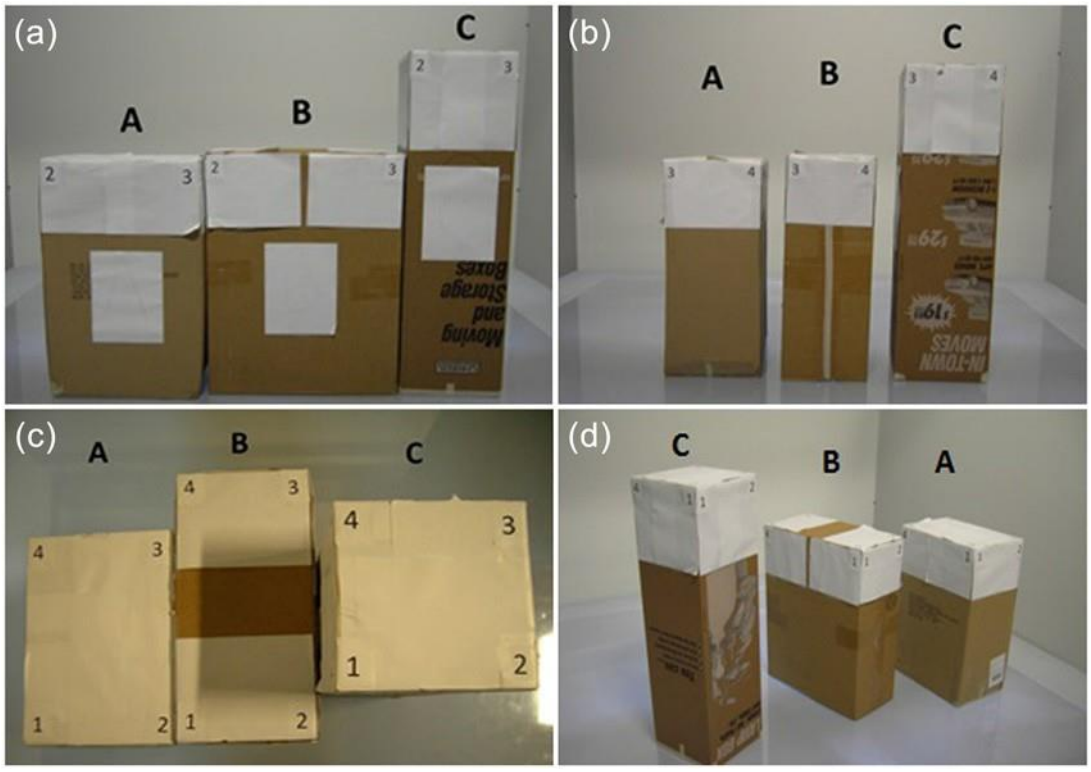

Figure 3.4. Views of three physical boxes from different planes and angles showing their relative sizes. Images a, b, and c display the boxes in the order of Boxes A, B, and C (from left to right). Box A's dimensions were (length × width × height, in centimeters) 47 × 32 × 72, Box B's were 59 × 28 × 74, and Box C's were 31 × 34 × 102. Image d displays the boxes in the order of C, B, A (from left to right). The illustrations show the (a) side view looking at the x-z plane, (b) side view looking at the y-z plane, (c) top view looking at the y-x plane, and (d) side view looking at boxes from an angle.

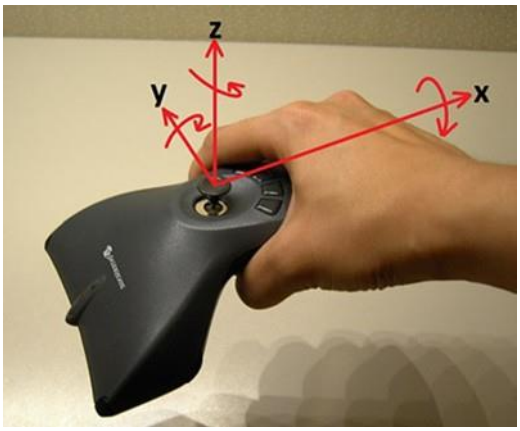

Figure 3.5. Three rotation directions of the wand about the three orthogonal axes.

3.3 Results

Mean overall error for the VR cases was plot- ted against trial number, and a log-log regression curve was fitted to examine potential practice effect over the 24 trials, $F(1, 22) = 11.96$, $p = .002$. Mean error of the first VR trial was the average error of all participants' first virtual box trial, and then subsequent data points were calculated similarly to obtain the mean errors of remaining VR trials. The difference in overall error between VR Trials 1 and 4 was 1.36 cm, whereas the difference between VR Trials 4 and 24 was 0.3 cm.

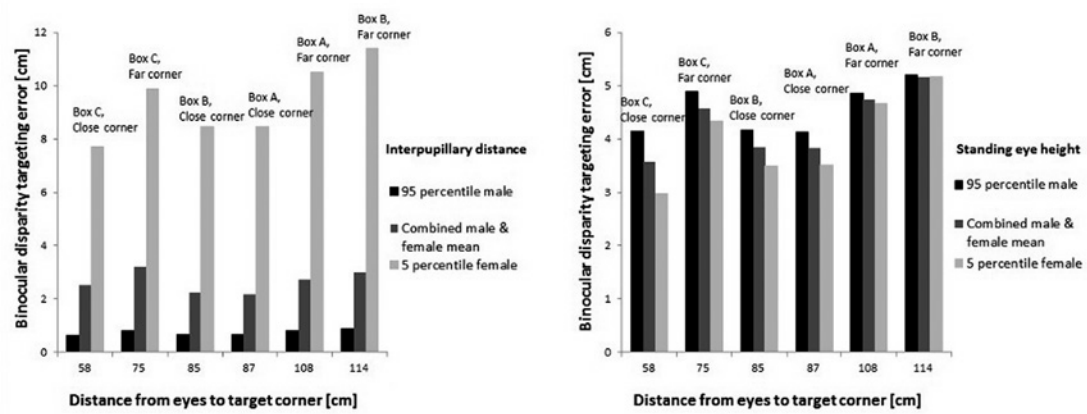

Figure 3.6. The left graph is the binocular disparity targeting error calculated from the geometric model against increasing distance to virtual point (DV) while holding user standing eye height at the mean of the U.S. Army Personnel Anthropometric Survey (156.86 cm) with varying interpupillary distance (IPD) from the U.S. Army Personnel Anthropometric Survey (Gordon et al., 1989). The right graph is the binocular disparity targeting error calculated from the geometric model against increasing DV while holding user IPD at the mean of the U.S. Army Personnel Survey (6.35 cm) with varying standing eye height from the U.S. Army Personnel Anthropometric Survey (Gordon et al., 1989). Binocular disparity error in all cases increased with increasing IPD or increasing standing eye height. Closer corners were Corners 1 and 2, and far corners were Corners 3 and 4 (Figures 3.2 and 3.4).

The first replicate of each corner for all three virtual and three physical boxes was excluded from data analysis to remove practice effects and also to maintain a full factorial experiment. To test if the practice

effect was removed, we regressed the errors over order for the remaining VR trials. No statistically significant effect of time on error was observed, $F(1, 10) = 2.51$, $p = .144$.

Though the experimenter did not observe any physical box touches, potential touch instances were still analytically verified. Wand trajectories were sampled at 60 Hz, and the velocity and acceleration profiles were calculated using numerical differentiation for each participant to assess potential physical box contacts. High- frequency noise of the profiles was filtered out using a Gaussian smoothing algorithm. It was anticipated that the wand would have zero velocity and rapid deceleration if a touch occurred. Assuming that it would take at least 90 ms to react to a touch, at a 60 Hz sampling rate, we would expect at least five data points that were at or near zero velocity while rapid deceleration occurred. Trajectory data for 10 s before and after every click response of all physical box trials were examined, and it was determined that no profiles matched the criteria listed. It was concluded that the participants did not touch the physical boxes as instructed.

3.3.1 Overall error

Overall error was significantly affected by box type, $F(1, 12) = 31.2$, $p < .001$, and corner, $F(3, 11) = 3.70$, $p = .046$. Post hoc analysis revealed that average virtual boxes error was1.64 times greater than physical box error ($p < .05$). In general, farther corners (Corner4) from the participant resulted in greater error (1.1 times greater) than closer corners (Corner 2), statistically controlling for box type and box (A, B, and C). Two-way interactions were observed for Box Type × Box, $F(2, 12) = 69.2$, $p < .001$; Box Type × Corner, $F(3, 11) = 5.92$, $p = .012$; and Box × Corner, $F(6, 8) = 9.49$, $p = .003$. Errors of the three boxes (collapsed across corners) for the different box types are graphically compared in Figure 3.7.

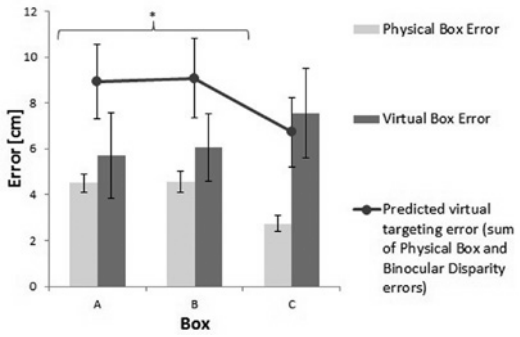

Figure 3.7. The bars represent mean overall physical box and virtual box errors collapsed across corners for different boxes (±1 SD). The predicted virtual box error was significantly greater than the physical box error for all boxes ($p < .05$). The circles represent the summed physical box and predicted errors. The bracket with a star (*) sign indicates the statistical significant difference between the summed predicted errors and virtual box errors ($p < .05$) for Boxes A and B, yet the summed predicted error was not statistically significantly different from the virtual error of Box C.

3.3.2 Errors in the forward, lateral, and vertical directions

Error in the forward direction was represented by the x-component of the coordinate, and it was significantly affected by box type, $F(1, 13) = 95.0$, $p < .001$, and box length along the forward direction, $F(3, 11) = 19.2$, $p < .001$. On average, virtual box error was 5.54 times greater than the physical box error in the forward direction (Figure 3.8). Post hoc analysis indicated that error in the forward direction was significantly greater for the farther targets ($p < .05$). However, there were no statistical significant differences between the average forward errors of the targets that were 47 cm and 59 cm distance from 0.0 cm. There was a two-way interaction for Box Type × Box Length, $F(3, 11) = 150.7$, $p < .001$. Average virtual target error at 59 cm in the forward direction was 1.9 times greater than the virtual target at 0.0 cm, yet the average physical target errors were not different (Figure 3.8).

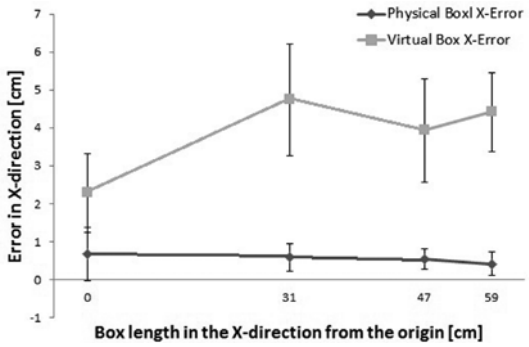

Figure 3.8. Error in the x-axis with respect to change in box length in x-axis (box length in the x-axis presented in the order of origin: Box C, Box B, and Box A). Error bars are ±1 SD.

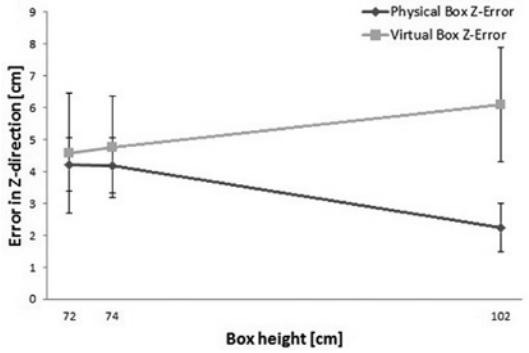

Figure 3.9. Error in the z-direction with respect to change in box height (in increasing height order: Box A, Box B, and Box C). Error bars are ±1 SD.

Error in the lateral direction, represented by the y-component of the coordinate, was not significantly affected by box type or box width (length in the y-axis). Error in the vertical direction, represented by the z-component of the coordinate, was significantly affected by box type, $F(1, 13) = 14.6$, $p = .002$, and corners, $F(3, 11) = 5.31$, $p = .017$. Average virtual box error in the vertical direction was 1.45 times greater than that for the physical boxes ($p = .002$). Regard- less of box type and box height, error at farther corner (Corner 3) from the participant was 1.1 times greater than at the closer corner (Corner 1) to the participants. Significant two-way interactions between box type and box height, $F(2, 12) = 66.9$, $p < .001$, and box height and corners, $F(6,8) = 9.82$, $p = .003$, were observed. Error for the tallest virtual box was

1.33 times greater than for the shortest virtual box, yet error for the tallest physical box was 1.89 times less than for the shortest physical box (Figure 3.9).

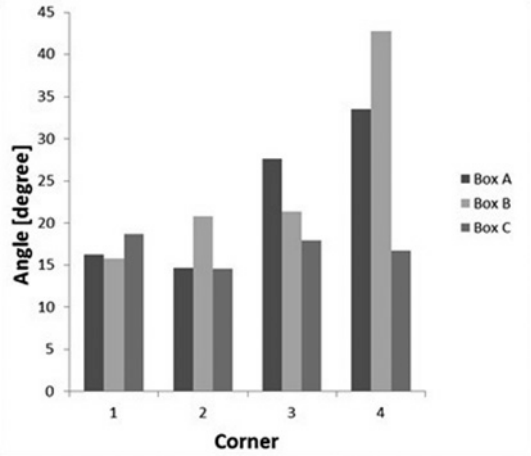

Figure 3.10. The differences of angles between the unit vector when approaching a physical target and the unit vector when approaching a virtual target.

3.3.3 Wand rotation Angles

Three distinctive wand angles of each trial were converted into individual unit vectors in polar coordinate (Equation 3.5). Each unit vector represented the direction where the wand was approaching the corner from at the time of trigger for that specific trial.

$$X = \cos(\text{elevation angle}) \times \cos(\text{azimuth angle})$$

$$Y = \cos(\text{elevation angle}) \times \sin(\text{azimuth angle}) \qquad \text{(Equation 3.5)}$$

$$Z = \sin(\text{elevation angle})$$

Dot product of the physical and virtual unit vectors of the same box and corner was calculated to determine the angle between the physical and virtual unit vectors, which would suggest variation in approaching directions. The approaching directions varied the greatest for the farthest corners. The greatest difference in corner approach directions between the physical and VR trials was Box B, which had the longest length in the x-direction (forward), followed by Box A and then C (Figure 3.10).

3.3.4 Task time

Task time was significantly affected by box type, $F(1, 13) = 8.7$, $p = .011$, and box size, $F(2,12) = 6.32$, $p = .013$. On average, task time for the virtual boxes (4.57 s) was 1.49 times longer than for the physical boxes (3.06 s) ($p = .011$). Average task time decreased as box height increased. Users on average spent 1.43 times more time to complete the trials involving the shortest box (4.62 s) than they did the tallest box (3.22 s).

3.3.5 Predicted binocular disparity error and observed error

The observed physical box error was generally less than observed virtual box error ($p < .05$) (Figure 3.7). Further analysis was conducted to examine the role of binocular disparity on user performance in terms of observed error and to understand the contribution of binocular perception in VR. We first confirmed that IPD and stature distribution among our participants were not biased from the U.S. anthropometric survey (Gordon et al., 1989) and then calculated the binocular disparity error using the geometric model and our collected data (Ponto et al., 2013). A calculated variable, the predicted virtual targeting error, was the sum of the bin- ocular disparity errors and the physical box errors. The predicted virtual target error represented the expected virtual box error for this task. Post hoc pairwise comparisons were conducted between the predicted virtual targeting error and the virtual box error for all four corners of all three boxes, with the Holm-Bonferroni adjusted alpha.

Predicted virtual targeting errors were always significantly greater than virtual box error for all corners of Boxes A and B ($p < .001$), and the predicted virtual targeting error was 1.13 cm greater than the virtual box error for Corner 1 (close-up corner) of Box C, $F(1, 13) = 6.77$, $p = .02$, and they were not statistically significantly different for the other three corners ($p > .05$). Collapsed across the corners, predicted virtual targeting errors were 3.22 cm and 3.00 cm greater than virtual box errors for Box A, $F(1, 13) = 79.1$, $p < .001$, and Box B, $F(1, 13) = 87.5$, $p < .001$, respectively. The predicted virtual targeting errors were on average 1.53 times greater than the virtual box errors for Boxes A and B. Overall virtual box errors were 0.83 cm greater than the predicted virtual targeting errors for Box C, which was not significantly different, $F(1, 13) = 2.87$, $p = .11$.

3.4 Discussion

In the present study, we investigated targeting of virtual and physical objects in a CAVE. The results indicated that user performance based on accuracy and time involving virtual objects was significantly poorer than with physical objects, and this finding was consistent with previous literature. More importantly, user performance was related to the location of the target as other depth cues compensated at different distances.

Prior to any statistical data analysis, we examined the mean overall error of the VR trials and observed a 1.36-cm decrease in error after the fourth VR trial and then no obvious improvement in mean overall user error in the subsequent trials. This finding suggested a practice effect, and therefore the first trial of the two replications of corner targeting was removed. We regressed the remaining VR trials against time, and there was not a statistically significant difference of error over time. The participants did not receive any visual feedback from the VR system or verbal feedback from the experimenter regarding their performance, as we would anticipate greater improvement in performance if the participants adjusted their final wand location by considering the feedback pro- vided. Relatively smaller error observed in the physical box trials confirmed that even if a practice effect existed for the physical boxes, the effect was much smaller than for the virtual boxes, and therefore their effects were not considered.

A limitation of the experiment was the participants were not instructed to look away at the bull's-eye between two consecutive touches that involved the same box. However, the presentation of boxes was randomized, and there were no observable systematic trends among consecutive trials.

3.4.1 User accuracy (error)

Users generally had significantly greater accuracy when reaching for corners of a physical box versus a virtual box. Averaged across all three boxes of the same type (physical or virtual), participants triggered the wand at 6.6 cm away from the virtual corners, and the error was 4 cm for the physical corners. It was hypothesized that human performance in VR and PE are different, and this hypothesis is supported by our data. Similar trends were previously reported for traversed and verbal estimated distances (Alexandrova et

al.,2010; Witmer & Kline, 1998). Interestingly, there was on average 4 cm of physical box error, which may be explained by participant instructions not to actually make contact with the physical box surface. It is expected that the difference between the virtual and physical box errors would increase if participants were permitted to touch the physical corners.

Errors were further analyzed with distinctive components along the x-, y-, and z-axes. Results indicated that errors in the forward and vertical directions (x-axis and z-axis, respectively) were influenced by corner location (i.e., target distance) but not in the lateral direction (y-axis). Virtual box error in the forward direction (along the x-axis) was significantly greater for the farther corners than for the closer corners, yet the physical box errors were not statistically significantly different among the corners of the same direction. Moreover, users had greater error when they aimed at far virtual targets in the horizontal direction (4.4 cm error for the far corners compared to 2.3 cm error for the closer corners). This result suggested that the accuracy of aiming at a virtual target is related to its location, and it is consistent with the literature (Interrante, Ries,& Anderson, 2006), but this relationship was not seen in physical targets. It is plausible that virtual box errors were related to the reaching posture since they increased as the target was farther in the forward direction. Images taken by the CAVE video camera were also reviewed, and we observed that users reached for virtual box corners with relatively different bending postures compared to reaches for physical box corners. There was more bending and wrist turning for far virtual box corners. On the basis of this finding, we would suggest that the source of the physical box error was not due to target location or reaching posture instability since the physical box error did not change significantly in relation to the increase in target distance in the forward direction (Figure 3.8).

The magnitude of virtual box error increased with increasing box height, but physical box error decreased. In this study, taller boxes represented closer targets to the participants since all boxes were shorter than all participants' standing eye height. As a result, virtual box errors were the greatest when the target was the closest to the participants' eyes along the z-axis. On the other hand, greater accuracy was observed for closer physical targets that varied in vertical distances (Figure 3.9). It is anticipated that

physical targeting error is affected by whole-body posture such that when fewer degrees of freedom and fewer body joints are involved in pointing at a target, the error should decrease. Targeting the 102-cm-height box often did not involve torso movement, and therefore less error was anticipated. We hypothesize that close-up virtual box errors may be due to visual perception, and farther virtual box errors observed in the forward direction may be due to physical reach and postural constraints. In order for users to interact with virtual objects based on their perceived location of the object, targets may need to be adjusted for activation boundaries.

Another plausible explanation for the observed effects was the use of a physical wand to aim at virtual targets, such that users may have viewed the physical wand while aiming for a virtual box corner, which may have resulted in an accommodation mismatch (Drascic & Milgram, 1996). In this condition, accommodation and the one vergence point for the physical wand and physical box are the same. However, the accommodation of the virtual target was on the CAVE screen, whereas the vergence point for the wand was on the virtual box corner. We suggest that the virtual box errors were most likely perceptual, which relates back to the earlier discussion. The possibility that an accommodation mismatch was responsible for the errors observed should be considered in future studies.

Though it is possible that the shutter glasses may have interfered with the users' ability to perceive the location of the physical box corners, the shutter glasses allowed the users to see through them, and therefore we do not anticipate interference. Assuming the physical box errors were not attributed to wearing the shutter glasses, then the physical box errors would be the smallest possible error in this type of task and setting. If this effect exists, it is representative of the conditions that would arise in a CAVE simulation involving people interacting with virtual objects, and therefore the findings of this study reflect that experience.

The present study outcome was consistent with other studies that resulted in greater error for virtual targets and less error for the physical targets, although we primarily investigated user interaction with

virtual and physical objects within arm-length distances with boxes as opposed to longer distance estimation. Errors in the x-axis and z-axis were also significantly affected by box type. Both x-axis and z-axis errors in VR were greater than for the PE.

3.4.2 Task time

Task time was also significantly affected by virtual and physical box types. Our participants spent 1.49 times longer to complete virtual box trials than physical box trials, and Liu et al. (2009) also reported less efficient aimed movements in VR. The result suggested that users moved more cautiously when aiming at virtual corners, and this finding is important to consider when analyzing movement time in VR. Since users were slower in aiming virtual targets, simulated tasks may not be completely transferrable to the physical equivalent.

3.4.3 Approach angles

Participants used the wand to approach different corners from various angles. Wand approach angles were significantly different among the four corners regardless of box type, implying that users approached the same corner number similarly in both physical and virtual box types. Although overall wand approach angles were not significantly different between the virtual and physical boxes, an increase in the difference between the virtual and physical approach angles was observed for the farthest corner. This finding could be explained by potential obstruction of the projection to form virtual objects by the participant's hand when reaching for the farthest corner. It would be relatively more difficult to aim at a corner when parts of the image were blocked. This possibility reinforces the importance of visualizing complete objects to perform tasks that require accuracy in VR. The participants may have approached the corners from an angle that would minimize blocking the images, which could explain smaller errors observed for closer virtual corners in the forward direction. On the other hand, users may have taken a more natural route when approaching the physical corners by moving across the box since they did not have to be concerned about blocking visual information because none of the physical box components relied on projector image creation.

3.4.4 Predicted targeting error and observed error

We found no significant difference between the predicted virtual targeting error and the virtual error for Box C but found that participants tended to perform better than anticipated for Boxes A and B (Figure 3.7). We propose that the difference in performance was due to the difference in target locations (distances) to the eyes. Box C (102 cm in height) was the tallest box, and therefore the target locations were closer to the eyes of the participants than were the targets on Boxes A and B (72 cm and 74 cm in height, respectively). Moreover, the virtual box error of the closer corner of Box C was statistically significantly greater than its predicted virtual targeting error, supporting the suggestion that participant targeting accuracy decreased for closer targets. Specifically, the mismatch of visual accommodation and vergence increases for virtual objects that are closer to the eyes in the CAVE, which may be related to the decreased targeting accuracy. These results mirror those found by Pollock, Burton, Kelly, Gilbert, and Winer (2012) when studying difference in perception of non-tracked users in VR and by Woods, Docherty, and Koch (1993) when studying image distortions in stereoscopic video systems.

A recent study conducted by Renner, Velichkovsky, Helmert, and Stelzer (2013) also pointed out that accounting just for IPD in the CAVE set- ting was not sufficient to completely reduce the error of the users, in which IPD was related to binocular disparity. We further suspect that users utilized depth cues other than binocular disparity when viewing farther virtual targets, as authors of some studies have suggested that depth information in VR does not solely rely on binocular disparity cues, and the type of visual cues utilized is dependent on the type of task (Bradshaw et al., 2000; Hibbard & Bradshaw, 2003). It is likely possible those visual cues not based on binocular disparity assisted in overcoming the incorrect perceived position of the target location, specifically for the corners of Boxes A and B (relative to Box C). Kelly et al. (2013) recently reported that leftward and right- ward displacement from the center of projection caused less distortion than predicted by predictions of models based on monocular and binocular viewing geometry.

Results of this study revealed that there are varying levels of user aiming accuracy and approach angle due to target location, which provides some insights for future designs of visually mediated objects in VR. It is important to account for user aiming inaccuracy by modifying the activation boundary of virtual objects in order to provide users better experience when studying natural gestures and manipulation of virtual objects. Moreover, user accuracy was lower for targets in the far horizontal location as well as for close-up corners. Consequently, users performed better when they aimed at corners that were not too far or too close. This result suggests that there may be a range that users would best operate in for a target aiming task.

Any virtually projected object on a screen should appear to be at that location, as there is no virtual disparity (Ponto et al., 2013). As the virtual object moves away from the screen, the artifacts of VR become more pronounced (Woods et al., 1993). For instance, as the object comes farther out from the screen, depth compression becomes a greater factor. Additionally, motion parallax will increase as the object is closer to the user, resulting in increased problems from any incorrect head tracking/positioning (Cruz-Neira et al., 1993). Adjustment of the CAVE bin- ocular disparity setting relative to user IPD to account for differences in user binocular disparity individually might help reduce some error, but the results of this study indicated that bin- ocular disparity may be just one source that contributed to user accuracy. Furthermore, individual IPD adjustments may not be feasible when multiple observers are participating in a CAVE simulation.

3.5. Conclusions

Human performance in VR was less accurate (greater error) and less efficient than in the PE, as error was greater for both close and far virtual objects. Users approached the virtual and physical targets (within 1 m) from similar angles. It is important to consider how users approach and acquire virtual objects within a distance range, which will help researchers better understand the activation boundaries of virtual objects and then manipulate VR to allow more natural interactions. Our data indicated that physical target error was not due to the target location or the postural instability of the user reaching for the target because the

magnitude of error was not affected by distance to the target. We anticipate that farther virtual target error was associated with the awkward reaching posture, and the closer virtual target error was associated with binocular disparity because closer targets involved less awkward reaching posture. The evaluation of user perception of virtual and physical objects provides some insights to user performance, which may contribute to future studies involving natural interactions of hands and virtual objects in VR.

Finally, we anticipate that other depth cues in addition to binocular disparity may be involved with targeting farther virtual objects, because users performed better than our prediction using a geometric model. The geometric model accounted for the binocular disparity but did not take into account all factors related to performance, as it is a gross model. For instance, other means of determining depth besides binocular disparity could be used to determine corner position. We also suspect that mismatch of visual accommodation and vergence played a role in the increased targeting inaccuracy in aiming for closer virtual targets. In future studies, we will aim to better understand these factors.

3.6 Acknowledgement

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3.7 Key Points

- Virtual box errors were generally greater than physical box errors.
- Participants approached the physical and virtual box corners from similar angles, but the variation increased as the distance from the user to the corner increased.
- Inaccuracy of the nearer virtual targets is associated with binocular disparity, and the inaccuracy of the farther virtual targets is associated with user reaching posture.
- Task time was longer with the virtual trials.

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4. Virtual Exertions: Evoking the Sense of Exerting Forces in Virtual Reality Using Gestures and Muscle Activity

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Objective: This study was a proof of concept for virtual exertions, a novel method that involves the use of body tracking and electromyography for grasping and moving projections of objects in virtual reality (VR). The user views objects in his or her hands during rehearsed co-contractions of the same agonist-antagonist muscles normally used for the desired activities to suggest exerting forces.

Background: Unlike physical objects, virtual objects are images and lack mass. There is currently no practical physically demanding way to interact with virtual objects to simulate strenuous activities.

Method: Eleven participants grasped and lifted similar physical and virtual objects of various weights in an immersive 3-D Cave Automatic Virtual Environment. Muscle activity, localized muscle fatigue, ratings of perceived exertions, and NASA Task Load Index were measured. Additionally, the relationship between levels of immersion (2-D vs. 3-D) was studied.

Results: Although the overall magnitude of biceps activity and workload were greater in VR, muscle activity trends and fatigue patterns for varying weights within VR and physical conditions were the same. Perceived exertions for varying weights were not significantly different between VR and physical conditions.

Conclusions: Perceived exertion levels and muscle activity patterns corresponded to the assigned virtual loads, which supported the hypothesis that the method evoked the perception of physical exertions and showed that the method was promising.

Application: Ultimately this approach may offer opportunities for research and training individuals to perform strenuous activities under potentially safer conditions that mimic situations while seeing their own body and hands relative to the scene.

Keywords: simulation and virtual reality, electromyography (EMG), forces and moments, computer interface, virtual environments

4.1 Introduction

Simulation of physical activities is important not only for research, testing, and development but also for training individuals to perform physically demanding tasks safely, preventing over-exertions, or avoiding the risks of falling. Immersive virtual reality (VR) has been demonstrated useful for numerous training and simulation applications involving physically demanding activities, including emergency medicine and disaster preparedness (Andreatta et al., 2010; Reznek, Harter, & Krummel, 2002), crowd evacuation from an area under a terrorist bomb attack (Shendarkar, Vasudevan, Lee, & Son, 2006), manufacturing processes (Mujber, Szecsi,& Hashmi, 2004), posttraumatic stress disorder and stress inoculation training (Wiederhold & Wiederhold, 2008), physical rehabilitation (Henderson, Korner-Bitensky, & Levin, 2007), mining (van Wyk & de Villiers, 2009), Tai Chi training (Chua, et al., 2003), and maintenance of industrial equipment (Oliveira, Cao, Hermida, & Rodríguez, 2007). Bailenson et al. (2008) have shown that immersive VR was superior for training individuals to perform physical movements, such as physical therapy and exercise, compared to video training according to objective performance measures.

While simulation studies in VR provide safe experimental conditions to mimic images and situations and to explore human behavior, virtual objects created by computer graphics lack weight and force feedback. Unlike in the physical environment, individuals produce forces by muscle contraction to counter the

forces of physical objects. A common control device used for manipulating virtual objects in a Cave Automatic Virtual Environment (CAVE) is a hand-operated controller or a "wand." As a result, users may not experience the usual physiological reactions, such as appropriate muscle contraction, force production, and exertions, in response to weight and forces in VR. Various techniques have been developed to introduce force and haptic feedback, such as a pen-like device (PHANToM™) that exerts a force vector on the fingertip of the user, incorporation of tangible physical objects into the virtual environment, an actuator-based tactile feedback device (FEELEX), and a wearable haptic hand or fingered gloves that provide resistive forces or shear stress (Bau & Poupyrev, 2012; Burdea, 2002; Burdea, Popescu, Hentz, & Colbert, 2000; Connelly et al., 2010; Iwata, Yano, Nakaizumi, & Kawamura, 2001; Minamizawa, Kajimoto, Kawakami, & Tachi, 2007; Popescu, Burdea, Bouzit, & Hentz, 2000; Sallnäs, Rassmus-Gröhn, & Sjöström, 2000).

These types of force and haptic feedback rely on additional devices or small physical objects that are specifically made for that task. Users are sometimes bound to a fixed location in order to receive feedback from immobile instruments, which may limit the integration of the task into the virtual scenario. Moreover, these devices mostly focus on feedback to the hand region, and thus providing force feedback for tasks involving gross motor activity may be challenging. Therefore, we are motivated to incorporate a mechanism in VR that suggests muscle con- traction when directly manipulating virtual objects without control devices.

In this study, we explore if we can create more evocative experiences of muscle contraction during a physical task when interacting with virtual objects through the concept of virtual exertions, a method utilizing biofeedback from electromyograms (EMG) as well as gestures and movements for interacting with virtual objects in VR. Our experience in creating VR scenarios in a CAVE finds that this feature is an important aspect of the simulation that currently lacks a practical solution. The objective of virtual exertions is not to faithfully simulate physical exertions in VR but rather to devise a methodology for evoking the sense that one is exerting forces in a VR simulation. Correspondingly, VR simulations could

include physical tasks alongside cognitive activities for observing participant behaviors and for experiencing tasks for training and research without the risk of injuries or falls. Examples of such applications involve activities performed by factory workers, first responders, and those in military, mining, manufacturing, and many other both cognitively and physically demanding jobs.

Physical exertions are the contraction and expenditure of energy by skeletal muscle groups in the physical environment for doing mechanical work against a load and for performing gross or fine-motor tasks. We define virtual exertions as a mapping of human-generated forceful actions, postures, and movements that are generally used to manipulate physical objects against projections of objects in the hands as an interface into the virtual environment. In order to create virtual exertions, EMG activity is monitored during rehearsed co-contractions of agonist-antagonist muscles used for specific actions, and contraction patterns and levels are combined with tracked motion of the body and hands for identifying when the participant is exerting sufficient force to displace the intended object in a CAVE. EMG electrodes affixed to the forearm and arm muscles feed back this information to the computer to cause the motion of the virtual object to respond according to the physical laws that allow the virtual objects to visually react as they would if they were massive objects.

Simulated resistance to virtual objects comes directly from co-contracting antagonist muscles that stiffen the joints. Hogan (1984) demonstrated that humans co-contracted both biceps and triceps in an isometric elbow flexion posture while grasping a 5-lb weight, which represented a usual task under normal physiological conditions. It was suggested that co-contraction contributes to postural stabilization even during a weight-bearing task in the physical environment. Furthermore, continuous visual feedback is provided to the users of virtual exertions to display mechanical work performed against virtual objects with simulated inertial properties. Virtual exertions may be a more evocative method of interfacing humans and virtual objects because they involve the expenditure of energy by common muscle groups used for physical tasks, although absent of external resistance or loads.

It is well known that rectified surface EMG approximates the linear relationship with force produced by muscles during isometric contraction (De Jong & Freund, 1967; Milner-Brown & Stein, 1975; Moritani & DeVries, 1978; Weir, Wagner, & Housh, 1992). Muscle torque and integrated EMG signals are generally linear in the forearm flexors and the leg extensors (Weir et al., 1992). However, some studies have shown that summation of muscle-unit EMG potentials is nonlinear at high force levels or a general non- linear relationship between EMG and muscle tension (Milner-Brown & Stein, 1975; Zuniga & Simons, 1969). These findings suggested direct relationships between EMG and forces, which makes it feasible for us to impart physical characteristics to the virtual objects and thus allow the manipulation of virtual objects based on the monitored EMG values.

The use of EMG signals in controlling and activation of objects, similar to the virtual exertions concept in VR, has long been implemented for prosthetics and robotics. This method was proposed as early as 1947 by Norbert Weiner (Bottomley, 1965). Battye, Nightingale, and Whillis (1955) were the first to successfully control the movement of hand prosthesis, controlled by EMG, to grasp and hold a pencil. Bottomley (1965) has described the early hand prosthesis control mechanism as the activation of a pair of agonistic-antagonistic muscles. It required the myoelectric signal of the flexors to activate the closing movement of the prosthetic hand, and then it was necessary for the activation of the extensor myoelectric signal to relax the grasping movement. More complex EMG controlled prosthetic movements could be made possible with the additional EMG inputs of additional numbers of muscles to achieve the multiple degrees of freedom that a physiological hand has (Weir, Troyk, DeMichele, & Kerns, 2006). Furthermore, it has been identified that EMG could be used for controlling virtual arm movements displayed on computer screens for studying motor control and even injuries (Manal & Buchanan, 2005; Manal, Gonzalez, Lloyd, & Buchanan, 2002).

Previous researchers have explored the idea of interfacing with EMG sensors for the purposes of human–computer interaction. Costanza and colleagues (Costanza, Inverso, & Allen, 2005; Costanza, Inverso, Allen, & Maes, 2007; Costanza, Perdomo, Inverso, & Allen, 2004) have explored the idea of using

EMG sensors to create intimate user experiences that analyze subtle movements. This method allowed for the sensing of "motionless gestures" that could not be determined from outside observers. Whereas these works are mainly focused on gesture recognition and classification of physical actions using EMG signals, we are interested in using graded exertions as an interface for virtual environments where users interact directly with virtual objects in their hands using postures, muscles, and poses typically assumed for the simulated task.

Another motivation for virtual exertions is to permit users in VR to be able to see flexibly virtual objects manipulated directly in the hands and to possibly improve user performance in VR. Our previous research has compared user physical interaction between physical objects and equivalent stereo virtual objects presented in a CAVE using a target location task to examine how human performance (accuracy, time, and approach) is affected by various target locations (Chen et al., 2014). Fourteen participants completed a manual targeting task that involved reaching for corners on equivalent physical and virtual boxes in three different sizes. Users were 1.64 times less accurate ($p < .001$) and spent 1.49 times more time ($p = .01$) in targeting virtual than physical box corners. Consequently, we think that the alignment of visual feedback, among other visual factors and physical actions, is important for creating a plausible physical simulation, which led to the concept of virtual exertions—seeing a virtual object in the hand of the user and co-contracting to interact with it. We anticipate that some of these discrepancies stem from incorrect geometric viewing parameters, specifically, that physical measurements of eye position are insufficiently precise to provide proper viewing parameters (Ponto, Gleicher, Radwin, & Shin, 2013). Consequently, we investigate the effects of VR immersion (i.e., 2-D bland visuals vs. 3-D stereo visuals) in the current study.

This study is a proof of concept of the virtual exertions method for simulating the handling of virtual objects. Participants performed simple biceps curl dumbbell-lifting tasks in both the physical and immersive virtual environments. It was hypothesized that virtual exertions can create responses of physical interaction against visually mediated objects by moving and contracting the same muscles

normally used for activities including lifting, pushing, or pulling to suggest exerting forces. We also tested the hypothesis that users' performance in VR that has a greater level of immersion will be closer to their performance in the physical environment. Both physiological (EMG) and psychophysical (ratings of perceived exertion and task load) responses were recorded.

4.2 Method

4.2.1 Participants

Eleven participants were recruited from the University of Wisconsin–Madison campus with informed consent and having the demographics summarized in Table 4.1. Inclusion criteria were self-reported normal or corrected-to-normal vision, willingness to continuously lift a 4.54- kg (10-lb) weight for 2 min, and ability to stand for at least 20 min. Exclusion criteria comprised self-report of neuromotor impairments, claustrophobia in a 3 m × 3 m × 3 m cubic room, Lasik eye surgery, experiences of epileptic seizure or blackout, a tendency for motion sickness when experiencing visual motion conflicts, sensitivity to flashing lights, or taking perception-altering medication. One participant did not complete one of the 2-D virtual environment sessions out of the three sessions required. All participants were of at least 18 years of age.

Table 4.1: Participant Demographics and Characteristics

Variable	n
Gender	8 females 3 males
Age (SD)	24.5 years (3.53)
Height (SD)	170.25 cm (11.62)
Interpupillary distance (SD)	61.92 mm (3.73)
Handedness	2 left-handed 9 right-handed
Vision	9 corrected to normal 2 normal

4.2.2 Instrumentation

VR CAVE. The virtual scenarios (3-D stereo and 2-D bland) were created in a 2.93 m × 2.93 m × 2.93 m six-faced (C6) rear-projection CAVE that consisted of one ceiling, one solid acrylic floor, and four walls (Figure 4.1). Two 3-D projectors (Titan Model 1080p 3D, Digital Projection, Inc., Kennesaw, GA) with maximum brightness of 4,500 lumens per projector, with a total of 1,920 × 1,920 pixels combined, projected images on each surface of the CAVE. The projectors refreshed at 144 Hz frame rate, which had the capability to provide stereo display to two independent viewers simultaneously by time multiplexing. The visuals were either retrieved from an online open-source 3-D model repository (Trimble 3D Warehouse, Google, Mountain View, CA) or created in SketchUp (SketchUp, Trimble Navigation, Ltd., Sunny- vale, CA), and then the virtual scenarios were rendered by a set of four workstations (2 × Quad-Core Intel Xeon). Shutter glasses (CrystalEyes 4 Model 100103-04, RealD, Beverly Hills, CA) were worn to view images in stereoscopy. Audio was generated by a 5.1 surround sound audio system.

Tracking. Position data were acquired using a wireless ultrasound tracking system (VETracker Wireless 6R36 Model IS-900, InterSense, Inc., Billerica, MA), which included two position trackers (MicroTrax Model 100-91300-AWHT, InterSense, Inc., Billerica, MA) and 30 ultra- sound emitters that were evenly embedded along the upper (two per edge) and vertical (three per edge) edges of the CAVE to allow full 6-degrees-of-freedom position tracking. One position tracker was mounted on the top rim of the shutter glasses to create images from the user's viewpoint, and the other tracker was attached to a glove worn over the dominant hand of the user to track the hand location. Motion of the hand was tracked and recorded, and the trackers were sampled at 60 Hz.

Muscle activity and user interface. The EMG data acquisition system included the 16-channel EMG transmitter unit (TeleMyo Model 2400T G2, Noraxon, Inc., Scottsdale, AZ), four EMG active leads with one ground lead, CF Wi-Fi radio card, PCMCIA receiver card (Cisco Aironet 802.11a/b/g wireless card bus adapter, Cisco Systems, Inc., San Jose, CA), and a data collection laptop computer with custom programmed data collection software. EMG signals were collected by the transmitter unit and then

transmitted to and stored on the laptop at 3000 Hz sampling frequency. The EMG system also served as the interface between the user and the visual objects; EMG data feedback was relayed to the CAVE workstations to compare against the calibrated virtual object lifting threshold of that individual during that particular experimental session for obeying the laws of physics.

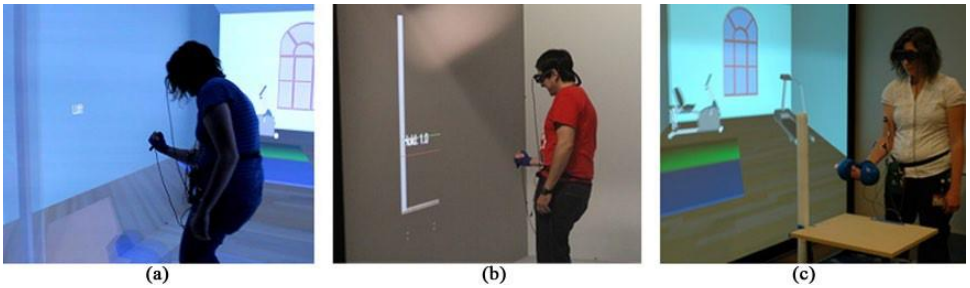

Figure 4.1. Panels (a) and (b) illustrate the participant performing virtual exertions inside the Cave Automatic Virtual Environment in the stereo immersive and the bland conditions, respectively; panel (c) illustrates a participant performing the equivalent task in the physical environment.

The virtual exertions muscle activity control algorithm was written in C++ and programmed in Microsoft Visual Studio (Microsoft, Redmond, WA). Data collection software interface was developed in Qt (Qt Project Hosting, Oslo, Norway). During data collection a moving root mean square (RMS) of real time EMG with a window of 850 samples was calculated, and then the integrated RMS was sent to the CAVE workstations at 60 Hz. This integrated RMS was compared against the user-specific linear regression of biceps muscle RMS that was collected during calibration, which was the threshold value for moving the virtual object. The calibration curve illustrated in Figure 4.2 is representative of a typical calibration relationship between weight, height, and RMS EMG amplitude, although the exact relationship varied for each participant.

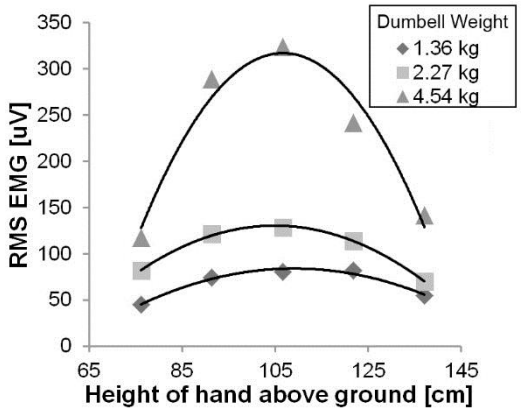

Figure 4.2. Typical calibration data regression curve of the biceps obtained from the experiment. All calibration curves of the biceps muscles exhibited a quadratic trend.

The EMG values of the biceps served as the virtual object lifting threshold since biceps were the selected prime mover in this elbow flexion task. The threshold value was calculated based on the regression slope that was determined from calibration and the current tracked height of the hand (Equation 4.1). If the real time EMG value was less than the threshold, the virtual object would "drop."

$$\text{Lifting threshold value} = \text{slope} \times \text{height}^2 + \text{intercept} \qquad \text{(Equation 4.1)}$$

4.2.3 Procedure

A complete experiment consists of three sessions; each participant completed tasks in the physical, 3-D stereo, and 2-D bland conditions whereby each condition was a separate session that was at least 24 hr apart (Figure 4.1). The physical condition took place outside of the CAVE, and the stereo and the bland conditions were conducted in a virtual environment created inside the CAVE. A simple stereovision check was performed before the start of the experiment to verify the participants' ability in seeing stereoscopic images. They then completed a self-reported demographic questionnaire that included age, gender, ethnic background, weight, handedness, vision correction, and upper-extremity injury history. All participants were able to see stereoscopy and did not have injuries that prevented them from performing

simple lifting tasks. Interpupillary distance was measured using a digital pupilometer (Digital PD ruler PM-100, Luxvision, www.luxvsion. net), and stature was measured using an anthropometric caliper. Surface EMG dual electrodes were affixed to the four muscle groups (extensor carpi radialis [ECR], flexor carpi radialis [FCR], triceps, and biceps) that were monitored using the EMG transmitter unit.

Participants were instructed to stand in the ready position before the start of any trial, which was demonstrated by the experimenter: standing upright with palms inward. The system was calibrated to participants' muscle activity profile at every session, which established the EMG threshold that was required to reach during virtual exertions. Participants then performed (a) a simple biceps curl dumbbell-lifting task and (b) a 2-min dumbbell endurance task. The rated perceived exertion (RPE) on a 0 to 10 scale (Borg, 1990) was used to assess the level of exertion after every trial during Task 1 (biceps curl dumbbell lifting) only. The NASA Task Load Index (NASA-TLX) that assessed the workload of tasks was administered at the end of every session (Hart & Staveland, 1988).

4.2.4 Calibration

During every session, participants lifted three physical dumbbells of known weights (1.36 kg, 2.27 kg, and 4.54 kg) to five controlled heights (76.2 cm, 91.4 cm, 106.7 cm, 121.9 cm, and137.2 cm) and sustained holding the weight at that height for 5 s. They were instructed to keep the upper arm parallel to their torso and only flex at the elbow. The dumbbells were standard weights and the heights were selected to span the flexion and extension range of the elbow joint. EMG was recorded during the 5-s isometric contraction, and then the integrated biceps RMS EMG was calculated to determine the regression equation. The integrated biceps RMS EMG magnitude served as the action threshold that the participants were required to produce and to maintain in order to achieve a successful "lift" in the 3-D stereo and 2-D bland conditions. After each dumbbell-lifting calibration trial, a 30-s rest break was provided.

Additionally, three elbow flexor maximum voluntary contractions (MVCs) were performed at heights of 91.4 cm, 106.7 cm, and 121.9 cm during every session. Elbow flexor MVCs were performed by pulling against a handle that was connected to an adjustable metal chain, which was affixed to a solid board on

which the participants stood. The associated RMS EMG values from an angle-specific maximal isometric voluntary contraction were selected to be the normalization reference values in this study, which was similar to Burden (2010), who used the peak EMG from a maximal isometric voluntary contraction for the same muscle and joint angle for normalization. Extended rest breaks of 3 min were provided after each MVC trial.

4.2.5 Tasks

Biceps curl dumbbell-lifting task. Participants lifted three objects of identical appearance but of varying weights (1.36 kg, 2.27 kg, and 4.54 kg) to three controlled heights (91.4 cm, 106.7 cm, and 121.9 cm). For the physical condition, the physical dumbbells were customized hollow dumbbell containers that were filled with lead shot to measured weights. Photographs of the customized physical dumbbells were taken to create the graphics for the virtual dumbbells used in the stereo condition. For the bland condition with minimal immersion, the dumbbell visuals were replaced with a single line that represented minimal graphics.

At the initiation of a physical trial, the experimenter placed a physical dumbbell on a table in front of the participant; for the virtual trial, the computer rendered a virtual dumbbell in the stereo condition or a line in the bland condition on a virtual table in front of the participant. For all conditions, participants first assumed the ready position, and then a synthetic verbal cue announced, "Please grasp and lift the weight up to the instructed height using sufficient effort to overcome the load, but without over exerting or becoming fatigued." In the physical condition, the experimenter verbally announced one of the heights that were marked on a stick, and in the virtual conditions, the computer rendered the appropriate label on a stick, and then the participant lifted the object and sustained at that height for 5 s. In the physical environment, the experimenter counted down 5 s and then instructed the participant to "please return the weight to the table and then relax."

All heights were randomized. The criterion for holding virtual objects in the hand is based on the real time biceps EMG RMS magnitude while the position is tracked. When the real time biceps EMG was at least equal to or greater than the calibrated EMG threshold, the virtual object was displaced relative to the hand motion. At the initiation of a trial, the word Lift appeared on the CAVE wall in front of the participant. The virtual object was superimposed in the tracked hand, so when participants performed a biceps curl and they were at or above the threshold, the virtual object appeared to move along with the hand. If the real time EMG fell below the threshold, the object would instantaneously return to the table and the word "Dropped" would appear on the CAVE wall, and then the participant would have to lift the dumbbell from the table again. The threshold was weight and height specific; trials that involved heavier virtual objects had greater thresholds that varied across the range of elbow flexion positions. After successfully sustaining the virtual load at the given height for 5 s in the CAVE, a synthetic verbal cue announced, "Please return the weight to the table and then relax." Thirty- second rest breaks were provided between each trial, and there was a rest break of at least 5 min at the end of biceps curls trials.

Two-minute endurance task. After the completion of the biceps curl dumbbell-lifting task, the participants were instructed to grasp, lift, and hold a 4.54-kg dumbbell at 90° elbow flexion and to sustain it for 2 min. In the physical condition, the experimenter reminded the participant at 1 min and then 10 s before reaching 2 min. In the virtual conditions, a countdown timer appeared on the CAVE wall in front of the user that indicated the time. Participants rated their level of fatigue after the endurance task with the following instruction: "With 0 being not fatigued, and 10 being the most fatiguing situation you've experienced, how would you rate your level of fatigue right now? Fatigue feels like discomfort, a slight burning sensation, or pain in the muscles."

4.2.6 Experimental design, Variables, and data Analysis

Participants completed a total of 27 biceps curl trials (three replications for the three weights at three different heights) per session. They performed one endurance task per session after the biceps curl task and then completed the NASA-TLX at the end of each session.

Independent variables were virtual environment condition (three levels), weight (three levels), and height (three levels). Dependent variables were EMG of the four muscle groups, RPE, and NASA-TLX. Mean power frequency (MPF) from the initial and final 10 s of the endurance task was extracted to analyze muscle fatigue.

All EMG data were normalized against the level of contraction of the muscles recruited during an elbow flexion MVC at each height for a specific session. Since the normalization MVCs were performed only for elbow flexion, only the normalized biceps EMG values were tested for the effects of condition, weight, and height using repeated-measures ANOVA, and then post hoc pairwise comparisons were conducted to examine the differences between conditions with Holm-Bonferroni alpha correction for the biceps. Normalized triceps, FCR, and ECR were tested only for the effect of weight and height within the same condition. Biceps MPF was tested for the effect of condition and endurance time; the MPF of triceps, FCR, and ECR were tested only for the effect of endurance time within the same condition. The significance level was at .05 for all tests.

4.3 Results

4.3.1 Biceps curl task EMG

Biceps. The two-way and three-way interactions were not statistically significant. There was a significant main effect of condition for the biceps, $F(2, 8.65) = 10.74$, $p = .005$ (Figure 4.3). Statistically controlling for weight and height at their means, we found pairwise comparison revealed that EMG activity in the physical condition was 0.158, $F(1, 9.15) = 16.86$, $p = .005$, and 0.053, $F(1, 10) = 7.09$, $p = .024$, normalized units less than in the bland and stereo conditions, respectively. On average, weight significantly affected biceps activities ($F(1, 9.97) = 76.67$, $p < .001$), but there was no effect of height.

Triceps, FCR, and ECR. Overall, activities of these three muscles increased as the weight of the object increased. Weight significantly affected the triceps for the physical, $F(1, 10) = 45.97$, $p < .001$, and stereo conditions, $F(1, 10) = 17.50$, $p = .002$. FCR was also affected by weight for the physical, $F(1, 10) = 50.48$, $p < .001$, and bland, $F(1, 9) = 9.67$, $p = .013$, conditions. In ECR, the effect of weight was significant in

the physical, F(1, 10) = 67.40, $p < .001$; stereo, F(1, 9) = 19.91, $p = .002$; and bland, F(1, 10) = 12.64, $p = .005$, conditions. There was no effect of height on EMG level.

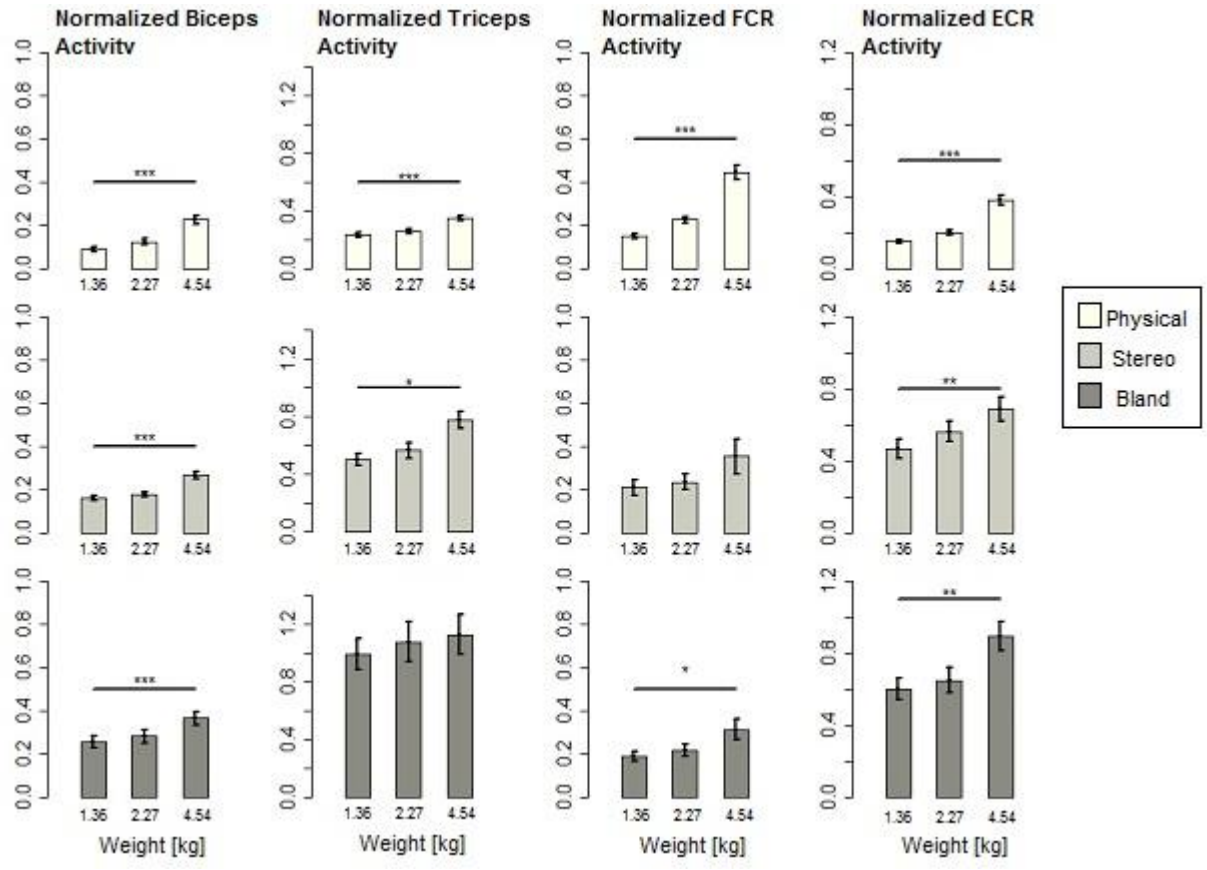

Figure 4.3. Normalized biceps, triceps, flexor carpi radialis, and extensor carpi radialis activities are plotted by weight for the physical, stereo, and bland conditions (±1 SE; *$p < .05$, **$p < .01$, and ***$p < .001$). The unit on the vertical axis is normalized EMG activity.

4.3.2 Perceived exertions

The RPE was analyzed using a 3 (condition) × 3 (weight) × 3 (height) mixed-effects repeated measures ANOVA. There was a two-way interaction between weight and condition, F(2, 8.86) = 16.23, $p < .001$. For every 1-kg increase in weight, RPE increased 1.385 units, F(1, 10) = 83.10, $p < .001$, in the physical condition; increased 0.636 units, F(1, 10) = 21.49, $p < .001$, in the stereo condition; and increased 0.350 units, F(1, 9.84) = 5.13, $p = .047$, in the bland condition (Figure 4.4). There was a significant effect of weight, F(1,10) = 97.66, $p < .001$, and there was no significance for condition or height ($p > .05$).

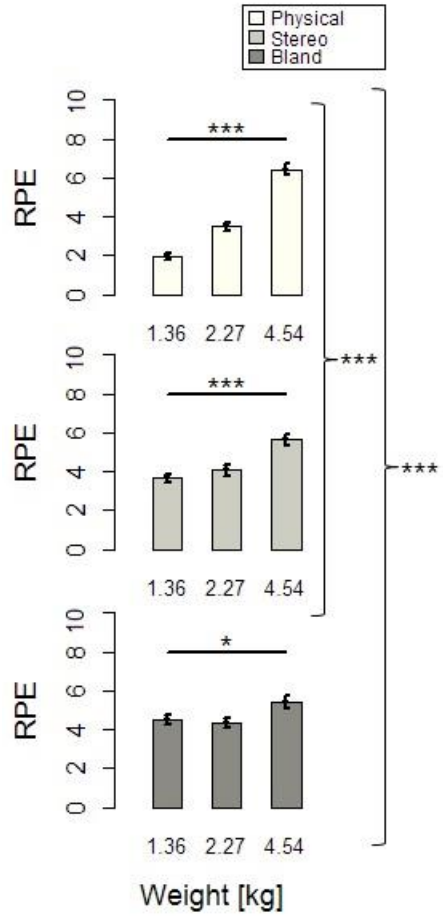

Figure 4.4. Perceived exertion in terms of rated perceived exertion (0 to 10 scale) by weight for the physical, stereo, and bland conditions (±1 SE; *p < .05, **p <.01, and ***p < .001). Interaction between condition and weight are denoted by curly braces, indicating the rate of change in weight in the physical condition was statistically significantly different from the rate of change in weight in the stereo and the bland conditions.

4.3.3 EMG MPF

Biceps. The two-way interaction between condition and endurance time was not statistically significant. There was a significant main effect of condition for the biceps MPF, F(2, 8.53) = 5.66, p =.027. On average, the physical condition had the lowest MPF; pairwise comparison indicated that the physical condition was 12.24 Hz, F(1, 9.91) = 12.38, p =.006, and 10.93 Hz, F(1, 9.87) = 5.87, p =.036, lower than the bland and stereo conditions, respectively (Figure 4.5). There was 5.07 Hz decrease shift in MPF, F(1, 9.91) = 12.71, p =.005, over the course of 2 min.

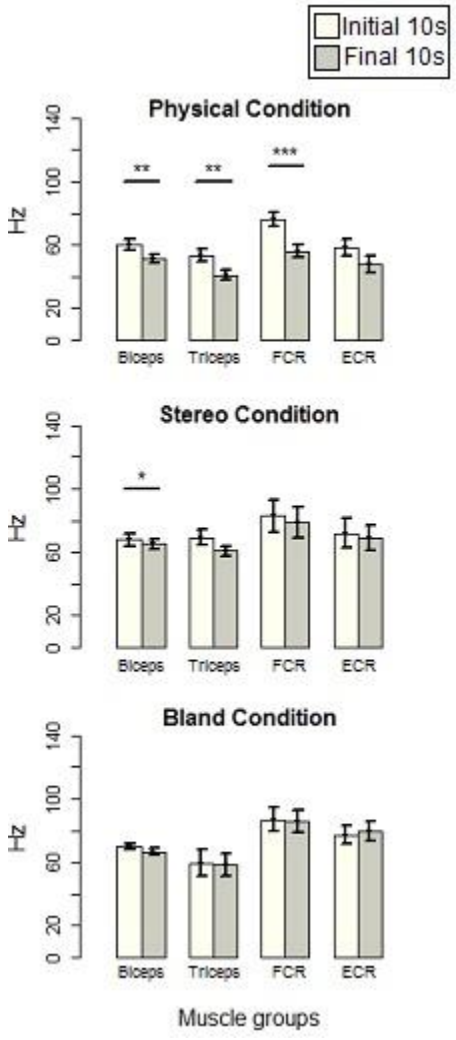

Figure 4.5. Mean power frequency (Hz) by muscle groups over time for physical, stereo, and bland conditions (±1 SE; *$p < .05$, **$p < .01$, and ***$p < .001$).

Triceps, FCR, and ECR. Over the course of 2 min, a significant decrease shift of MPF was observed for the physical condition; a decrease of 12.52 Hz was observed for the triceps, $t(10) = 4.52$, $p = .011$; 20.11 Hz for the FCR, $t(10) = 5.14$, $p < .001$; and 10.92 Hz for the ECR, $t(10) = 5.30$, $p < .001$. No significant decrease shift in the bland or stereo conditions was observed.

4.3.4 NASA-TLX

One-way repeated measures ANOVA was used to compare NASA-TLX (overall and subscale scores) among all conditions (three levels). Significant effect of condition was observed in Frustration, $F(2, 8.67) = 32.63$, $p < .001$; Mental Demand, $F(2, 8.60) = 5.78$, $p = .026$; and Temporal, $F(2, 8.70) = 4.51$, $p = .045$, subscales. In general, overall score, effort, performance, and physical demand were not affected by condition. With the physical condition as the reference level, further pairwise comparison results of the three statistically significant subscale scores are illustrated in Figure 4.6.

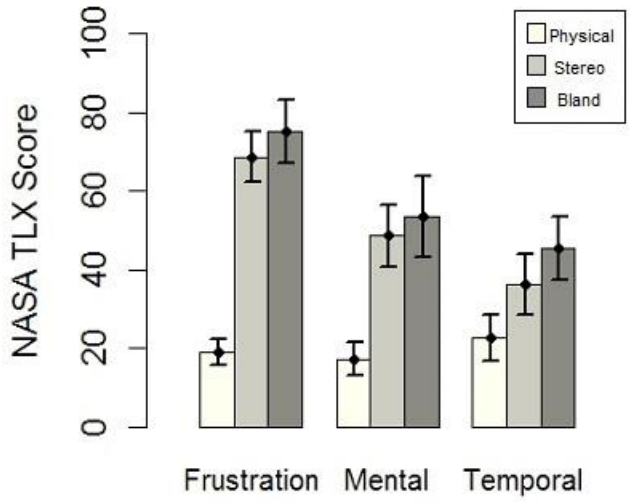

Figure 4.6. Raw scores (range from 0 to 100) of three subscales of NASA Task Load Index (Frustration, Mental Demand, and Temporal) across the three conditions (±1 SE). Within the same subscale, pairwise comparisons indicated statistically significant difference between conditions, with physical condition as the reference level (*$p < .05$, **$p < .01$, and ***$p < .001$).

4.4 Discussion

This study was a proof of concept for the method of virtual exertions, and it demonstrated that users were able to successfully manipulate virtual objects in the hands and simulate forceful exertions through the use of body movement tracking and EMG. The novelty of virtual exertions is that we involve the same muscle group co-contractions used for that activity in the physical environment as the interface with the virtual objects. It enables users to perform exertions when interacting with virtual objects as with physical objects, without manipulating or grasping supplemental control inputs or physical items to interact with virtual objects. Virtual exertions offer inherent haptic feedback through the proprioceptors and muscle

stretch and tension receptors involved in the exertions and may provide a flexible method of simulating physically demanding activities in VR as users are not bound to a fixed location due to stationary or bulky interfacing and feedback devices. Virtual exertions may prove important for safely simulating physically demanding activities, rehabilitating patients from stroke and injuries, and understanding how to make safer environments and workplaces, but the potential of virtual exertions has yet to be exploited.

In this study, we created three environmental conditions for studying human performance, which included a physical condition that involved lifting dumbbells in the physical environment, a 3-D stereo condition with stereoscopic visuals of virtual dumbbells in the virtual environment, and a 2-D less immersive bland condition with minimal 2-D visuals in the virtual environment. We examined EMG values that were normalized against each muscle's respective reference values collected during an elbow flexion MVC, which was the same posture as the experimental task. Since the MVC normalization was performed only for elbow flexion in order to avoid fatiguing the participants, only the biceps EMG would be considered normalized. Although it might be expected that the observed triceps, FCR, and ECR were representative of their associated recruitment levels during an elbow flexion MVC, there were no assurances that recruitment for these muscles was consistent from session to session, and therefore only the biceps EMG was compared across conditions.

When participants sustained and held the virtual object in the task posture, they co-contracted the agonistic and antagonistic muscles against projections of virtual objects in the two virtual conditions, and the trend of the biceps EMG and perceptions of virtual loads corresponded to lifting the dumbbells in the physical condition. Participant physiological responses in terms of EMG recordings indicated increased muscle activity with increased object weight and fatigue patterns, which was a common trend mostly within the physical and stereo conditions. Although the EMG recording indicated greater biceps activity in the virtual conditions, no statistically significant effects were observed for RPE that were solely related to condition.

One major difference between the physical and virtual tasks was the absence of physical reaction forces, or gravity, for the virtual conditions. Visual feedback and biofeedback in suggesting weights of virtual objects may have enhanced user experience, as it might have helped evoke the experience of physical exertion in VR and in turn helped provide a simulation that better represented the characteristics of the physical world. In this study, we controlled the weight of a virtual object through the calibration procedure for each participant, by mapping muscle activity to the corresponding activity generated for the physical weight. EMG activity of the two pairs of agonist-antagonist muscles, the biceps–triceps and the FCR–ECR, increased as the weight of the dumbbells increased for the physical and the two virtual conditions.

Previous studies have incorporated force simulation in VR via various modes of user feedback. One way to simulate object weight and gravity is by incorporating physical kinematics in the VR simulation. Users touched physical objects and the movement of the physical object was tracked by sensors and in return controlled the movement of the same virtual object seen in a head-mounted display (Hoffman, 1998). The need of having physical objects limited the simulation to have physical objects for all interactive items, and users could not precisely see their own body and hands, which is critically important for performing dexterous activities. Alternatively, force feedback was provided through touch feedback devices, such as the PHANToM or the Cyberglove (Burdea et al., 2000; Popescu et al., 2000; Sallnäs et al., 2000). These devices, too, sometimes limited the ability to simulate a full, functional range of motion movement. Correspondingly, a pneumatic skeletal glove may impede movements and the direct interaction with virtual objects.

The biceps were the selected prime mover in this study because both tasks involved elbow flexion, whereas other elbow flexors, including the brachialis, were not included for simplicity. Although biceps activity in the virtual exertions simulation exhibited the same patterns in response to the weight of the objects for the two virtual and physical conditions, the biceps EMG was significantly greater for the two virtual conditions than for the physical condition. It is probable that the lifting threshold imposed a

limitation to the muscles and force production, which resulted in the increased recruitment of muscle fibers (De Rugy, Loeb, & Carroll, 2012). Since the EMG control algorithm for the virtual conditions was based on biceps muscle activity for the corresponding physical task, the biceps activity was the threshold for exertions against the VR object.

If the normalization reference values for the triceps were representative of their recruitment between conditions, the control algorithm may have produced triceps co-contractions that were much greater than the antagonistic muscle compensation observed in the physical condition. This effect was biomechanically plausible since the insertion of the triceps muscles provides a much smaller moment arm than the opposing object in the hands, and therefore the triceps must generate greater forces in order to produce the same elbow moments as the physical task. In some cases, triceps contraction in the two virtual conditions exceeded the reference level obtained from the calibration, perhaps due to different muscle recruitment (Figure 4.3) for the co-contraction exertions in substitution. Furthermore, in order for the flexors to reach the same level of muscle activity given an exertion and a posture (e.g., biceps curl), the co-contracting extensors served as the "load" that the flexors worked against during virtual exertions. The extensors co-contracted excessively in VR to counter the torque produced by the flexors. Performing virtual exertions might also accelerate the arm faster before activation of the antagonist due to the lack of a physical weight. Moreover, as suggested by De Luca and Mambrito (1987), co-contraction is present when individuals are uncertain about the task or need compensatory force for the task, which both may be the case for novel users of virtual exertions.

To mitigate the excessive exertion of the antagonist muscles, in future studies we plan to proportionally lower the threshold of the prime mover in a particular virtual task (e.g., in a lifting task) so that users of virtual exertions will not need to overexert the antagonist. In other words, we would programmatically balance the required EMG threshold of the prime movers against the necessary torque produced by the antagonist to counter the torque produced by the agonist for joint stabilization. Additionally, MVC exertions would be performed for all muscles involved in doing the task for EMG normalization. This

method could lead to more comparable overall muscle activity levels between physical and virtual environments for the same task and is the topic of future work.

Further examination of biceps activity using pairwise comparisons revealed that the difference in muscle activity between the physical and the bland conditions was generally greater than the difference between the physical and the stereo conditions. The main difference between the two virtual conditions was that the stereo condition had greater correspondence and visual match to the physical condition than did the bland condition. Consequently, the stereo condition was more immersive (Slater, Usoh, & Steed, 1995) than the bland condition. Previous studies have suggested positive effects of immersion on user learning performance (Gutiérrez et al., 2007; Patel, Bailenson, Hack-Jung, Diankov, & Bajcsy, 2006) and user performance measured in terms of accuracy (Narayan, Waugh, Zhang, Bafna, & Bowman, 2005) in a virtual environment. The findings of the current study support the previous literature that user performance and responses in the more immersive simulation better corresponded to the physical condition.

Muscle fatigue over time was also observed, which was suggested by a decreasing shift in MPF during the endurance task (Figure 4.5). The shift in MPF was observed for all four muscle groups in the physical conditions, and in the stereo condition, only the biceps revealed a decreasing shift. This occurrence could be explained by the threshold parameter of the control algorithm. In this experiment, the participant's biceps activity was the only determinant in the EMG threshold for moving the virtual objects, which may lead to fatigue of just the biceps. Some participants experienced "drops" of the objects in the virtual conditions throughout the endurance task due to insufficient muscle activity. In the process of retrieving the dropped virtual dumbbells, the participants may have recovered somewhat from the endurance task. It is also probable that this measure of fatigue is not very indicative in the two virtual conditions, compared to the physical condition.

The psychophysical measure, RPE, was significantly affected by weight. The participants perceived increased effort required for lifting heavier weights under all VR conditions. A statistical interaction between weight and condition for RPE was also observed, which revealed that perceived effort by weight was related to condition. For instance, on average, the participants indicated a 1.385 increase in RPE for a 1-kg increase in weight in the physical condition, yet they indicated only a 0.350 increase in RPE for a 1-kg increase in weight in the 2-D bland condition. This finding suggested greater rate of perceived effort increase when the weight of the dumbbell increased in the physical condition than in the bland condition. Moreover, the participants perceived only a practically small difference in the amount of effort needed to move objects across the three environments, particularly between the physical and 3-D stereo VR conditions. Despite the notable significant differences in the biomechanical and physiological responses of the biceps and greater antagonist activity, the same RPE trends in response to weight in the three conditions suggest that users were able to suspend belief while performing suggested exertions in the virtual environment. How these physiological response differences might actually alter behavior in a more complex simulation, or be constrained, is the topic of future study.

It is also worth noting that the physiological response differences between the physical and bland conditions observed in biceps EMG magnitudes were greater than the differences between the physical and stereo conditions, although this finding was not reflected in the RPE. A possibility is that given a lack of familiar visual cues (i.e., the objects did not appear in the hands for the bland condition), participants approached lifting tasks more forcefully out of uncertainty. It is also possible that the bland condition influenced the participants to exert differently and less efficiently. Yet, it seems surprising that the extra muscle activity was not "felt" by the participants. In some ways, this finding brings into question the meaning of subjective assessments for virtual tasks. For each condition, the participant was given the same task and subjectively believed he or she had acted the same way, but the difference was observed in the subconscious muscle activations. The extent of the effect of visual cues on biomechanics was not the emphasis of this study but may be investigated in future experiments.

Moreover, the participants responded that mental demand, frustration, and temporal demand (i.e., time pressure) for the virtual conditions were greater ($p < .05$) than for the physical condition, as indicated by the NASA-TLX subscale scores. These results suggest that the participants expended more cognition when performing the task in the virtual conditions, and unsuccessful lifts (e.g., dropping the virtual weight) led to frustration and not being able to perform the task properly. However, overall workload, effort, performance, and physical demand were not significantly affected by condition. These findings coincide with the RPE scores, as the participants did not subjectively believe that the efforts were different among conditions. Overall, the virtual conditions imposed a greater workload on the participants.

Controlled heights were not participant corrected in this study in order to observe how varied attributes (i.e., participant size) affect performance, as is the case when simulating actual tasks in VR. The EMG calibration curves for varying heights may have been affected by the force–length relationship observed in typical isometric contractions, or possibly, muscle sliding under the skin resulted in fewer EMG signals being detected by the surface electrodes. In this experiment, the participants calibrated the system by lifting known weights to several controlled discrete heights above the ground. When the participants lifted the weight to the lowest and the highest locations, muscle activity was relatively less than the muscle activity when they lifted the weight to the medium height (Figure 4.2).

Participants mentioned the unnatural "drops" of virtual weights falling out of their hands as soon as the EMG threshold was not met. The EMG control algorithm could be improved so that the virtual weight may gradually lower and move away from the hands to indicate that the threshold is not met. The current study was limited to biceps EMG comparisons across different virtual environment conditions because the reference value used in EMG normalization was obtained for elbow flexion MVCs from each session. To allow comparisons of all muscles across conditions, MVCs for all muscles should be performed during all sessions. Alternatively, though less feasible due to participant fatigue, is to conduct all experimental conditions on the same day. Another EMG control algorithm improvement would be

establishing an EMG threshold that evokes more appropriate exertions in the co-contraction muscle pairs when lifting virtual objects (e.g., producing EMG signals that are not statistically significantly different between physical and virtual environments). Also, the visuals and animations of the virtual objects are another area for improvement. Another interesting variable to study is time to fatigue, which was not examined in the current study. This variable may provide more insights regarding how long individuals will be able to perform tasks or undergo training in the virtual environment. The use of virtual exertions for cognitively demanding tasks should be evaluated because the users of this system have indicated high mental demand when performing virtual exertions.

We anticipate numerous benefits from using the virtual exertions approach for evoking the sense of physical exertions in VR using a CAVE. Virtual exertions do not depend on physical items and objects, which may be impractical to use inside a CAVE because one cannot drop physical objects in a fragile CAVE. Also, objects that the users interact with can be located anywhere in the virtual environment, such as on tables or behind doors or obstacles, which would not be possible otherwise. These objects can be easily programmatically varied in size and loading characteristics for a more flexible simulation than physical simulations. It does not involve bulky apparatus or external objects (light surface electrodes only) for force reflection or haptic feedback equipment in suggesting muscle contraction. Users use the same postures and muscle groups that are used in the physical task during virtual exertions rather than operating wands (i.e., remote control of the CAVE) and hand-operated controls for doing physical tasks. Virtual exertions may provide an alternative and an evocative method to interact with virtual objects. Instead of interfacing with the virtual objects with a controller or involving physical items, users were able to maneuver virtual objects directly through their tracked hand positions and muscle contractions.

Virtual objects could be flexibly programmed into the VR environment at any given location in space, and users of virtual exertions could use the posture that they would normally pose in the physical environment to grasp or lift a virtual object. A virtual exertion does not necessarily need to recreate the experience of the physical activity; it merely needs to provoke the participant in eliciting muscle co-

contractions and positioning himself or herself the way that he or she would behave in the physical situation such that a mapping will be possible. Demonstrating the feasibility to control and interact with virtual objects through muscle activity provides the opportunity to conduct simulations that involve both cognitive and physical demands simultaneously; users will be able to perform physical tasks and interface with the virtual objects through direct interactions and then allocate their attention for the more mentally demanding portion of the task. For instance, attention allocation and cognitive loading in a first respondents rescue training task take precedence over performing exertions.

4.5 Conclusions

Virtual exertions are the mapping of quasi-static co-contractions and forceful actions for simulating exertions against objects using projections of objects in the hands as an interface with the virtual environment. Virtual exertions do not aim to replicate the exact exertions of people in the physical environment, and it was observed that the participants did produce more effort than they necessarily needed for a physical exertion. Our findings reveal, however, that virtual exertions are evocative of physical exertions and do have similarities to physical exertions in the prime mover of the task. The trend of increase in all muscle activity in response to increasing load weight was observed in the physical and the two virtual conditions, and the trend of decrease in shift in EMG MPF for the biceps had the same fatigue patterns over time. Although the overall biceps activity and workload were greater in the virtual conditions, the subjective perceived effort of the users was not statistically significantly different among the conditions. These results revealed that virtual exertions might help contribute to better training as well as provide a safer way for conducting laboratory studies in human factors and ergonomics. Finally, we anticipate that virtual exertions may be useful for physical training and rehabilitation and still achieve comparable levels of physical activity.

4.6 Acknowledgments

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4.7 Key Points

- Muscle activity level and subjective effort rating were affected by the load weight in the physical and virtual environments, and the trends for all environments were the same.
- Trends in ratings of perceived effort in response to weight were the same across physical and virtual environment conditions, with small differences between the physical and stereo virtual reality conditions.
- Participants indicated greater cognitive load in the virtual environment conditions.
- The muscle activity in the more immersive stereo environment differed less from the physical condition than the bland condition.

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5. Evaluation of Older Driver Head Functional Range of Motion using Portable Immersive Virtual Reality

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ABSTRACT

BACKGROUND: The number of drivers over 65 years of age continues to increase. Although neck rotation range has been identified as a factor associated with self-reported crash history in older drivers, it was not consistently reported indicators of older driver performance or crashes across previous studies. It is likely that drivers use neck and trunk rotation when driving, and therefore the functional range of motion (ROM) (i.e. overall rotation used during a task) of older drivers should be further examined. OBJECTIVE: Evaluate older driver performance in an immersive virtual reality, simulated, dynamic driving blind spot target detection task. METHODS: A cross-sectional laboratory study recruited twenty-six licensed drivers (14 young between 18 and 35 years, and 12 older between 65 to 75 years) from the local community. Participants were asked to detect targets by performing blind spot check movements while neck and trunk rotation was tracked. Functional ROM, target detection success, time to detection were analyzed. RESULTS: In addition to neck rotation, older and younger drivers on average rotated

their trunks 9.96°and 18.04°, respectively. The younger drivers generally demonstrated 15.6° greater functional ROM (p<.001), were nearly twice as successful in target detection due to target location (p=.008), and had 0.46 seconds less target detection time (p=.016) than the older drivers.
CONCLUSION: Assessing older driver functional ROM may provide more comprehensive assessment of driving ability than neck ROM. Target detection success and time to detection may also be part of the aging process as these measures differed between driver groups.

Keywords: Virtual reality; older driver; range of motion; performance

5. 1 Introduction

The number of drivers over 65 years old is increasing, which is indicated by a rise in the percentage of older individuals possessing a driver's license, and also an increase in car access and number of trips traveled by car for older drivers (Sivak & Schoettle, 2012; Stav et al., 2008). Driving is a complex task, and the safe operation of a motor vehicle requires good vision, motor function, and cognition (Desapriya et al., 2014). Changes in physical and cognitive abilities are part of a normal aging process. These changes include visual attention, visual impairment, physical fragility and function, reaction time and processing speed, which are associated risk factors for older drivers and adverse driving incidents (Anstey, Wood, Lord, & Walker, 2005; Dukic & Broberg, 2012; Eby, Trombley, Molnar, & Shope, 1998). One particular physical change, the neck axial rotation range of motion (ROM), has been identified as a risk factor for older drivers (Isler et al., 1997; Marottoli et al., 1998).

Neck ROM or neck rotation has been studied in various driving and road safety related research. In addition to investigating the relationship between neck rotation and driving performance or risk in driving, some studies aimed to provide a reliable test battery or explored predictors of safe driving characteristics in older adults. However, the association between neck rotation and driving varied across studies (Ball et al., 2006; Edwards, Bart, O'Connor, & Cissell, 2010; Isler et al., 1997; Marottoli et al., 1998; Molnar et al., 2007; Stav et al., 2008; Wood, Anstey, Kerr, Lacherez, & Lord, 2008). It was identified that the reduction in neck rotation ROM doubled the risk of crashing (Isler et al., 1997;

Marottoli et al., 1998). A statistically significant difference in total neck rotation was found between safe and unsafe older drivers, yet neck rotation was not a good statistical predictor among the measured variables of driver on-road performance rated by an occupational therapist experienced in driving assessment (Wood et al., 2008). It was also reported that neck rotation did not demonstrate a positive association with motor vehicle crashes or poor driving performance (Ball et al., 2006; Molnar et al., 2007; Stav et al., 2008). In a 10-year longitudinal study, Edwards et al. (2010) showed that head-neck rotation was not statistically associated with driving cessation. These findings provided valuable information by associating individually measured physical characteristics to driver traffic incidents or decision to continue driving, yet their findings or recommendations were not always consistent. It is possible that during an actual driving situation, such as backing up or lane changing, drivers utilize motions other than neck rotation for tasks that require more dynamic movements.

In addition to considering neck rotation and its relation to driver safety, both neck and trunk rotation and flexibility were taken into account in other studies. Trunk rotation was also measured in the test battery assessment of Marottolli et al. (1998), however only neck rotation was found to be statistically related to crashes. Instead of separating spinal flexibility into neck rotation and trunk rotation, Reimer et al. (2008) examined the involvement of overall spinal flexibility in rear-window checking and backing up situations between younger and older drivers, and the younger drivers demonstrated greater spinal flexibility. As countermeasures to driving accidents in older drivers, training programs or physical therapy interventions have been implemented and the results were generally positive (Ashman et al., 1994; Marottoli et al., 2007; Ostrow et al., 1992). These interventions were either instructor-led courses or self-administered exercises at home for which the older drivers performed neck and trunk rotation drills that lasted a few class periods or over the course of three months. During on-road performance assessment after these interventions, the older drivers demonstrated an improvement in driving performance (Ashman et al., 1994; Marottoli et al., 2007; Ostrow et al., 1992). Neck and trunk ROM have also improved over the

course of training (Caragata, Tuokko, & Damini, 2009). These findings implied the importance of the neck and trunk rotation in older adult drivers.

Due to the impracticality of evaluating older driver performance on-the road, some studies have used driving simulators to study driver safety. Park et al. (2011) compared driving behavior between older and younger drivers in a driving simulator, and their results indicated that unsafe driving and car crashes were more prevalent in older than in younger drivers. Although simulators provided complex driving situations were used in studying driver performance, driver physical capabilities were not always measured (H. C. Lee, Lee, Cameron, & Li-Tsang, 2003; Park et al., 2011; Romoser, Fisher, Mourant, Wachtel, & Sizov, 2005). Examining the rotational movement of drivers in a driving context with other dynamic objects, such as moving cars, may provide a more comprehensive understanding of older driver performance including neck and trunk rotations since spinal rotation and flexibility are important in driving safety (Reimer et al., 2008).

Immersive virtual reality (VR) created by computer graphics and 3D displays presents a new research paradigm and offers potential solutions to the challenges posed by traditional research technology. Recent innovations have made this technology portable, inexpensive, and widely available, eliminating the need for a fully immersive driving simulator and motion tracking instruments. Programmable systems make studies or prototyping in VR more cost-effective since changes could be done in software. It is inherently safe for simulating hazardous tasks or for training because the virtual environment constitutes graphics and the users are not exposed to physical dangers. Utilizing the flexibility of VR, researchers have used it as an educational tool (Dalgarno & Lee, 2010; E. A.-L. Lee & Wong, 2008), training (Dugdale et al., 2004; Lange et al., 2000), and rehabilitation (Holden, 2001). Virtual reality also has been used for assessment, such as to measure human motion, evaluate physical risk factors in ergonomics, evoke senses of exertion and biomechanical measurements, and capture human movement (Chen, Ponto, Tredinnick, & Radwin, 2015; Pontonnier et al., 2013; Sarig-Bahat et al., 2009). Given the flexibility and low cost of VR, we propose using VR for studying older driver performance. Immersive VR can provide

greater graphical and visual fidelity, and users may be able to perform driving tasks more similar to how they typically do. Moreover, VR permits participants to perform the experiment with lower risk than actual driving on streets, and the outcome measures can be directly collected by the VR system.

The objective of this study was to explore driver performance during a blind spot checking task in a VR environment with moving virtual cars to represent a dynamic driving situation. Specifically, the extent of rotational movement of the drivers was examined. For the purpose of this study, driver functional ROM during the experimental task was defined as the overall rotation movement performed by the driver to execute the experimental task. Conventional neck rotation ROM was also measured, but it was obtained independently of the experimental task at the start of a session. Additionally, the performance differences between younger and older drivers were compared. It was hypothesized that the functional ROM during the task is different from the neck rotation ROM. It was also hypothesized that the older drivers would exhibit different biomechanical characteristics and performance from the younger drivers.

5.2 Methods

5.2.1 Participants

Fourteen younger (mean age 24.5, SD 5.2 years; eight females) and 12 older (mean age 70.3, SD 3.2 years; seven females) drivers were recruited from the local community. The volunteers were self-identified drivers who responded to a flyer posted in the local community, or they were participants of previous studies who agreed to be contacted for future studies. Volunteers were screened via telephone contact for eligibility. Exclusion criteria for both driver groups were inability to see three-dimensional (3D) stereo images, neuro-motor impairments or injuries that prevented the individual to reach for an object overhead or rotating the neck, a condition that limits the individual's ability to exercise the neck and shoulder, experience of epileptic seizure or blackout, high tendency for motion sickness or nausea when experiencing visual motion conflicts, and have or had an occupation that required more than 50% of work time driving. Inclusion criteria of age for the younger group was between the age of 18 to 35 and for the older group was between 65 to 75, self-report of normal or corrected-to-normal vision, and

possessed a valid driver's license at the time of the study. All participants self-reported that they were actively driving at the time of the study, and none reported being and have been a vehicle operator as an occupation (e.g. not a taxicab driver). Written informed consent was obtained from all participants and the study was approved by the New England Independent Review Board.

5.2.2 Instrumentation

The VR system, which included a steering wheel and pedal set (G27 Racing Wheel, Logitech, Newark, CA, USA) for driver input and a head-mount display with inertial sensors (Development Kit 1 Oculus Rift, Oculus VR, LLC, Menlo Park, CA, USA) primarily for visual feedback and also provided head-neck orientation tracking, is depicted in Figure 5.1. The head-mounted display had 110° field of view in diagonal and a combined resolution of 1280×800, and a sampling frequency of 60Hz. An active marker infrared motion tracking system (Optotrak Certus, Northern Digital Inc., Ontario, Canada) recorded body kinematics of the participant. The active marker motion tracking system had a resolution of 0.01 mm, a 3D accuracy of 0.1mm, and the sampling frequency was synchronized to the head-mounted display at 60 Hz. The VR scenario was written in C++ and based on Ogre, an open source 3D graphics rendering engine. The visuals were retrieved from an open source 3D model repository (Trimble 3D Warehouse, Google, Mountain View, CA, USA) and modified in SketchUp (Trimble Navigation, Ltd., Sunnyvale, CA, USA).

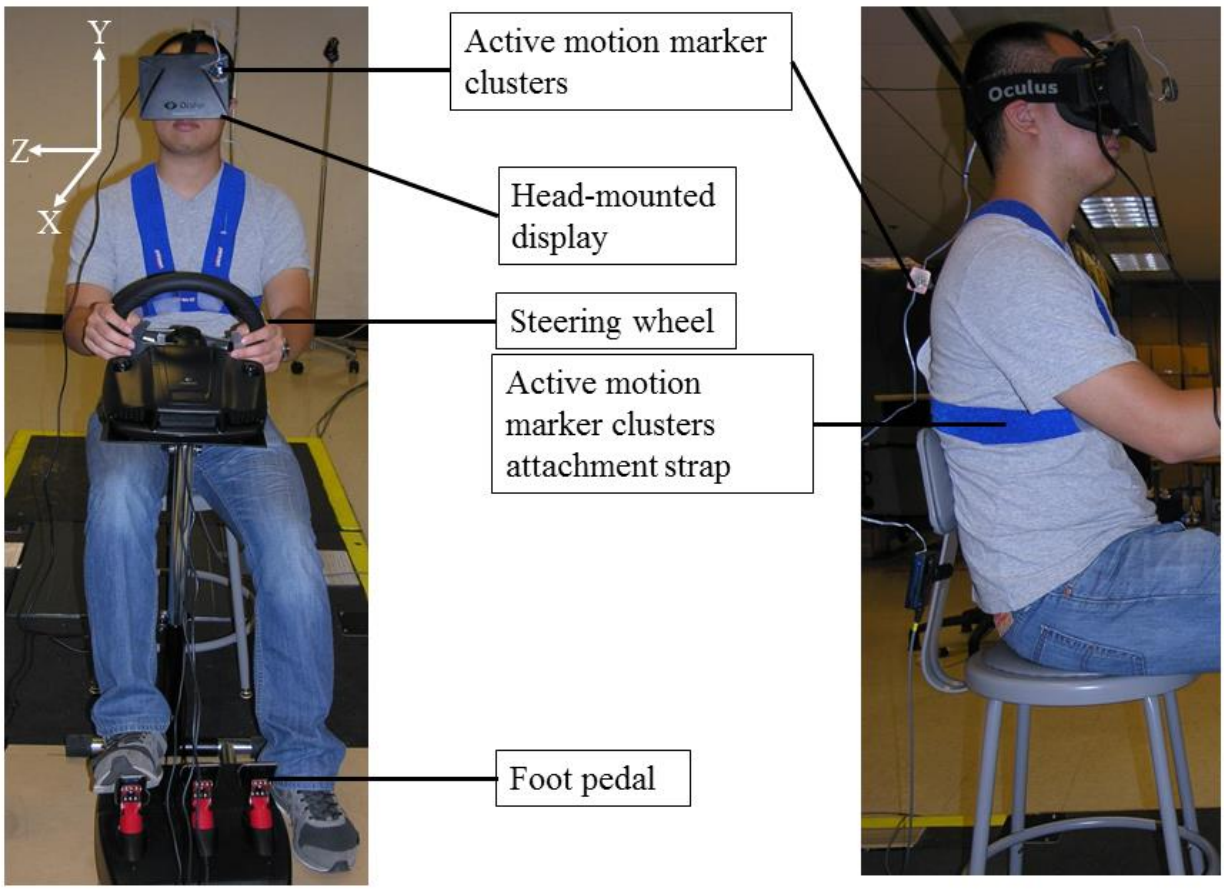

Figure 5.1. A participant wore a head-mounted display and positioned the hands on a steering wheel, while the foot rested against one foot pedal. Active motion marker clusters were placed on the head-mounted display and on the trunk of the participant. The left image corresponds to the coordinate system indicated in the figure.

5.2.3 Experimental Procedure

Participants were seated in a stationary chair with a backrest but without armrests and wore a head-mounted display (Figure 5.1). They assumed a "ready position" that was a neutral upright posture with the participants looking forward and the head and trunk aligned. The calibration and the coordinate system were based on a study by Xu et al. (2015). The global coordinate system at the ready position had the x-axis normal to the coronal plane pointed forward, the y-axis normal to the transverse plane pointed upward, and the z-axis normal to the sagittal plane pointed to the right side of the participant. A total of two active motion marker clusters were placed onto the participant: one of which was affixed to the surface of the head-mounted display and another cluster was attached to the upper trunk by a strap.

Anatomical landmarks were digitized when the participants situated in an upright posture at the start of every session. Sternal notch, xiphoid process, C7, T8 were digitized with respect to the clusters on the upper trunk, while the left and right tragion, vertex, and the four corners of the head-mounted display were digitized with respect to the cluster mounted on the head-mounted display. The trunk local coordinate system followed the International Society of Biomechanics standards (Wu et al., 2005). For the head, the z-axis was from the left to the right tragion, and the x-axis was normal to the plane that included the z-axis and the x-axis vertex pointed forward. The head-mounted display local coordinate system x-axis was normal to the front surface of the display pointed forward, and the z-axis was from the lower left to the lower right corner.

The baseline neck ROM was measured by the head-mounted display at the start of the session, which included axial rotation, flexion and extension, and lateral bending. These ROM measurements were obtained following the same verbal instructions as Youdas et al. (1992). Participants then performed the experimental task that consisted of 40 repetitions of a head-neck rotation movement, which was similar to a blind spot checking movement in a driving situation. At least five practice blind spot checking task trials were given. Each participant attended one session that lasted no more than 60 minutes.

5.2.4 Experimental Task

The experimental task was to perform blind spot check movements that are typically carried out prior to making a lane change maneuver while driving, and then to step on the foot pedal if a stationary white ambulance target appeared. The target was visually distinct from other cars in the VR scenario. There were a total of 40 trials and only 20 trials had a target, which were randomized throughout the task. The first 20 trials involved checking the blind spot on the right side and the remaining 20 trials involved checking the blind spot on the left side, or vice versa. The order of the sides was randomized, and it was counterbalanced where half of the participants started with the right side and the other half of the participants started with the left side. Each side had either a near or a far target, resulted in four possible target locations: left near, left far, right near, and right far (Figure 5.2). The near targets were located at a

position that required approximately 60° of overall axial rotation to become visible, and the far targets were placed at a position that required approximately 90° of overall axial rotation to become visible.

The standard instruction to the participant was, "For this task, please check your blind spot as if you are about to change lane. If you don't see a white truck, tap the blinker handle on the steering wheel to signal. If you happen to identify a white truck when you are checking the blind spot, step on the foot pedal. Do you have any questions?" Before the start of each trial, the experimenter verbally indicated the side (i.e., left or right) to be checked, and then announced "go" to instruct the participant to start checking the blind spot. Participants returned to the "ready position" before the start of each trial, and the head-mounted display was zeroed at the "ready position" as soon as a trial was initialized.

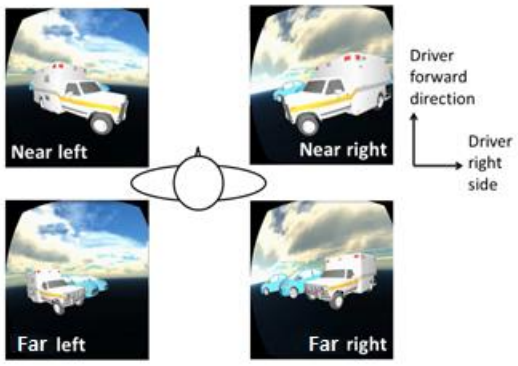

Figure 5.2. Four different locations where the target (e.g., white ambulance) appeared relative to the driver. The sizes of the target were also relative to the location from the driver.

5.2.5 Variables and data Analysis

Independent variables were target side, target location, task situation, and driver group. Target side (left and right), target location (near and far), and task situation were within-subject variables. Task situation referred to the state where the drivers did not have to perform the blind spot checking task at baseline, and other situation was that the drivers checked the blind spot. The only between-subject variable was driver group (younger and older).

Dependent variables included kinematics and performance measures. Axial ROM was a kinematics measurement made at baseline and during the task. The baseline neck axial ROM was the active cervical spine rotation about the global y-axis (i.e. axial rotation) at baseline measured in a seated upright neutral posture. The baseline neck axial ROM angle was measured from the driver's head ready position when facing along the x-axis, to the farthest extent that the drivers could turn the neck until feeling tightness and without causing pain. The functional axial ROM was operationally defined as the ROM involved during the experimental task, which was the overall rotation movement performed by the driver when checking the blind spot. The functional axial ROM angle was measured from the driver's head ready position when facing along the x-axis, to the head orientation at the instance when the driver stepped on the brake or signal the blinker. The trunk axial rotation was also measured during the experimental task, and it was measured from the driver's trunk ready position facing along the x-axis to the trunk orientation at the instance when the drivers stepped on the brake or signal the blinker.

Performance measures were target detection and detection time. Detection was a dichotomous variable (0 or 1) when a driver respectively missed or successfully identified the target in a trial. Detection time was the time elapsed for detection, and detection was marked at the instance when the drivers stepped on the brake.

Baseline axial ROM was first analyzed using an independent t-test to compare between the driver groups. The axial ROM was analyzed using a two-way (driver group × situation) repeated measures ANOVA. Trunk axial rotation was analyzed using an independent t-test by comparing between the driver groups. Detection was analyzed against age group and target location using logistic regression of generalized linear modeling. Detection time was analyzed using a two-way (driver group × target location) repeated measures ANOVA. Only the trials with a target were used for the analysis of detection and detection time. Type I error was set at α=.05. All statistical analyses were performed with R for Windows, version 3.1.2 (Comprehensive R Archive Network, R Foundation for Statistical Computing, Vienna, Austria).

5.3 Results

There was no statistical difference in ROM and detection time between the left and right side neck, and therefore the data for both sides were pooled. The mean baseline axial ROM measured before the task was 63.48° (SD 10.96) and 78.10° (SD 8.58) for the older and younger drivers, respectively. The baseline axial ROM was statistically significantly different between the driver groups ($t(24)=3.81$, $p<.001$).

During the task, the mean functional ROM of older and younger drivers were 71.93° (SD 12.48) and 101.61° (SD 13.68), respectively. An effect of situation on axial ROM (Figure 5.3) occurred when the functional ROM during the blind spot checking movement was 15.6 degrees greater than the baseline neck axial ROM ($F(1,24)=41.68$, $p<.001$). While including task situation as a covariate, or, statistically controlling for task situation, the ROM of the younger drivers was 16.3 degrees greater than the older drivers ($F(1,24)=51.61$, $p<.001$). There was also a significant interaction between task situation and driver group ($F(1,24)=9.99$, $p=.004$), suggesting that the difference in ROM between the situations for the younger drivers was 15.3 degrees greater than the older drivers.

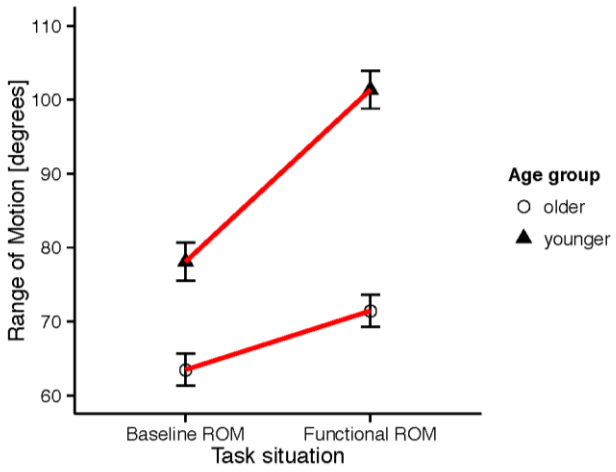

Figure 5.3. Axial range of motion measured at two situations by driver groups (±1S.E.).

Trunk axial rotation during the blind spot movement of the younger drivers 8.2 degrees greater than the older drivers, and this difference between the groups was statistically significant ($t(24)=2.25$, $p=.03$) (Figure 5.4).

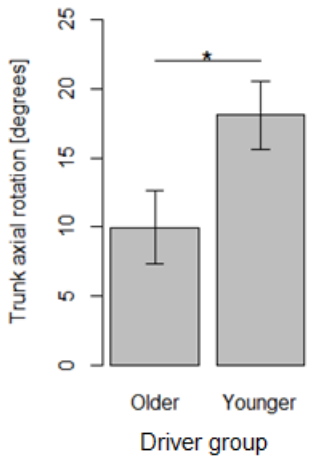

Figure 5.4. Trunk axial rotation during the blind spot checking task of the two driver groups (±1S.E.).

The younger drivers detected all trials out of a total of 280 trials that had a target, which yielded a 100% detection rate. The older drivers overall detected 128 trials out of a total of 236 trials with a target, which yielded a 54% detection rate. Logistic regression further revealed that there was no effect of age group (χ^2 (1,N=26)=.02, p>.05) on detection rate. Instead, the target location significantly affected the detection rate (χ^2 (1,N=26)=6.97, p=.008). Detection frequency and detection rate by driver group and target location is show in Table 5.1.

Table 5.1. Target detection frequency out of the trials with a target by driver groups and by target locations. The data are displayed in number of detected target trials / total number of trials with a target.

Target location \ Driver group	Older	Younger
Left near	57 / 58	69 / 69
Left far	5 / 60	69 / 69
Right near	58 / 60	70 / 70
Right far	8 / 58	70 / 70
Overall detection frequency	128 / 236	278 / 278
Overall detection rate	54%	100%

Detection time was statistically significantly different between the driver groups, with the younger drivers on average detected the target 0.46 seconds faster than the older drivers ($F(1,24.85)=6.70$, $p=.016$). Target location also significantly affected detection time ($F(1,16.20)=56.41$, $p<.001$), where the detection time for the farther targets were 0.36 seconds greater than for the nearer targets (Figure 5.5).

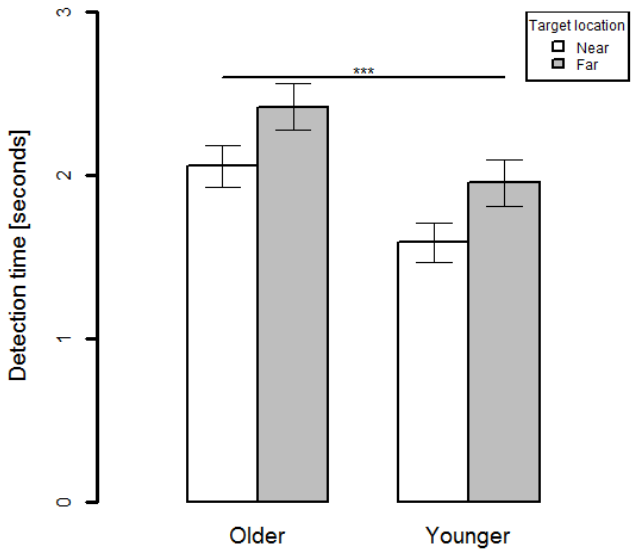

Figure 5.5. Detection time difference between the two age groups by target location (±1S.E.). ***$p<.001$.

5.4 Discussion

This study used inexpensive VR technology for examining driver neck and trunk rotation. During the task a target would not have been visible unless an axial rotation movement was sufficient. Detection rate and the time to detect the target were also examined. Generally, the younger drivers exhibited greater functional ROM, detected more targets, and were faster at detecting the targets than the older drivers. The functional ROM in this study was defined as the overall rotation movement performed by the driver to execute a blind spot checking movement.

The first hypothesis was that the functional ROM during blind spot checking was different from the baseline neck axial ROM, and this was supported by the data. Across both driver groups, the mean functional ROM was 15.6° greater than the baseline neck axial ROM. This suggested that the functional ROM, or the overall rotational movement exhibited by drivers when blind spot checking, was greater than

their typical neck ROM. Through observation during the experiment, it was confirmed that older and younger drivers engaged both neck and trunk rotational movements while they checked blind spots. Moreover, biomechanical measurement and observation indicated that the functional ROM during this task was a combination of neck and trunk rotational movement. Given the instructions provided for this task, where the drivers were told to perform as they normally would, the functional ROM may have closer resemblance to the ROM involved in an actual driving event.

In a study by Reimer et al. (2008), younger (18 to 25 years of age) and older (65 years of age or above) drivers' spinal rotation angle during a car backing up task was evaluated, and they reported that on average the younger drivers rotated 113° to 115° and the older drivers rotated 99° to 100° during the task. In our study the mean functional ROM of the younger and older drivers was 101.63° (SD 101.1) and 71.82° (SD 10.3), respectively. Although Reimer et al. (2008) reported greater rotation angle, their backing up task was different from our blind spot checking task, and they also permitted the drivers to brace the back of the passenger seat when backing up the car. The results from Reimer et al. (2008) indicated that greater rotational movement when backing up a car, yet the current study suggested that during blind spot checking the drivers may not involve as much rotation.

To make certain that the baseline neck axial ROM of the participants from the present study was not different from others, the baseline neck axial ROM was compared with previous studies. The neck ROM of the younger drivers from the present study is similar to those described by Chiu and Lo (2002) that was 78.0° (SD 6.4) and 77.2° (SD 7.6) for right and left rotations, and Swinkels and Swinkels-Meewisse (2014) 79° (SD 6.6) and 78° (SD 8.0) for right and left rotation in both men and women, whose study participants were free of musculoskeletal conditions and their mean age was between 20 to 30 years. The mean neck ROM of the older drivers from the present study was approximately on average 7° to 10° greater than what was reported by Youdas et al. (1992), which were 53.6° (SD 7.4) and 56.6° (SD 6.7) for right and left neck rotation in healthy men 60 to 69 years in age. The baseline neck axial ROM of current study population is somewhat comparable to other studies and therefore this result might not be atypical

in blind spot checking. However, it cannot be concluded whether the drivers rotated their neck to their fullest extent during the experimental task. It may be possible that through the trunk rotation movement the drivers did not have to expend as much of neck rotation movement in order to detect the target.

Although this study revealed functional ROM to be different from neck ROM, neck axial ROM alone in the past has been a common measurement for driver ability evaluation. For instance, Marottoli et al. (1998) has found neck rotation angle to be a strong factor associated with adverse driving events but not trunk rotation angle. However not all studies reached similar conclusions; neck ROM was not considered to be one of the best predictors of poor driver performance or crashes in older drivers, or driving cessation in older adults (Edwards et al., 2010; Molnar et al., 2007; Stav et al., 2008). The current Gross Impairment Screening Battery (GRIMPS) General Physical and Mental Abilities (Staplin, Lococo, Gish, & Decina, 2003) includes the upper torso rotation as part of the head/neck rotation assessment in the test battery, which assessed the drivers' ability to look over their shoulder, yet it is scored as pass or fail. The results from the present study agree with the GRIMPS assessment in considering neck and trunk rotation, and the present study provides greater information in drivers' biomechanical measurements. Possibly, including a simple technology to create a simulation of an on-road environment at driver license issuing locations to evaluate driver functional ROM. In order to further screen for high risk drivers, a follow-up functional ROM study using VR should be conducted. Such a study could recruit drivers who had different incidents of at-fault crash histories, and then evaluate their functional ROM in the VR environment.

Results from the current study still shared similarities with previous studies, where the younger drivers demonstrated greater spinal flexibility than older drivers in general. The mean baseline neck axial ROM of the younger and older drivers was 78.1° (SD 8.6) and 63.48° (SD 11.0), respectively. Also, the degree of trunk axial rotation was different between the driver groups, with the mean trunk rotation angle being 18.1° (SD 11.15) and 9.94° (SD 6.13) for the younger and older drivers, respectively.

In addition to ROM, target detection success and detection time were examined for the trials that had a target. The younger drivers successfully detected all the trials with a target. However, the older drivers only had a 54% detection rate, meaning that the older drivers only successfully identified a target slightly more than half of the time. After statistically controlling for the location of the target, it was found that the older drivers did not detect the far right and far left targets, which were farther away from the forward view. The effect of target location on detection was more pronounced in the older driver group, which could be related to the change in physical capabilities during the normal aging process.

In general, the near targets had shorter detection time than the far targets. Spatially it took longer for both driver groups to complete the functional ROM rotation and to observe the far targets. The positive relationship in target acquisition time to target distance has been demonstrated by Radwin, Vanderheiden, and Lin (1990), where users rotated their heads from an initial point to a target location on a computer screening with a head-controlled input device. In the present study, the younger drivers were 0.46 seconds faster to detect the targets than the older drivers, which suggested that younger drivers may be able to react quicker to identify objects during this task. Similarly, in reaction time tasks the older participants responded slower to visual stimuli than younger participants (Hultsch, MacDonald, & Dixon, 2002). The older drivers' ROM, target detection success, and target detection time differed from younger drivers in this study, which may suggest that there are several factors that should be considered when evaluating the driving capacity of older drivers.

Conducting this experiment in VR provided a safe study environment, convenience, and straightforward data collection, yet it was different from actual physically driving. It is possible that drivers react and respond differently to on-road events in an actual driving scenario, such as using mirrors to assist in speculating the environment before performing lane change maneuvers. It was also possible that other strategies could have assisted in target detection during a blind spot checking task, such as utilizing the peripheral visual field in the lateral direction. Checking the blind spot is a multi-factor action and many components are involved, but the functional ROM was the primary focus of this study and therefore the

contribution of visual field of view was not measured. In addition, the field of view in a VR environment was different from the physical environment, and the participants might not be able to use their natural peripheral vision to aid in the detection of the target in the blind spot checking task. Specifically, the VR environment of this study had 110° of field of view in *diagonal*. This suggested that the horizontal visual field of the VR environment was likely to be less than the normal human horizontal visual field in the lateral direction, which is approximately 100° (Spector, 1990). Moreover, blind spots could vary among different vehicle manufacturers, and therefore the targets were not placed at locations that mapped into any specific vehicle models. The targets were placed at general locations outside of the front visual field of view and would require drivers to axially rotate before the targets became visible. It should be noted that the seat in this study was different from a car seat, lacked a seatbelt and a head cushion, which could have further restricted driver motion. However, in order to place active motion marker cluster on the back of the participants it was not feasible to use chair with a larger chair back as it would occlude the marker. Lastly, it was not studied what would be an appropriate cut-off value for functional ROM or detection time to conclude which drivers at more at risk, which could be a possible future direction. Despite these limitations we conclude that VR testing of functional ROM is a more representative method for evaluating driver ability than conventional neck ROM measures.

In conclusion, the functional ROM of younger and older drivers in performing blind spot checking movements in a VR environment was greater than their active axial neck ROM. The functional ROM observed in this study consisted of neck and trunk rotation motion, which suggested that drivers rotated both neck and trunk when they checked blind spot. Trunk rotation in driving may not be neglected and its role should be further studied. Target detection and detection time were also different between the driver groups, which suggested that these measures may also be important factors of the aging process.

5.5 Conflict of Interest

The authors have no conflicts of interest.

5.6 Acknowledgement

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6. Manipulated visual feedback for chronic neck pain using virtual reality

6.1 Introduction

Neck pain is a common problem and a major health concern (Hogg-Johnson et al., 2009). In the United States, it was reported that 14.4% of adults over the age of 18 has had neck pain (National Center for Health Statistics, 2015). Musculoskeletal pain not only negatively impacts individuals' health but is also associated with the costs of lost workdays and productivity loss, medical treatment, rehabilitation, worker's compensation insurance, and human suffering (Côté et al., 2008). It therefore becomes important to establish interventions to effectively and affordably manage disability in populations that enable people to return to productive lives and contribute to society at large.

Some individuals with chronic pain could possibly develop a psychological pain-related fear, which is associated with avoidance of movement and physical activity, i.e. kinesiophobia (Picavet, Vlaeyen, & Schouten, 2002). The true functional capacity is often masked due to pain-related fear (Vlaeyen & Crombez, 1999). People with high pain-related fear avoidance have reduced range of motion, decreased strength and are less active (Goubert et al., 2004). Rehabilitation becomes increasingly important for improving physical function as well as quality of life for these conditions, yet progress is often arrested by fear of performing therapeutic exercises.

Virtual reality (VR), an environment created by computer generated stereoscopic images, has been previously used as a desensitization tool in treating individuals with specific phobia (Lewis & Griffin, 1997; Linares et al., 2012). It has also been used to distract user attention from pain during wound care and induced pain (Chan, Chung, Wong, Lien, & Yang, 2007; Gold, Kant, Kim, & Rizzo, 2005; Hoffman, Doctor, Patterson, Carrougher, & Furness III, 2000; Hoffman, Garcia-Palacios, Kapa, Beecher, & Sharar, 2003). This suggests that immersive VR might be useful for providing visual feedback that encourages movement and mitigates fear from performing exercises and movements for chronic neck pain. Since visual feedback could be programmed and altered in an immersive VR, we hypothesize that rehabilitation in VR can mitigate fear avoidance by either amplifying or attenuating visual feedback during exercises.

Altered visual feedback through either the amplification or the attenuation of visual feedback in VR is based on the concept of C-D gain (Poupyrev, Weghorst, Otsuka, & Ichikawa, 1999). The C-D gain is the ratio of the mapping between a user's movement in VR and the corresponding changes of visual feedback (Kopper, Stinson, & Bowman, 2011). There may exist a C-D gain in VR at which the patients would not notice the visual feedback has been altered. This would be the C-D gain with the just-noticeable difference (JND). Providing patients with altered visual feedback at JND in VR may encourage them to perform certain therapeutic exercises or movements at their true functional capacity, without being fearful of pain in VR.

Rehabilitation in VR is not completely new, and studies have adapted commercial grade game consoles to conduct rehabilitation-related activities (Deutsch, Borbely, Filler, Huhn, & Guarrera-Bowlby, 2008; Flynn, Palma, & Bender, 2007; Sugarman, Weisel-Eichler, Burstin, & Brown, 2009) Several advantages were identified. Virtual rehabilitation could possibly facilitate patients' motivation through the use of game-like experience in VR and help patients stay engaged during their exercises (Halton, 2008; Sveistrup et al., 2004). It also eliminates the need and cost to travel to a clinic and seeing an actual therapist (Burdea, Popescu, Hentz, & Colbert, 2000; Holden, 2001, 2005).

The purpose of this study was to examine how individuals with and without chronic neck pain perform therapeutic exercises under the influence of altered visual feedback in VR. The first experiment was to examine the JND of individuals without neck pain. The second experiment was to determine the JND of patients with chronic neck pain and then evaluated their performance in VR under altered visual feedback at JND.

6.2 Methods

The normals study recruited individuals free from musculoskeletal conditions, and the patient study involved individuals with chronic neck pain. The common inclusion criteria for both studies were participants needed to be at least 18 years old and had normal or corrected-to-normal vision. The exclusion criteria for both studies were epileptic seizure or blackout, prone to motion sickness or nausea,

Lasik eye surgery, and taking perception-altering medication. Individuals who had Lasik eye surgery were excluded because it affected performance in VR (Chen et al., 2014).

6.2.1 Participants

6.2.1.1 Normals study

Twenty healthy, college-age students (11 females and 9 males) were recruited from the University of Wisconsin-Madison with informed consent approved by the Institutional Review Board. Participant mean age was 23±3 (range 19-29). The specific exclusion criterion for the study was presence of neuro-motor impairments or injuries in the neck and shoulder regions.

6.2.1.2 Patient study

Eight patients with chronic (> 3months) neck pain (7 female and 1 male) were recruited from a University of Wisconsin clinic with Institutional Review Board approved informed consent. Participant mean age was 56±11 (range 39-75). The mean years since neck diagnosis is 11±12 (range 1-35 years). The inclusion criteria were pain in the neck and/or shoulder region for at least 3 months.

6.2.2 Instrumentation

The VR system used an infrared-depth camera and a head-mounted display (HMD) with inertial sensors for visual feedback and head orientation tracking. The motion sensing and position tracking depth camera was a Microsoft Kinect (Redmond, WA, USA), which was used in both the preliminary and the patient studies. The HMD was a Development Kit 1, Oculus Rift, (Oculus VR, LLC, USA) that was used in the preliminary study, which had 110° of field of view in diagonal and a combined resolution of 1280 × 800 pixels , or 640 × 800 pixels per eye. The Development Kit 1 has been validated (Xu, Chen, Lin, & Radwin, 2015). Development Kit 2 Oculus Rift (Oculus VR, LLC, USA) became available and was used at the time of the patient study, which had 100°a combined resolution of 1920 × 1080 pixels, or 960 × 1080 pixels per eye.

The VR scenario was written in C++ and it was based on OGRE, an open source 3D graphics rendering engine (www.ogre3d.org). Visuals were retrieved from an open source 3D model repository (Trimble 3D

Warehouse, Google, Mountain View, CA, USA) and modified in SketchUp (Trimble Navigation, Ltd., Sunnyvale, CA, USA).

6.2.3 Procedure

6.2.3.1 Normals study

Neck JND task

Ten participants performed this task. The task was to perform two head rotation movements in a trial, and compare whether those two head movements were the same or different. Within the same trial, one head movement was set to unity gain (C-D gain = 1) and the other movement was a random C-D gain ≠ 1. Participants performed the task facing the camera seated in a stationary chair with a backrest but without armrests and wore the HMD (Figure 6.1).

Figure 6.1. Participant wore the HMD in a seat in front of a camera.

A target object (e.g. football) and a secondary object (e.g. goal post) were visible to the participant in the HMD (Figure 6.2). The target was stationary and it randomly appeared in one of the four corners in the HMD field of view. The secondary object was affixed to the center of the field of view and its position was controlled by the participant's head-neck movements. The participant assumed the ready position at the beginning of a trial, which was a neutral posture sitting upright and facing forward, with the shoulders relaxed. The participant aligned the secondary object against the target by neck rotation and then returned to the ready position. After the target disappeared another target appeared at the same location as the

previous target. The participant aligned the secondary object against the new target, and then returned to the ready position. Following the second alignment movement, the experimenter verbally asked "Were the two head-neck movements the same or different?", and the participant pressed on a button on the controller to respond. The response is recorded either as 1 or 0, which corresponded to yes or no, respectively.

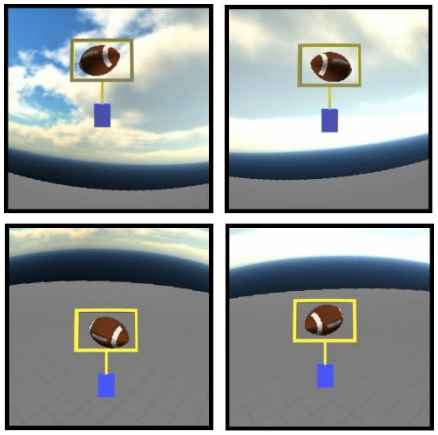

Figure 6.2. Four possible locations of the target object (e.g. football), shown with the secondary object (e.g. goal post). The four possible locations were upper left and upper right corners, and lower left and lower right corners.

A 15 second rest break was provided between each trial and the participant could request longer rest breaks. There were a total of 36 trials. Participants completed a brief demographic questionnaire included questions on age, gender, ethnicity, and hand dominance during a three to five minute break that was provided half way during the session. The experimental session was approximately 40 minutes in length and each participant was provided a small monetary compensation.

The four target locations were determined based on the average allowable ROM demonstrated during a diagonal head-neck movement (Figure 6.2). A diagonal head-neck movement included a neck flexion or extension motion, followed by a left or right rotation (Piva, Erhard, Childs, & Browder, 2006). There were a total of nine different C-D gains ranging from 0.7 to 1.5 in 0.1 increments.

Shoulder JND task

Ten participants performed this task. The task was to perform two shoulder abduction movements in a trial, and compare whether those shoulder abduction movements were the same or different. Within the same trial, shoulder abduct movement was set to unity gain (C-D gain = 1) and the other movement was a random C-D gain ≠ 1. There were a total of seven different C-D gains ranging from 0.7 to 1.0 in 0.05 increments. Participants performed the task while pulling against a resistance band (e.g. Thera-band), facing the camera seated in a stationary chair with a backrest but without armrests and wore the HMD (Figure 6.3).

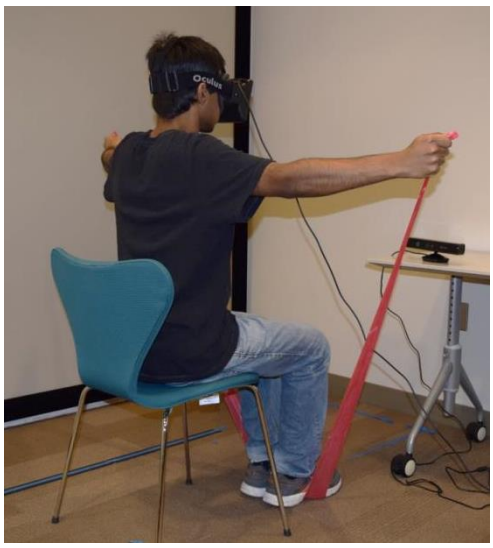

Figure 6.3. Participant performing shoulder abduction movement while pulling against a Thera-band.

Two pairs of virtual avatar arms that had distinctive colors were visible to the participant in the HMD. One pair of virtual avatar arms was colored in pink, and their shoulder joints were programmed to appear affixed near the physical shoulder area of the participant. Participants controlled the movement and position of these pink virtual arms by directly moving their physical arms. Another pair of virtual arms was colored in gray, and they were the targets of this target that remained stationary. Participants assumed the ready position at the beginning of a trial, which was a neutral posture sitting upright and facing forward, with the shoulders relaxed. They controlled the pink virtual arms and superimposed them on the gray virtual arms by moving their physical arms, and then returned to the ready position. The gray

virtual arms disappeared and then reappeared at the same location as shown previously. The participant superimposed the pink virtual arms with the gray virtual arms again, and then returned to the ready position. Following the second superimposition movement, the experimenter verbally asked "Were the two arm-shoulder movements the same or different?", and the participant verbally responded to the question. The response was recorded either as 1 or 0, which corresponded to yes or no, respectively.

There were two possible gray virtual arm locations: locations that formed 70° or 110° degrees from the body. A 30 second rest break was provided between each trial and the participant could request longer rest breaks. There were a total of 14 trials. Participants completed a brief demographic questionnaire included questions on age, gender, ethnicity, and hand dominance during a three to five minute break that was provided half way during the session. The experimental session was approximately 40 minutes in length and each participant was provided a small monetary compensation.

The four target locations were determined based on the average allowable ROM demonstrated during a diagonal head-neck movement. A diagonal head-neck movement included a neck flexion or extension motion, followed by a left or right rotation (Piva, Erhard, Childs, & Browder, 2006).

6.2.3.2 Patient study

All participants were referred patients of author J. L. as potential volunteers. Additional exclusion criteria were neurological conditions (e.g. spinal cord injury, multiple sclerosis), progressive disorders (e.g. rheumatoid arthritis), cervical spine surgery, and major depressive and anxiety symptoms. Patients clinically diagnosed with major depressive symptoms were not referred. Patients interested in participating were screened for eligibility over the phone using the inclusion/exclusion criteria and the Generalized Anxiety Disorder 7-item (GAD-7) to screen for anxiety symptoms. Patients scoring less than or equal to 10 on the GAD-7 were eligible to participate. Eligible participants were scheduled for a one-time study session.

There were two tasks in the patient study: the JND task (20 trials) and the evaluation task (12 trials). The JND task was performing two head rotation movements and then comparing whether those two head movements were the same or different. The evaluation task was performing one head rotation movement when the C-D gain was set at the JND. All VR visuals of the target and the secondary objectives were identical to the pilot study. Both the JND and evaluation tasks were performed in a stationary chair with a backrest but without armrests (Figure 6.4). Participants wore a HMD and performed all movements in front of a camera.

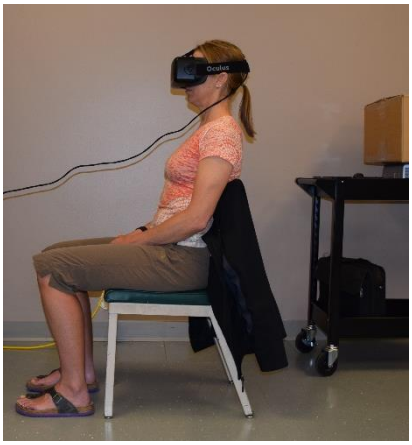

Figure 6.4. A seated participant while wearing a HMD.

The participant indicated their pain level using a visual analog scale (VAS) at the beginning of the session. The standard neck range of motion (ROM) was measured at the start of the session using the HMD. After a five minute rest break, the participant completed the JND task, which was identical to the JND task performed in the preliminary study and a 15 second rest break was provided between each trial. Extended rest breaks were provided upon request. Participants rated their pain on the VAS after the JND task. They took a 15 minute rest break while completing the demographic, Tampa Scale for Kinesiophobia (TSK-11) and the Neck Disability Index (NDI) questionnaires before the evaluation task.

The evaluation task was to visually locate a target object and then align it with a secondary object, which was similar to the JND task. However, the four locations of the target object were customized to the neck movement capability of the participant. The locations of the target object were determined using a

diagonal head-neck movement described by Piva et al. (2006). Once the participant aligned the secondary object against the target, the experimenter verbally asked the participant whether the movement was "feasible as expected, feasible but slightly challenging, or challenging and not feasible." The participant returned to the neutral posture before the next trial. The participant rated again their pain on the VAS at the end of the session. The experimental session took approximately 75 minutes and the participant was compensated $20.

Upon the analysis of the JND from the preliminary study, we identified that individuals noticed the C-D gain when it deviated 0.2 from unity (e.g. gain=0.8). In considering the ability and potential fatigue when working with the patient population, we narrowed range of C-D gains. In the patient study, the C-D gain ranged from 0.8 to 1.0 in 0.05 increments. We did not test gains above 1.0 because in those cases the patients would not be doing more than they could, but rather turning their neck less.

6.2.4 Variables and Analysis

6.2.4.1 Normals study

For the neck JND task, a 9 × 4 (gain × target location) within-subjects experimental design was presented for a total of 36 trials. The shoulder JND task was a 7×2 (gain × virtual arm location) within-subjects design with a total of 14 trials. The dependent variables were gain detection (same/different) and neck angle during target alignment. The detection threshold (DT) was defined as .25 probability of detecting a difference from unity gain (Steinicke, Bruder, Jerald, Frenz, & Lappe, 2008). The significance level was set at $p < .05$ for all analyses.

6.2.4.2 Patient study

The JND task was a 5 × 4 (gain × target location) within-subjects design. The dependent variables were gain detection (same/different) and neck angle during target alignment. The gains were evaluated using logistic regression with the same detection threshold.

The evaluation task was a 3×4 (gain × target location) within-subjects design. The gains were unity, patient-specific JND, and a "nudge JND" that was 0.5 less than JND. Neck rotation angle was regressed against gain and target location. The significance level was set at $p < .05$ for all analyses.

6.3 Results

6.3.1 Normals study

6.3.1.1 Neck JND task

Logistic regression models were used to analyze the effect of gain and target location on the probability of detection. Detection was significantly affected by gain ($\chi^2(1)=26.91$, $p<.001$) for the lower bound, while statistically controlling for target location. The detection threshold was gain = 0.903 for the overall model of the lower bound (Figure 6.5). There was a significant effect of target location ($\chi^2(3)=8.60$, p=.035) on detection, while statistically controlling for gain at unity. Post-hoc analysis revealed that the detection of the gain during left-flexion (i.e., looking over the left shoulder) was significantly different from neck left- and right-extension movements with Holm-Bonferroni correction ($p<.05$). The DT for neck left-flexion was modeled to be gain = 0.814. There was a significant effect of gain on detection ($\chi2(1)=34.52$, $p<.001$) for the upper bound of C-D gain, while statistically controlling for target location. The DT was gain = 1.159 for the overall model of the upper bound (Figure 6.6). However, target location did not have a statistically significant effect on detection ($p=.22$).

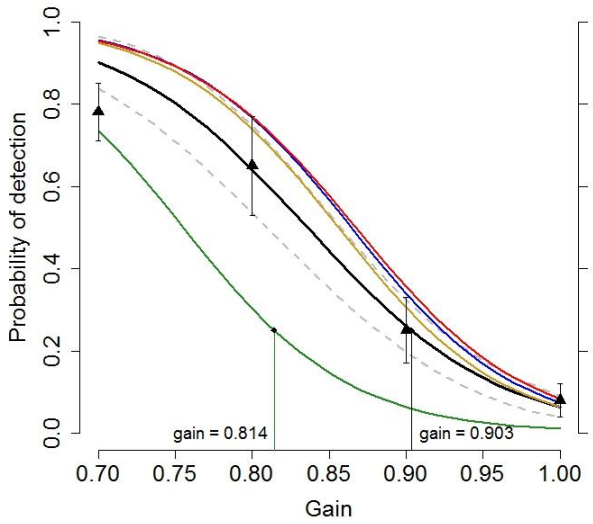

Figure 6.5. The lower bound of gain, ranges from 0.7 to 1.0. Black line depicts the probability of detection of the overall model (dashed lines representing ±1 S.E). Blue and red lines indicate the probability of detection during neck right- and left-extension movements, respectively. Gold and green lines indicate the probability of detection during neck right- and left-flexion movements, respectively. Black triangles depict the mean probabilities across all participants at each gain (±1 S.E.).

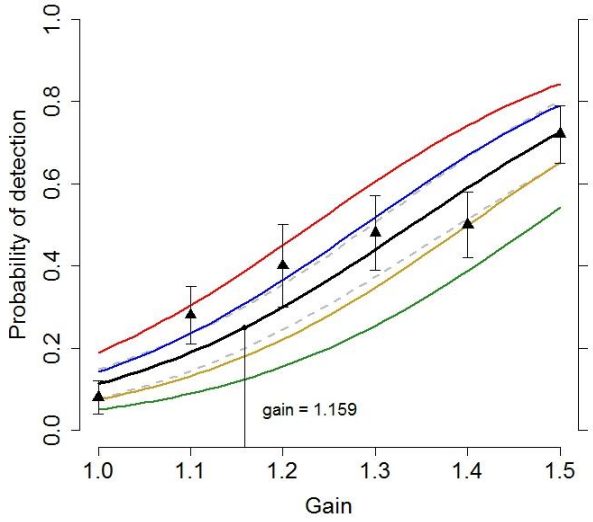

Figure 6.6. The upper bound of gain, ranges from 1.0 to 1.5. Black line depicts the probability of detection of the overall model (dashed lines representing ±1 S.E). Blue and red lines indicate the probability of detection during neck right- and left-extension movements, respectively. Gold and green lines indicate the probability of detection during neck right- and left-flexion movements, respectively. Black triangles depict the mean probabilities across all participants at each gain (±1 S.E.).

A generalized model was used to analyze the effect of gain and target location on neck motion (Figure 6.7). There was a significant main effect for gain ($F(2,8)=1282$, $p<.001$) but not for target location

(p=.51). At unity gain, the neck angle was 54.28°, and it was expected to be 5.45° less or more for every 0.1 change in gain (F(1,9)=1786, p<.001), respectively.

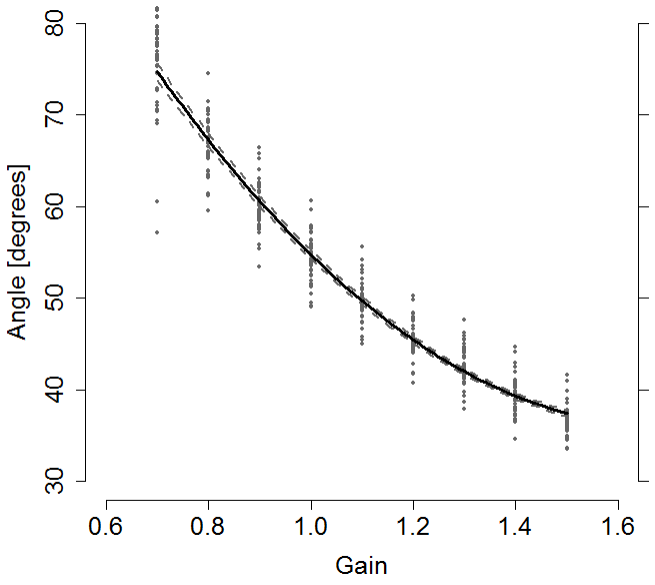

Figure 6.7. Neck rotation angle across the range of gains (0.7 to 1.5). Dashed lines represent ±1 S.E., with the raw data points plotted.

6.3.1.2 Shoulder JND task

The effect of gain and gray virtual arm location on the probability of detection was analyzed using logistic regression. Detection was significantly affected by gain ($\chi^2(1)$= 38.75, p<.001) for the, while statistically controlling for target location. The detection threshold of the overall model was gain = 0.91 (Figure 6.8). There was a significant effect of target location ($\chi^2(3)$=8.04, p=.004) on detection while statistically controlling for gain at unity.

A generalized model was used to analyze the effect of gain and gray virtual arm location on shoulder abduction movement (Figure 6.9). There was a significant main effect for gain (F(2,8)=328.57, p<.001) and for gray virtual arm location (F(2,8)=15.12, p=.006). At unity gain, the shoulder abduction angle was 87.81°, and it was expected to be 3.60° less or more for every 0.1 change in gain, respectively.

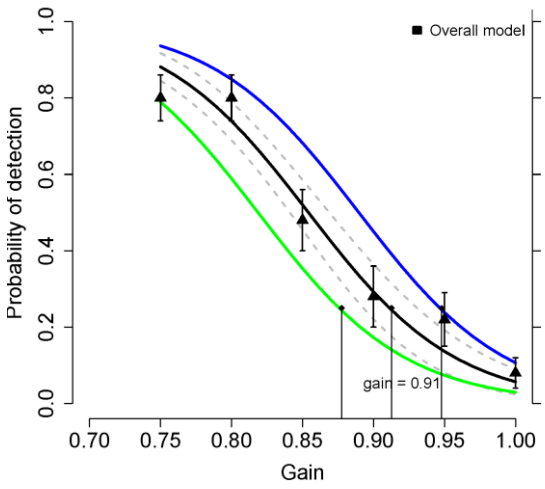

Figure 6.8. Probability of detection over the range of gains (0.7 to 1.0). Black line depicts the probability of detection of the overall model (dashed lines representing ±1 S.E). Blue and green lines indicate the probability of detection at 110° and 70° shoulder abduction, respectively. Black triangles depict the mean probabilities across all participants at each gain (±1 S.E.).

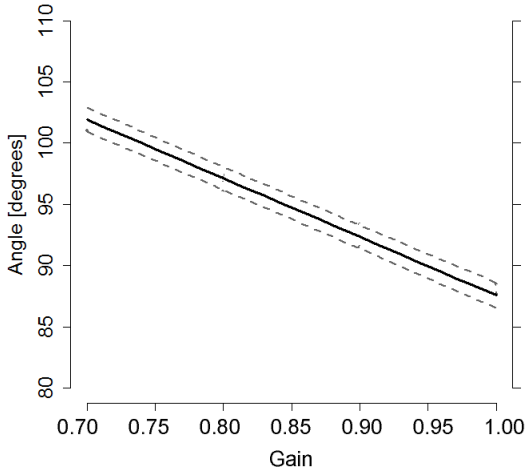

Figure 6.9. Shoulder abduction angles across the range of gains (0.7 to 1.0). Dashed lines represent ±1 S.E.

6.3.2 Patient study

The patients on average had a self-reported pain level of 2.1±1.3 on the visual analog pain scale (0=no pain, 10=maximum pain). Their Neck Disability Index was 15.3±4.7 (0=no disability, 50=maximum

disability). Their mean Tampa Scale for Kinesiophobia score was 23±5.9 (0=not kinesiophobic, 44=very kinesiophobic).

Logistic regression models were used to analyze the effect of gain and target location on the probability of detection. Detection was significantly affected by gain ($\chi^2(1)=26.91$, $p<.001$) but not affect by target location ($p>.05$). The detection threshold was at gain = 0.9455 (Figure 6.10).

A linear model was used to analyze the effect of gain and target location on neck motion (Figure 6.11). There was a significant main effect for gain ($F(1,7)= 44.52$, $p<.001$) and target location (, $p=.002$). At unity gain, the neck angle was 45.0°. For every 0.1 increase or decrease in gain, the neck rotation was expected to be 4.29° less or more.

For the evaluation task, a linear model was used to analyze the effect of gain on neck rotation angle. There was an effect of gain ($F(1,7)=16.43$, $p=.005$) on neck rotation angle. There was not a statistical significant effect of target location on neck rotation angle ($p>.05$). Patients provided verbal feedback after each trial on their perceived difficulty of the task (Figure 6.12).

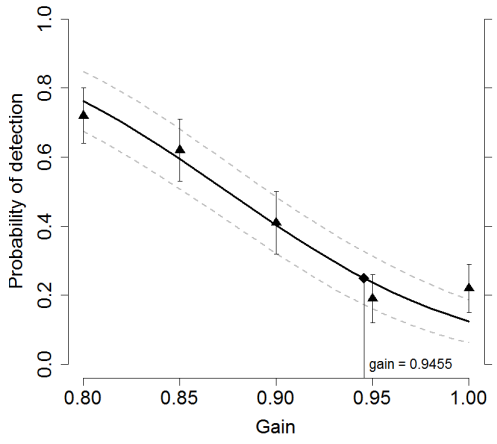

Figure 6.10. Probability of detection by gain (dashed lines representing ±1 S.E). Black triangles depict the mean probabilities across all participants at each gain (±1 S.E.).

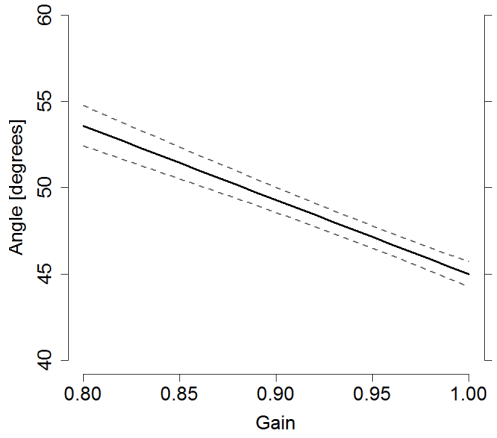

Figure 6.11. Neck rotation angle across the range of gains (0.8 to 1.0). Dashed lines represent ±1 S.E.

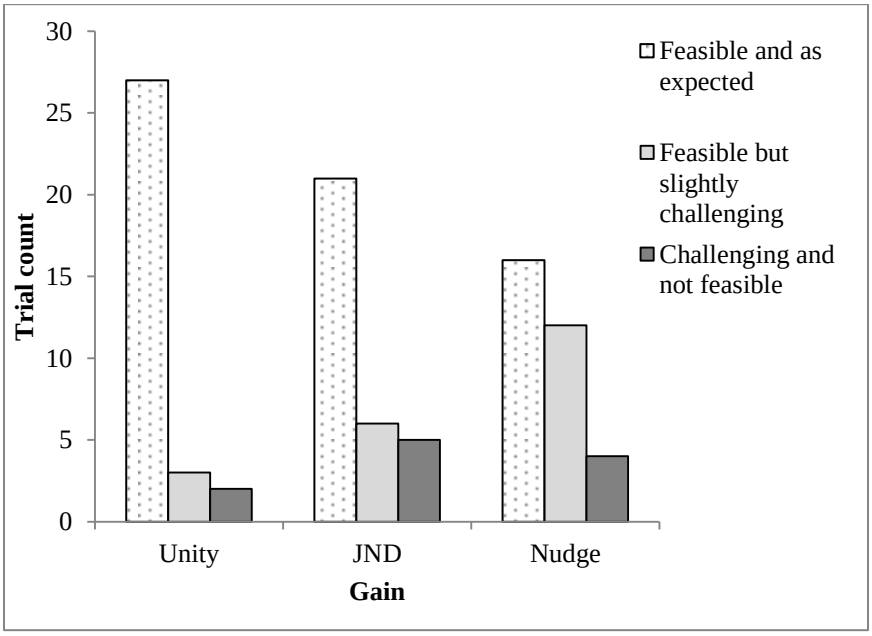

Figure 6.12. Patient perceived difficulty of neck rotation movement in the evaluation task. Three gains were evaluated: unity, JND, and "nudge".

6.4 Discussion

Virtual reality (VR) presents a new health intervention paradigm as it may be a more cost-effective method for rehabilitation. This study examined how individuals with and without chronic neck pain performed therapeutic exercises in VR under the influence of altered visual feedback. Specifically, the

JND of gain was determined in both study populations. The patients performed therapeutic exercises in VR when altered visual feedback was applied at JND.

In general, the VR system was successful in providing altered visual feedback using C-D gain in influencing neck movement. The neck turning angle was significantly affected by gain in both study populations (Figures 6.5 and 6.10), such that participants were able to extend or flex their neck more or less without changing the location of the target during the JND task that involved neck movement. The probability of detecting the altered visual feedback was significantly affected by C-D gain. As the C-D gain deviated from unity, there was a higher probability of detecting the altered visual feedback and this was observed in both healthy and chronic pain individuals.

The preliminary study was conducted with individuals without any musculoskeletal conditions, and altered visual feedback at a wide range of C-D gain (0.7 to 1.5) was examined. Healthy participants performance and responses were separated into responses to lower (less than or equal to unity gain) and upper (greater than or equal to unity gain) gains. The mean detection probability suggested that C-D gain greater than unity gain may be more tolerable for individuals compared to C-D gain less than unity gain. Steinicke et al. (2008) similarly observed that individuals had asymmetrical of gains at detection threshold (DT) for directed walking, although their results showed a wider lower bound.

The effect of target location on probability of detection was observed in the healthy individuals. Specifically when healthy participants performed left-flexion movement of the neck, the modeled JND gain = 0.814 for the lower bound, which is almost 0.1 less gain than the JND of the overall model. This may be due to different normal ranges of motion in an extension versus a flexion movement. Since patients had more restricted neck range of motion and neck pain than the healthy individuals, and therefore the patients' perception of targets in various locations did not affect probability of detection.

In both study populations, some participants were relatively more sensitive to the visual-proprioceptive mismatch and they were able to consistently detect that two neck movements were of different gains.

These participants were considered to have more precise level of detection. Other participants indicated half of the trials that the neck movements did not feel different. For instance, in one trial the participant indicated that two movements were the same, yet in another trial with the same C-D gain, the participant perceived the movements to be different. Both healthy and chronic pain individuals reported that was the neck muscle proprioceptive cues that indicated the difference when they performed movements beyond their JND. This suggests that when individuals are exposed to C-D gains within the JND, there is visual dominance over proprioception, which was similar to the findings in the proprioception literature (Burns et al., 2005, 2006).

Not all participants had the same JND. It is probable that the between-subjects JND variation was related to their regular activities of daily living or exercise habits, as one participant without neck pain indicated in a verbal conversation that she performs yoga and her individual data show wider JND tolerance range. As of the patients, they were receiving different medical treatments (e.g. massage, physical therapy, cortisone injection) and it was difficult to conclude if it was the medical treatments that resulted in different JND between the patients.

For the patients, their unique JND as well as unity gain and "nudge gain" were applied to the movements of the evaluation task. The patients first set the target location based on their perceived-maximum-allowable neck rotation range. The neck rotation angle was the greatest when the patients were exposed to the "nudge" gain, yet the neck rotation angles were not statistically different between unity and JND conditions. When the participant self-reported their perceived difficulty, they generally reported that the trials were feasible, and more trials in the nudge condition were "feasible but slightly challenging".

6.5 Conclusions

In VR, neck and shoulder movements of healthy individuals and neck rotations of neck pain patients were affected by altered visual feedback. Altered visual feedback led to increased magnitude of neck and shoulder movement in VR. Not all participants were affected by the visual feedback to the same extent since the JND varied individually for each participant. This study also demonstrated that the visual

feedback in VR could override muscle proprioceptive cues at or within the JND. It may be possible to use altered visual feedback at JND to encourage patients with chronic musculoskeletal pain to perform therapeutic exercises. The transferability of increased neck rotation magnitude of patients from VR to the physical environment still needs to be explored.

6.6 References

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7. Conclusions

This thesis studied human performance in immersive VR and explored possible applications of VR simulations. The studies on "Manually Locating Physical and Virtual Reality Objects" (i.e. Box Project) and Virtual Exertions were the initial studies that examined human performance and biomechanical activities in VR, using a CAVE. The studies on driver ROM and neck pain patients explored two viable practical applications of VR, using a HMD.

Through the Box Project and Virtual Exertions, we saw differences and similarities of human performance in VR and the physical environment. The accuracy of locating a virtual target was lower than locating a physical target. When we asked people to co-contract muscles in VR to control the position of a virtual object, it was observed that muscle activities in VR were generally greater than muscle activities in the physical environment. Differences of human performance in VR provided insights to future designs of a virtual environment. For instance, there could be a permissible error range in the VR system where users do not need to be 100% accurate when they reach for or interact with virtual objects. When users reach for a virtual object, they can successfully acquire the virtual object as long as they are within that permissible error range for reaching. Some similarities of human performance in VR and the physical environment included increasing muscle activities in VR while increasing weight of the virtual object. Evoking senses of exertions in VR showed promise for conducting research involving physically demanding activities, as we demonstrated manipulation of muscle activity in VR through predetermined threshold.

On the applications side, other scenarios were created to serve as visual stimuli or feedback to the user in VR. Scenarios created were dependent on the purpose of each study. The driver ROM study examined neck ROM of drivers when they checked their blind spots. Given the purpose of the ROM study, dynamics cars in the scenario were visual stimuli to the drivers. Driver ROM at the instance when they responded to the visual stimuli was measured. The ROM was conveniently assessed in a safe environment. For the neck pain study, the patients were also asked to respond to visual stimuli, which

were footballs that were visually distinct and identifiable. In this case, visual stimuli were programmatically altered to have a slight visual-motion mismatch to encourage patients with neck pain to perform neck movement exercises to a greater extent. The results revealed that the patients not only responded to the stimuli but they also performed neck rotation movements that were greater than what they initially indicated. This demonstrated the ability to manipulate human performance in VR through altered visual feedback. It may be possible to obtain desired outcomes or user responses by controlling the feedback they were to receive, e.g. visual stimuli. This study also showed that visual feedback in VR could override other cues (e.g. muscle proprioceptive cues) when the visual feedback received by the patients were at the just-noticeable level of mismatch.

Virtual reality is a flexible environment where users receive visual stimuli to perceive their surroundings. It is a powerful entity for research since various scenarios can be created to satisfy the needs of a given research condition, including and not limited to studying human-VR interactions, human performance and behavior, and physical training and exercise. Conducting safety and health research in VR will be the research trajectory for future research.