Washington University in St. Louis
Washington University Open Scholarship

Arts & Sciences Electronic Theses and Dissertations   Arts & Sciences

Spring 5-15-2017

VRShape: A Virtual Reality Tool for Shaping Movement Compensation

Matthew Hale Foreman
Washington University in St. Louis

Follow this and additional works at: https://openscholarship.wustl.edu/art_sci_etds

Part of the Biomechanics Commons, Mechanical Engineering Commons, and the Occupational Therapy Commons

WASHINGTON UNIVERSITY IN ST. LOUIS

Program in Rehabilitation and Participation Science

Dissertation Examination Committee:
Jack Engsberg, Chair
Alexandre Carter
Caitlin Kelleher
Kerri Morgan
Michael Mueller

VRShape: A Virtual Reality Tool for Shaping Movement Compensation
by
Matthew Hale Foreman

A dissertation presented to
The Graduate School
of Washington University in
partial fulfillment of the
requirements for the degree
of Doctor of Philosophy

May 2017
St. Louis, Missouri

Table of Contents

List of Figures

List of Tables

<u>Acknowledgments</u>

There are a number of supportive and influential forces in my life that I would like acknowledge for making this research possible. I would first like to thank Washington University in St. Louis for providing me the opportunity for vast, continued, and collaborative education. In my undergraduate work, the School of Engineering and Applied Science instilled in me a problem-solving mindset and a set of analytical skills. In my graduate work, the Program in Occupational Therapy taught me to apply my previous training in a novel way towards directly helping those that experience health-related problems during their daily lives. Specifically, I would like to thank the Program in Occupational Therapy for supporting my work financially, providing the space and tools for my research development, and for helping me find a niche in rehabilitation science that I previously would not have thought possible.

I would also like to thank my mentor, Dr. Jack Engsberg, members of my dissertation committee, and all past and present members of the Human Performance Laboratory. I will always be grateful to Dr. Engsberg for introducing me to this interesting field that mixes engineering, biomechanics, and rehabilitation and for giving me the freedom to learn, design, and even teach in my own ways. Thank you to the members of my committee for guiding my work and helping me focus when there are so many questions to answer and problems to solve. Thank you to all of those that have come through the Human Performance Laboratory for letting me learn alongside you in the development and testing of technologies and methods. I would like to specifically express my gratitude to John Standeven, Tim Shurtleff, Bill Janes, Rachel Proffitt, Kerri Morgan, and Anna Boone.

Finally, I would like to thank my family and friends. This has been a long and difficult process that would not have been possible without your encouragement and companionship. I

would never have undertaken such an endeavor without the influence and support of my family: everything that I do, I do to make you proud.

I would like to dedicate this dissertation to my significant other, Kortney Lynn Moews. My hope is that the chapters in this document lead to a new chapter in our lifelong adventure.

Matthew Foreman

Washington University in St. Louis

May 2017

ABSTRACT OF THE DISSERTATION

VRShape: A Virtual Reality Tool for Shaping Movement Compensation

by

Matthew Hale Foreman

Doctor of Philosophy in Rehabilitation and Participation Science

Washington University in St. Louis, 2017

Professor Jack R. Engsberg, Chair

The majority of persons living with chronic stroke experience some form of upper extremity motor impairment that affects their functional movement, performance of meaningful activities, and participation in the flow of daily life. Stroke survivors often compensate for these impairments by adapting their movement patterns to incorporate additional degrees of freedom at new joints and body segments. One of the most common compensatory movements is the recruitment of excessive trunk flexion when reaching with the affected upper extremity. Long-term use of these compensations may lead to suboptimal motor recovery and chronic pain or injury due to overuse. Rehabilitation focuses on repetitive practice with the impaired limb to stimulate motor learning and neuroplasticity; however, few interventions achieve the required repetition dose or address the possible negative effects of compensatory movements. Virtual reality (VR) is an emerging tool in rehabilitation science that may be capable of (1) objectively measuring compensation during upper extremity movement, (2) motivating persons to perform large doses of repetitive practice through the integration of virtual environments and computer games, and (3) providing the basis for a motor intervention aimed at improving motor performance and incrementally reducing, or shaping, compensation. The purpose of this project was to develop and test a VR tool with these capabilities for shaping movement compensation

for persons with chronic stroke, and to achieve this we performed three separate investigations (Chapters 2-4).

First, we investigated the validity and reliability of two generations of an off-the-shelf motion sensor, namely the Microsoft Kinect, for measuring trunk compensations during reaching (Chapter 2). A small group of healthy participants performed various reaching movements on two separate days while simultaneously being recorded by the two sensors and a third considered to be the gold standard. We found that the second generation Kinect sensor was more accurate and showed greater validity for measuring trunk flexion relative to the gold standard, especially during extended movements, and therefore recommended that sensor for future VR development. Research with a more heterogeneous and representative population, such as persons with stroke, will further improve the evaluation of these sensors in future work.

Second, we tested a newly-designed VR tool, VRShape, for use during a single session of upper extremity movement practice (Chapter 3). VRShape integrates the Microsoft Kinect and custom software to convert upper extremity movements into the control of various virtual environments and computer games while providing real-time feedback about compensation. A small group of participants with stroke used VRShape to repetitively perform reaching movements while simultaneously receiving feedback concerning their trunk flexion relative to a calibrated threshold. Our tool was able to elicit a large number of successful reaches and limit the amount of trunk flexion used during a single practice session while remaining usable, motivating, and safe. However, areas of improvement were identified relative to the efficiency of the software and the variety of virtual environments available.

Third, we implemented VRShape over the course of a motor intervention for persons with stroke and evaluated its feasibility and effect on compensation during reaching tasks

(Chapter 4). A small group of participants took part in 18 interventions session using VRShape for repetitive reaching practice with incrementally shaped trunk compensation. Trunk flexion decreased significantly and reaching kinematics improved significantly as a result of the intervention. Even with extended use, participants were able to complete intense practice and thousands of repetitions while continually rating the system as usable, motivating, engaging, and safe. Our VR tool demonstrated feasibility and preliminary efficacy within a small study, but future work is needed to identify its ideal applications and address its limitations.

In summary, this project shows that use of a VR tool incorporating an accurate sensor (Chapter 2) and feedback from initial testing (Chapter 3) is capable of changing the amount of trunk flexion used during reaching movements for persons with stroke (Chapter 4). More research is needed to establish its efficacy and effectiveness, but improvements in motor recovery and associated decreases in compensation associated with the use of VRShape are important rehabilitation goals that may lead to improved participation and quality of life for persons living with long-term impairments due to chronic stroke.

Chapter 1: Introduction

1.1 Stroke Background

Stroke is one of the most devastating health conditions affecting adults in the United States, representing the fifth leading cause of death and a major leading cause of disability (Mozaffarian et al,. 2016). Motor impairments are some of the most common reasons for post-stroke disability, affecting between 55% and 85% of survivors at least six months following their stroke and leading to activity limitations, participation restrictions, and reduced quality of life (Hartman-Meier et al., 2007; Kelly-Hayes et al., 2003; Lai et al., 2002; Olsen et al., 1990). Rehabilitation services depend on severity and setting, but primarily focus on the promotion of functional recovery and independence (Winstein et al., 2016). Stroke and the related motor sequelae should continue to be prioritized in medical and rehabilitation research to reduce the immense burden placed on individuals living with the condition, the healthcare system, and the economy.

1.1.1 Stroke Prevalence

According to the American Heart Association's most recent statistical update, approximately 6.6 million adults over the age of 20 in the U.S. have experienced a stroke, representing a national prevalence of about 2.6% (Mozaffarian et al, 2016). Each year, an estimated 795,000 Americans have a stroke, with about 610,000 of these being new and 185,000 being recurrent strokes (Mozaffarian et al., 2016). Roughly half of Americans (47%) live with at least one of the three most well-known risk factors related to cardiovascular disease or stroke, including high blood pressure, high cholesterol, or current smoking (Fryar et al., 2012). By the

year 2030, projections suggest that another 3.4 million American adults will have a stroke, representing a 20.5% increase in national prevalence from 2012 (Ovbiagele et al., 2013).

There are generally three types of stroke: (1) ischemic, (2) intracerebral hemorrhage, and (3) subarachnoid hemorrhage. Ischemic stroke occurs due to blockage (thrombosis or embolism) that limits blood flow in a vessel supplying the brain. Hemorrhagic stroke occurs due to bleeding in a ruptured blood vessel supplying either the brain itself (intracerebral) or the area between the brain and its protective tissues (subarachnoid space). Both etiologies ultimately cause neurocellular death and the rapid onset of behavioral symptoms related to dysfunction in focal areas of the brain (Mohr et al., 1997). Approximately 87% of all strokes occur due to ischemia, 10% due to intracerebral hemorrhage, and 3% due to subarachnoid hemorrhage (Mozaffarian et al., 2016). While the vast majority of rehabilitation research focuses on those with ischemic stroke due to its relative prevalence, those with hemorrhagic stroke are known to have increased mortality rates and poorer long-term recovery (Grysiewicz et al., 2008).

1.1.2 Chronic Stroke

The rate of stroke deaths in the U.S. dropped by 18.3% from 2003 to 2013, largely attributed to advancements in the control of hypertension, diabetes, and smoking (Lackland et al., 2014). As a result, more people than ever are surviving and living with stroke. Immediate and long-term outcomes depend on the size, extent, type, and area of the lesion along with various individual and environmental factors (Coupar et al., 2012; Kwakkel & Kollen, 2013). In general, the behavioral symptoms of stroke are characterized by difficulties with cognition, speech, and movement of the limbs. The prognosis for recovery of these functions is difficult to define due to its variance in both cause and effect, but it is well established that the severity of initial impairment is the best predictor for long-term outcomes (Coupar et al., 2012). That being

said, it is hypothesized that even those categorized as having a "mild" stroke based on standardized measurements do not fully regain premorbid functioning in the long-term: about 65% of all stroke survivors cannot incorporate the stroke-affected hand into everyday activity, causing them to discontinue an average of 57% of their valued daily activities (Dobkin, 2005; Hartman-Meier et al., 2007). According to Medicare, only about 45% of patients recover enough function to be discharged to home following their acute hospital visit, while 24% are transferred to inpatient rehabilitation facilities and 31% are transferred to skilled nursing facilities for further rehabilitation (Buntin et al., 2010). About 31% of stroke survivors receive outpatient physical, occupational, or speech therapy for an ongoing stroke-related deficit (CDC, 2007).

Chronic stroke is typically defined as the persistence of stroke-related symptoms at least six months following the cerebrovascular event. Motor impairments related to muscle weakness, limited range of motion (ROM), reduced motor control or dexterity, and spasticity in the upper extremity (UE) or lower extremity (LE) are experienced by between 55% and 75% of persons with chronic stroke (Olsen, 1990). In addition, approximately 22% can experience long-term cognitive impairment known to affect attention, memory, and executive function (Douiri et al., 2013). Impairments in speech are also prevalent in this population: between 21% and 38% experience impairments such as aphasia that may require long-term rehabilitation (Berthier, 2005). Post-stroke depression occurs in about 31% of the chronic stroke population, mediating all aspects of recovery including improvements in the performance of activities of daily living (ADLs) (Robinson & Jorge, 2016). Finally chronic stroke is known to not only affect the individual, but also to create stress and restrict participation for families and caregivers, especially for those with less financial support (Adelman et al., 2014).

1.1.3 Hemiparesis

The amelioration of motor impairments and the improvement of motor functions related to everyday performance of activities are typically reported as the highest priority goals for persons with chronic stroke (Waddell et al., 2016). Often, persons living with long-term motor difficulties do not perform ADLs (dressing, bathing, use of stairs) or instrumental ADLs (IADLs, meal preparation, housekeeping, laundry) to their own satisfaction and therefore require assistance (Hartman-Meier et al., 2007). They also might be more probable to experience participation restrictions in the form of forfeiting valued activities, particularly high-demand leisure activities, or withdrawing from important societal roles due to their motor deficits (Hartman-Meier et al., 2007). Motor coordination and UE ability are known to be among the best predictors for long-term societal reintegration and continued participation following stroke (Desrosiers et al., 2006).

Hemiparesis is the most common motor disorder resulting from stroke, affecting the majority of those living the condition chronically (Kelly-Hayes et al., 2003). Hemiparesis can be categorized as a syndrome of coexisting motor impairments affecting one side of the body including weakness, spasticity, decreased motor control, and sometimes a higher order motor planning deficit (Sathian et al., 2011). Hemiparesis is caused by damage to the corticospinal system including the primary cortical motor areas and their connections to the spinal cord (Sathian et al., 2011). Reaching movements have been particularly well studied in hemiparetic stroke patients, and are known to be slower and less accurate than reaching movements in healthy control participants (Cirstea & Levin, 2000). Hemiparetic patients also typically have reduced reaching ROM and uncoordinated recruitment of muscles to flex the shoulder, extend the elbow, orient the wrist, and position the hand during reach-to-grasp movements (Roby-Brami et al., 2003; Wagner et al., 2007). These impairments are well correlated with the extent of

initial damage to the brain and often affect distal muscles to a greater extent than proximal muscles (Colebatch, 1989). Motor function related to reaching, as measured by high fidelity kinematic testing, can recover significantly but often plateaus after 90 days post-stroke (Lang et al., 2006). New evidence is emerging that shows the extent, accuracy, and efficiency of reaching movements can be improved through intense rehabilitation, even for persons with chronic stroke (Bosch et al., 2014; Lohse et al., 2014a).

1.1.4 Healthcare Costs

In 2011, the total U.S. economic cost of stroke was approximately $33 billion (Mozaffarian et al., 2016). This total can be divided into direct medical costs ($17.2 billion) associated with inpatient hospital stays, outpatient hospital visits, home health, and prescribed medicines and indirect costs ($15.2 billion) associated with productivity loss and informal caregiving (Joo et al., 2014; Mozaffarian et al., 2016). By 2030, the total economic cost of stroke is projected to approach $184.1 billion (Ovbiagele et al., 2013).

Having a stroke can incur an immense direct cost to an individual: the average hospitalization expense for an ischemic stroke is estimated to be $18,963 (Wang et al., 2014). The average cost of a singular instance of direct care of any stroke-related service, ranging from a visit to the emergency room to home health care, is estimated to be $4,830 (Mozaffarian et al., 2016). In the first year after discharge from inpatient care, the average cost for medications and outpatient rehabilitation services is estimated to be $11,145 (Godwin et al., 2011). In total, a person with chronic stroke due to ischemia can incur an estimated lifetime expenditure of over $140,000 (Taylor et al., 1996).

1.2 Motor Learning

Motor learning is a general term for the complex process by which a new motor skill is acquired and performed more efficiently over time. This is particularly important for stroke rehabilitation, which can generally be defined as a process of relearning movement abilities to better perform tasks required for daily living (Kleim & Jones, 2008; Krakauer, 2006). Best practice guidelines for post-stroke motor rehabilitation are based primarily on principles of motor learning and either the reacquisition of lost motor abilities or the integration of compensatory strategies (Winstein et al., 2016).

1.2.1 Theory

Dynamic systems theory is one of the prevailing theories in contemporary motor learning that attempts to solve the "degrees of freedom" problem, or the question concerning the neuromuscular system's ability to choose the correct combination of coordinated movements given an infinite number of degrees of freedom from which to choose (Bernstein, 1967). Dynamic systems theory proposes that the motor control system is made up the superposition of many separate control systems that convert various stimuli from the person (intrinsic) and environment (extrinsic) into usable information and ultimately a movement solution (Shumway-Cook & Woollacott, 2007). The supposition of separate control systems produce an individual's optimal solution based on the processing of personal (proprioceptive, psychological, cognitive) and environmental (visual, auditory, skin sensation) information. Motor learning is the process of improving the signal strength within and across these communicating control systems to improve the speed, accuracy, and efficiency of goal-driven movements (Krakauer, 2006).

The Computation, Anatomy, Physiology (CAP) model supports dynamic systems theory by modeling the different mechanisms of motor control (Frey et al., 2012). Given a goal,

movement can occur through feed-forward and feedback control. Feedback control results in slow movement that is constantly corrected based on a feedback loop calculating the difference between the intended action and the sensory input from the result of the action. Feed-forward control results in fast movements that are derived from experientially learned internal models that represent motor plans needed to achieve the action. Internal models can be forward (sensory results estimated based on the movement) or inverse (movement estimated based on sensory results). The formation of feed-forward control is driven by prior experience and motor learning through the repetitive completion of similar tasks. The main processing areas for this type of control are the primary motor cortex and corticospinal system; however, there is significant input from other structures such as the cerebellum, basal ganglia, and spinal cord (Frey et al., 2012). Improvements in these movement models are achieved through repetition of the intended movement that, over time, encourage dendritic growth, increases in spine density, increases in synapse size and quantity, and enhancements in neural activity within cortical motor areas (Nudo, 2013).

1.2.2 Repetitive Task-Based Training

The purpose of most motor therapy is to strengthen mechanisms of feed-forward and feedback control through neuroplastic change. The brain's ability to adapt cortical function based on repetitive stimuli, or the theory of neuroplasticity, requires specific, goal-driven movements to be repetitively practiced on the order of thousands of times (Nudo, 2013). In animal stroke models, it has been well established that healthy brain areas can take on the functions of injured areas to improve motor function when given enough repetitive practice in the specific task within the relevant context (Kleim & Jones, 2008; Krakauer, 2006). Unfortunately, these repetition doses are not achieved in typical therapy. It has been

recommended that at least 300 repetitions should be achieved within a single 1-hour therapy session to facilitate motor skill relearning; however, only an average of 32 repetitions is achieved in typical UE therapy (Birkenmeier et al., 2010; Lang et al., 2007). Repetition-based training is fundamental to current guidelines and best-evidence practice in physical and occupational therapy, and yet it is often not applied due to constraints on time, funding, and lack of motivation for compliance. New therapy modalities that may be able to improve patient motivation and facilitate repetitive practice of movements are research priorities in rehabilitation science (Bowden et al., 2013; Levin et al., 2015; Proffitt & Lange, 2015).

1.2.3 Motor Recovery vs. Compensation

There are two main ways in which functional recovery in the UE can occur following stroke: (1) motor recovery and (2) compensation. Motor recovery refers to the reacquisition of typical motor patterns, in relation to age matched controls or levels prior to neurological injury, in the impaired UE that can be used to complete tasks. Movement compensation refers to the use of atypical movement patterns, or the use of muscles and joints outside of the UE, to complete tasks (Levin et al., 2009).

Both motor recovery and compensation play important roles in functional recovery following stroke. True motor recovery may occur through mechanisms of neuroplasticity and targeted, carefully controlled therapy. In the absence of probable motor recovery, compensation strategies are often adopted to help with the completion of tasks, especially in the acute phase of stroke before significant recovery has been possible. These strategies move certain body parts into position for successful task completion, commonly at the trunk and shoulder, and can be related to the level of impairment in the UE. Trunk displacement and rotation, scapular elevation, and internal rotation of the shoulder are common compensations during reaching to

move the arm and hand into position (Cirstea & Levin, 2000; Levin et al., 2002; Roby-Brami et al., 1997; Roby-Brami et al., 2003). Furthermore, an atypical pattern of coordination that involves the trunk earlier in the process of a reach has been observed; healthy participants involve the trunk at about 90% of the time course of a reach, while persons with hemiparesis may involve the trunk as early as 30% into a reach and utilize 4.5 times the trunk displacement (Levin et al., 2002; Mark et al., 1997; Valdes et al., 2016).

When employed too frequently, compensation strategies may lead to "learned non-use" or "learned bad-use" in the impaired UE (Alaverdashvili et al., 2008; Taub et al., 1993). Learned non-use occurs when a person learns to complete all UE tasks with the unimpaired arm, and has been shown to lead to further muscle atrophy, hypertonicity and reduced ROM, and, in general, exacerbated motor impairments in the impaired arm due to lack of movement (Taub et al., 1993). Learned bad-use occurs when a person learns to use significant compensatory strategies to inconsistently complete tasks with the impaired arm, leading to suboptimal skill acquisition due to lack of high quality practice (Alaverdashvili et al., 2008). In animal models, stroke can be associated with an increase in unsuccessful, compensation-driven attempts to complete feeding tasks that actually inhibit improvements in the impaired limb (Alaverdashvili et al., 2013). In contrast, animals that are forced to perform high doses of movement repetitions without compensatory movements can actually recover close to premorbid motor function, depending on the severity of initial damage (Schmidt et al., 2014). Other research has shown that habitually utilized compensatory movements with the unimpaired limb can inhibit motor recovery in the impaired limb due to interhemispheric competition in primary cortical sensorimotor areas; in other words, overstimulating healthy brain regions may encourage maladaptive neuroplasticity in unhealthy and surrounding regions (Allred et al., 2010; Takeuchi & Izumi, 2012). Finally,

deviations from optimal UE biomechanics during movements such as reaching may lead to overuse injuries, pain, and reduced ROM in abnormally used body segments and joints (Levin et al., 2009).

Unfortunately, mechanisms of true motor recovery versus compensation are not reliably assessed, even in the largest rehabilitation studies and most well-researched clinical guidelines (Levin et al., 2009). This is a priority for future research, because compensation may (1) be attributed to unfavorable results in recent clinical stroke trials, (2) may limit stroke recovery, and (3) may be confused with true motor recovery during neural scans and behavioral assessments (Krakauer, 2006).

1.2.4 Evidence in Stroke

A recent review of all task-oriented practice interventions performed in the stroke population between 1950 and 2012 found there to be evidence that an increase in the amount of repetitive practice with the UE may lead to a significant decrease in UE motor impairment (Bosch et al., 2014). Another assessment of a large set of patient metadata from 138 research articles found a small, beneficial effect size (Hedge's $g = 0.35$) for a larger dose of therapy relative to control groups that received a smaller dose (Lohse et al., 2014a).

Further studies have shown that it is possible to translate the high repetition doses utilized in animal stroke model studies to real-world research and clinical situations, and that participants with stroke can improve significantly in terms of UE motor function, performance of ADLs, and participation. Birkenmeier and colleagues (2010) achieved a 97% adherence rate to intense UE therapy that elicited an average of 322 repetitions in just 1-hour sessions, and showed that this therapy was able to improve motor function as measured by the Action Research Arm Test (ARAT), on average, above what is minimally clinically important (Birkenmeier et al., 2010).

Michaelsen and colleagues (2006) examined the effect of task-based reaching practice, specifically practice with trunk restraint, that effectively limited compensation compared to practice without (Michaelsen et al., 2006). Trunk restraint was used in the form of a series of belts that forced the trunk and shoulder to remain in a neutral position. Researchers found that training with trunk restraint produced greater improvements in motor impairment (Fugl-Meyer), motor function (Upper Extremity Performance Test), and reaching kinematics (less trunk movement, more elbow extension) compared to training without. Average improvements in the control group were correlated with increased trunk compensation (Michaelsen et al., 2006).

While repetitive task training has been found to cause motor changes in some small studies and is grounded in theory from animal models, another recent study by Lang and colleagues (2016) found that larger doses of movement may not actually be better (Lang et al., 2016). In a study that asked participants to perform either 3200, 6400, 9200, or maximum allowable until fatigue (> 9600) repetitions, researchers found only a small relationship between the size of dose and the overall recovery of motor function and therefore no significant dose-response relationship in persons with chronic stroke as a result of intense repetitive task training (Lang et al., 2016). It is clear that further research is needed to uncover the mechanisms behind motor recovery in chronic stroke, and that currently used modalities may benefit from the inclusion of new strategies, particularly those that focus on the measuring compensatory movements.

Constraint-induced movement therapy (CIMT) is another intervention that has gained traction in rehabilitation, and it relies on the same principles as repetition-based training. In CIMT, the unaffected arm of a person with hemiparesis is constrained for an extended period of time, forcing the person to use his or her affected arm for functional tasks (Kwakkel et al., 2015;

Taub et al., 1993). Often the limb is restrained for most waking hours in the day, greatly

increasing the amount of practice achieved with the affected limb and driving motor learning as

described earlier. Several studies, including two large Phase II/III studies, have shown that

CIMT and modified CIMT in stroke populations can improve motor function as measured by the

Wolf Motor Function Test (WMFT) and ARAT, and may help improve the capacity to perform

ADLs (Wolf et al., 2006; Dromerick et al., 2009).

Results from CIMT research are subject to several limitations. First, persons involved in

such studies are often not motivated to have their unaffected arm constrained for several hours

per day, causing frustration and suboptimal psychological circumstances. Second, it is unclear

whether CIMT encourages motor recovery through the practice of efficient, purposeful

movement or compensation through the practice of inefficient compensatory strategies (Kitago et

al., 2013). Third, the clinical training, attention, and observation required for the execution of

successful CIMT therapy makes its application expensive and impractical for use in the clinic.

These limitations are representative of larger problems within the field of motor rehabilitation,

and again, suggest use of an alternative modality may be beneficial.

1.3 Virtual Reality

Virtual reality (VR) has gained widespread popularity in rehabilitation due to its ability to

solve various problems previously described. VR is a human-computer interface that, when

combined with motion sensing technology, allows the user to interact with a sensory immersing,

three-dimensional virtual environment (VE) through physical movement (Holden, 2005). VR is

a therapy tool that can (1) target specific movements with the impaired arm to facilitate use and

improve function, (2) quantify motion to monitor and record performance, (3) provide

meaningful contexts to sustain motivation to perform high volumes of repetitions, and (4)

provide feedback about performance and results to support motor learning (Holden, 2005; Levin et al., 2015; Proffitt & Lange, 2015; Schultheis & Rizzo, 2001). When combined with researcher or therapist knowledge in the correct setting, such a tool can amplify conventional care in the form of VR-based rehabilitation (Levac & Galvin, 2013). Many have lauded VR for its potential for motor and cognitive therapy, but have noted that future research should include more affordable devices, more accessible and easy-to-use systems, and should be developed with specific, theory-driven goals such as those of motor learning (Levin et al., 2015).

1.3.1 Devices

In general, VR systems may be categorized as "immersive" or "non-immersive" (Henderson et al., 2007). Immersive systems may include such devices as heads-up displays (HUDs), Computer Assisted Virtual Environments (CAVEs), expensive motion capture cameras, and custom-developed virtual environments (VEs). Non-immersive systems are often more affordable and may include off-the-shelf motion sensors, commercially available games or virtual environments (VEs), and widely available displays such as large screen monitors or televisions. The basic composition of VR systems constitutes (1) input devices, (2) middleware that converts movement into useful computer signals, and (3) software used to manipulate VEs.

Input devices can range from the everyday keyboard and mouse to expensive multi-camera motion capture systems and even robots. More accessible, commercially-available technologies such as the Nintendo WiiMote (Nintendo of America, Redmond, WA) or the Microsoft Kinect (Microsoft Corp., Redmond, WA) are gaining widespread use as input devices for rehabilitation. The WiiMote is a small device intended for use with a gaming console that contains an accelerometer and gyroscope for motion sensing (Proffitt et al., 2011). The Microsoft Kinect is a markerless camera system that uses a depth sensor and a regular red-green-

blue (RGB) camera to detect the skeletal joint positions of various anatomical markers on a person in real-time (Lauterbach et al., 2013; Sevick et al., 2016). The first (V1) and second (V2) versions of the Kinect have been used as input devices in a number of small-scale research studies, and have been shown to be valid and reliable relative to more expensive video motion capture cameras (Bonnechere et al., 2014; Clark et al., 2015, Reither et al., 2017).

Middleware is the behind-the-scenes software that converts signals from these hardware devices into usable information. For the Microsoft Kinect, the most popular middleware is the Microsoft Kinect Software Development Kit (SDK). This Kinect SDK provides the programming library for writing software that can communicate with the Kinect and contains algorithms for skeletal and gesture recognition. These programs "drive' the function of the sensor and convert mechanical signals into information such as joint positions and angles.

Finally, software is used to manipulate those joint positions and angles into computer control and the interaction with VEs. For the Microsoft Kinect, a common software program is the Flexible Action and Articulated Skeleton Toolkit (FAAST), which converts movement beyond certain thresholds into keyboard presses and mouse movement (Suma et al., 2013; Lauterbach et al., 2013; Sevick et al., 2016). This allows the FAAST program in conjunction with a Kinect to control nearly any VE available on a computer. For the purposes of the current research, custom software was developed within the MATLAB Integrated Development Environment (IDE) (Mathworks Inc., Natick, MA) to convert movement from the UE and trunk, as measured by the Microsoft Kinect, into the control of the keyboard/mouse, freely available VEs, and real-time feedback.

1.3.2 Evidence in Stroke Rehabilitation

Meta-analyses and systematic reviews of VR-based rehabilitation are useful for aggregating evidence from the explosion of small pilot studies in recent years. Lohse and colleagues (2014) investigated 26 studies and found moderate effect sizes for VR relative to conventional therapy in terms of improving impairment to body structures and functions ($g = 0.48$) and activity performance ($g = 0.58$). They also found a moderate effect size for improving participation following VR-based therapy ($g = 0.56$) (Lohse et al., 2014b). Saposnik and colleagues (2011) reviewed 12 studies involving 195 participants and found there to be an overall positive effect for VR use in terms of improving motor impairment and motor function. This group calculated a 14.7% improvement in motor impairment and a 20.1% improvement in motor function (Saposnik et al., 2011). Henderson and colleagues investigated the difference in immersive and non-immersive VR systems for rehabilitation and found widely varying levels of evidence, especially when considering comparison groups defined as typical therapy or no therapy (Henderson et al., 2007). In general, they found the greatest effect for training in immersive environments over no therapy at all, but found no evidence supporting training in immersive environments over typical therapy. They found conflicting results for training in non-immersive environments compared to no or conventional therapy (Henderson et al., 2007). Finally, the largest Cochrane review performed on the subject (2015) found 37 studies involving 1019 participants that utilized some form of VR for primarily motor therapy. Reviewers found a significant effect for using VR on improving UE function, gross UE movement, and performance of ADLs; however, there were no significant results for grip strength, global motor function, cognitive function, participation restrictions, or quality of life (Laver et al., 2015). Comprehensive reviews such as these have been used to define clinical guidelines for selecting

appropriate input devices, software, and VEs based on the needs of clients and the resources of the clinic (Anderson et al., 2015; Levac & Galvin, 2013).

While reviews have found general promise, the use or non-use of compensatory movements has been shown to modulate individual improvements that are possible through VR-based motor therapy (Cameirao et al., 2012). Only a few studies have sought to incorporate compensation into their overall VR strategy (Alankus & Kelleher, 2012). The most notable study to date that attempted provide feedback about compensation during reaching training involved the use of a CAVE and high doses of reaching movements in chronic stroke (Subramanian et al., 2013). Repetitive task training involved the performance of 72 reaching movements towards strategically placed targets within a virtual shopping environment. Participants were encouraged flex their shoulders, extend their elbows, and orient their wrists to their maximum ROM on each reach. Positive feedback was provided in auditory form when a reach was performed quickly and accurately; however, negative feedback was provided in the form of a "buzzer" sound if the person used too much trunk compensation to complete the reaching movement. A control group performed similar doses of reaching movements outside of the virtual environment. Results showed improvements in motor function (ARAT) and reaching quality (movement kinematics) in both groups, but most notably, improvements in reaching did not include the use of compensatory trunk movements in persons that trained in the VE. Improvements in reaching were correlated with increased trunk movement in the control group. This important study shows that it is possible to change the use of compensatory trunk movements during reaching in a VE through the provision of feedback.

1.4 Summary

Hemiparesis resulting from stroke can cause deficits in motor abilities that lead to poor activity performance, disengagement from participation in daily life, and immense psychosocial and financial burden. While stroke-related deaths in the U.S. are declining, the overall prevalence of stroke is increasing and more people than ever are living with chronic motor conditions. The best evidence in rehabilitation for persons with chronic hemiparetic stroke is grounded in theory surrounding motor learning and neuroplasticity, and generally centers on the massed and spaced repetition of large doses of movements with the impaired body systems. Unfortunately, these principles are not generally applied in practice and clients do not receive a sufficient dose of movement practice to change motor abilities. In addition, lack of distinction between targeted, purposeful movements and compensatory movements may lead to suboptimal outcomes and secondary chronic motor conditions such as pain and fatigue. A cutting-edge therapy modality such as VR may be capable of (1) eliciting high doses of movements, (2) improving motivation for therapy, and (3) addressing the use of compensatory movements through the provision of feedback.

The long term goal of this research is to improve motor recovery, function, and participation in persons with chronic upper extremity motor impairments. The purpose of this study was to use VR to develop a method for investigating the role of movement compensation during motor rehabilitation in persons with stroke. The expected outcome is a tool, namely VRShape, and initial evidence supporting the use of VRShape for measuring and shaping compensation during upper extremity movement practice, increasing motivation and therapy compliance, and monitoring motor performance for persons with hemiparetic stroke. The long term impact will be a simple, inexpensive method to improve upper extremity motor recovery and decrease compensation in persons with stroke.

1.5 References

Adelman, R. D., Tmanova, L. L., Delgado, D., Dion, S., & Lachs, M. S. (2014). Caregiver burden: a clinical review. *Jama, 311*(10), 1052-1060.

Alankus, G., & Kelleher, C. (2012). Reducing compensatory motions in video games for stroke rehabilitation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 2049-2058). ACM.

Alaverdashvili, M., Foroud, A., Lim, D. H., & Whishaw, I. Q. (2008). "Learned baduse" limits recovery of skilled reaching for food after forelimb motor cortex stroke in rats: a new analysis of the effect of gestures on success. *Behavioural brain research, 188*(2), 281-290.

Alaverdashvili, M., & Whishaw, I. Q. (2013). A behavioral method for identifying recovery and compensation: hand use in a preclinical stroke model using the single pellet reaching task. *Neuroscience & Biobehavioral Reviews, 37*(5), 950-967.

Allred, R. P., Cappellini, C. H., & Jones, T. A. (2010). The "good" limb makes the "bad" limb worse: Experience-dependent interhemispheric disruption of functional outcome after cortical infarcts in rats. *Behavioral neuroscience, 124*(1), 124.

Anderson, K. R., Woodbury, M. L., Phillips, K., & Gauthier, L. V. (2015). Virtual reality video games to promote movement recovery in stroke rehabilitation: a guide for clinicians. *Archives of physical medicine and rehabilitation, 96*(5), 973-976.

Bernstein, N. A. (1967). The co-ordination and regulation of movements.

Berthier, M. L. (2005). Poststroke aphasia. *Drugs & aging, 22*(2), 163-182.

Birkenmeier, R. L., Prager, E. M., & Lang, C. E. (2010). Translating animal doses of task-specific training to people with chronic stroke in one hour therapy sessions: a proof-of-concept study. *Neurorehabilitation and neural repair*, *24*(7), 620.

Bonnechere, B., Jansen, B., Salvia, P., Bouzahouene, H., Omelina, L., Moiseev, F., ... & Jan, S. V. S. (2014). Validity and reliability of the Kinect within functional assessment activities: comparison with standard stereophotogrammetry. *Gait & posture, 39*(1), 593-598.

Bosch, J., O'Donnell, M. J., Barreca, S., Thabane, L., & Wishart, L. (2014). Does task-oriented practice improve upper extremity motor recovery after stroke? A systematic review. *ISRN Stroke, 2014*.

Bowden, M. G., Woodbury, M. L., & Duncan, P. W. (2013). Promoting neuroplasticity and recovery after stroke: future directions for rehabilitation clinical trials. *Current opinion in neurology, 26*(1), 37-42.

Buntin, M. B., Colla, C. H., Deb, P., Sood, N., & Escarce, J. J. (2010). Medicare spending and outcomes after post-acute care for stroke and hip fracture. *Medical care, 48*(9), 776.

Cameirao, M. S., i Badia, S. B., Duarte, E., Frisoli, A., & Verschure, P. F. (2012). The combined impact of virtual reality neurorehabilitation and its interfaces on upper extremity functional recovery in patients with chronic stroke. *Stroke, 43*(10), 2720-2728.

Carr, J. H., & Shepherd, R. B. (1989). A motor learning model for stroke rehabilitation. *Physiotherapy, 75*(7), 372-380.

Centers for Disease Control and Prevention (CDC. (2007). Outpatient rehabilitation among stroke survivors--21 States and the District of Columbia, 2005. MMWR. *Morbidity and mortality weekly report, 56*(20), 504.

Cirstea, M. C., & Levin, M. F. (2000). Compensatory strategies for reaching in stroke. *Brain, 123*(5), 940-953.

Clark, R. A., Pua, Y. H., Oliveira, C. C., Bower, K. J., Thilarajah, S., McGaw, R., ... & Mentiplay, B. F. (2015). Reliability and concurrent validity of the Microsoft Xbox One Kinect for assessment of standing balance and postural control. *Gait & posture, 42*(2), 210-213.

Colebatch, J. G., & Gandevia, S. C. (1989). The distribution of muscular weakness in upper motor neuron lesions affecting the arm. *Brain, 112*(3), 749-763.

Coupar, F., Pollock, A., Rowe, P., Weir, C., & Langhorne, P. (2012). Predictors of upper limb recovery after stroke: a systematic review and meta-analysis. *Clinical rehabilitation*, *26*(4), 291-313.

Desrosiers, J., Noreau, L., Rochette, A., Bourbonnais, D., Bravo, G., & Bourget, A. (2006). Predictors of long-term participation after stroke. *Disability and rehabilitation, 28*(4), 221-230.

Dobkin, B. H. (2005). Rehabilitation after stroke. *New England Journal of Medicine, 352*(16), 1677-1684.

Douiri, A., Rudd, A. G., & Wolfe, C. D. (2013). Prevalence of Poststroke Cognitive Impairment. *Stroke, 44*(1), 138-145.

Dromerick, A. W., Lang, C. E., Birkenmeier, R. L., Wagner, J. M., Miller, J. P., Videen, T. O., ... & Edwards, D. F. (2009). Very early constraint-induced movement during stroke rehabilitation (VECTORS) A single-center RCT. *Neurology, 73*(3), 195-201.

Frey, S. H., Fogassi, L., Grafton, S., Picard, N., Rothwell, J. C., Schweighofer, N., ... & Fitzpatrick, S. M. (2011). Neurological principles and rehabilitation of action disorders:

computation, anatomy, and physiology (CAP) model. *Neurorehabilitation and neural repair, 25*(5_suppl), 6S-20S.

Fryar, C. D., Chen, T., & Li, X. (2012). Prevalence of uncontrolled risk factors for cardiovascular disease: United States, 1999–2010. *NCHS data brief*, *103*, 1-8.

Godwin, K. M., Wasserman, J., & Ostwald, S. K. (2011). Cost associated with stroke: outpatient rehabilitative services and medication. *Topics in stroke rehabilitation*, *18*(sup1), 676-684.

Grysiewicz, R. A., Thomas, K., & Pandey, D. K. (2008). Epidemiology of ischemic and hemorrhagic stroke: incidence, prevalence, mortality, and risk factors. Neurologic clinics, 26(4), 871-895.

Hartman-Maeir, A., Soroker, N., Ring, H., Avni, N., & Katz, N. (2007). Activities, participation and satisfaction one-year post stroke. *Disability and rehabilitation, 29*(7), 559-566.

Henderson, A., Korner-Bitensky, N., & Levin, M. (2007). Virtual reality in stroke rehabilitation: a systematic review of its effectiveness for upper limb motor recovery. *Topics in stroke rehabilitation, 14*(2), 52-61.

Holden, M. K. (2005). Virtual environments for motor rehabilitation: review. *Cyberpsychology & behavior, 8*(3), 187-211.

Joo, H., George, M. G., Fang, J., & Wang, G. (2014). A literature review of indirect costs associated with stroke. *Journal of Stroke and Cerebrovascular Diseases, 23*(7), 1753-1763.

Kelly-Hayes, M., Beiser, A., Kase, C. S., Scaramucci, A., D'Agostino, R. B., & Wolf, P. A. (2003). The influence of gender and age on disability following ischemic stroke: the Framingham study. *Journal of Stroke and Cerebrovascular Diseases, 12*(3), 119-126.

Kitago, T., Liang, J., Huang, V. S., Hayes, S., Simon, P., Tenteromano, L., ... & Krakauer, J. W. (2013). Improvement after constraint-induced movement therapy: recovery of normal motor control or task-specific compensation? *Neurorehabilitation and neural repair*, *27*(2), 99.

Kleim, J. A., & Jones, T. A. (2008). Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. *Journal of speech, language, and hearing research*, *51*(1), S225-S239.

Krakauer, J. W. (2006). Motor learning: its relevance to stroke recovery and neurorehabilitation. *Current opinion in neurology*, *19*(1), 84-90.

Krakauer, J. W., Carmichael, S. T., Corbett, D., & Wittenberg, G. F. (2012). Getting neurorehabilitation right what can be learned from animal models?. *Neurorehabilitation and neural repair, 26*(8), 923-931.

Kwakkel, G., & Kollen, B. J. (2013). Predicting activities after stroke: what is clinically relevant?. International Journal of Stroke, 8(1), 25-32.

Kwakkel, G., Veerbeek, J. M., van Wegen, E. E., & Wolf, S. L. (2015). Constraint-induced movement therapy after stroke. *The Lancet Neurology, 14*(2), 224-234.

Lackland, D. T., Roccella, E. J., Deutsch, A. F., Fornage, M., George, M. G., Howard, G., ... & Schwamm, L. H. (2014). Factors influencing the decline in stroke mortality. *Stroke, 45*(1), 315-353.

Lai, S. M., Studenski, S., Duncan, P. W., & Perera, S. (2002). Persisting consequences of stroke measured by the Stroke Impact Scale. *Stroke, 33*(7), 1840-1844.

Lang, C. E., Wagner, J. M., Edwards, D. F., Sahrmann, S. A., & Dromerick, A. W. (2006). Recovery of grasp versus reach in people with hemiparesis poststroke. *Neurorehabilitation and neural repair, 20*(4), 444-454.

Lang, C. E., MacDonald, J. R., & Gnip, C. (2007). Counting repetitions: an observational study of outpatient therapy for people with hemiparesis post-stroke. *Journal of Neurologic Physical Therapy, 31*(1), 3-10.

Lang, C. E., Strube, M. J., Bland, M. D., Waddell, K. J., Cherry-Allen, K. M., Nudo, R. J., ... & Birkenmeier, R. L. (2016). Dose response of task-specific upper limb training in people at least 6 months poststroke: A phase II, single-blind, randomized, controlled trial. *Annals of neurology, 80*(3), 342-354.

Lauterbach, S. A., Foreman, M. H., & Engsberg, J. R. (2013). Computer games as therapy for persons with stroke. *Games for Health: Research, Development, and Clinical Applications*, *2*(1), 24-28.

Laver, K. E., George, S., Thomas, S., Deutsch, J. E., & Crotty, M. (2015). Virtual reality for stroke rehabilitation. *The Cochrane Library*.

Levac, D. E., & Galvin, J. (2013). When is virtual reality "therapy"? *Archives of physical medicine and rehabilitation*, *94*(4), 795-798.

Levin, M. F., Michaelsen, S. M., Cirstea, C. M., & Roby-Brami, A. (2002). Use of the trunk for reaching targets placed within and beyond the reach in adult hemiparesis. *Experimental brain research, 143*(2), 171-180.

Levin, M. F., Kleim, J. A., & Wolf, S. L. (2009). What do motor "recovery" and "compensation" mean in patients following stroke?. *Neurorehabilitation and neural repair, 23*(4), 313-319.

Levin, M. F., Weiss, P. L., & Keshner, E. A. (2015). Emergence of virtual reality as a tool for upper limb rehabilitation: incorporation of motor control and motor learning principles. *Physical therapy, 95*(3), 415.

Lohse, K. R., Lang, C. E., & Boyd, L. A. (2014a). Is more better? Using metadata to explore dose–response relationships in stroke rehabilitation. *Stroke, 45*(7), 2053-2058.

Lohse, K. R., Hilderman, C. G., Cheung, K. L., Tatla, S., & Van der Loos, H. M. (2014b). Virtual reality therapy for adults post-stroke: a systematic review and meta-analysis exploring virtual environments and commercial games in therapy. *PloS one, 9*(3), e93318.

Mark, L. S., Nemeth, K., Gardner, D., Dainoff, M. J., Paasche, J., Duffy, M., & Grandt, K. (1997). Postural dynamics and the preferred critical boundary for visually guided reaching. *Journal of Experimental Psychology-Human Perception and Performance*, *23*(5), 1365-1379.

Michaelsen, S. M., Dannenbaum, R., & Levin, M. F. (2006). Task-specific training with trunk restraint on arm recovery in stroke. *Stroke, 37*(1), 186-192.

Mohr, J. P., Albers, G. W., Amarenco, P., Babikian, V. L., Biller, J., Brey, R. L., ... & Kase, C. S. (1997). Etiology of stroke. *Stroke, 28*(7), 1501-1506.

Mozaffarian, D., Benjamin, E. J., Go, A. S., Arnett, D. K., Blaha, M. J., Cushman, M., ... & Howard, V. J. (2016). Heart disease and stroke statistics—2016 update. *Circulation, 133*(4), e38-e360.

Nudo, R. J. (2013). Recovery after brain injury: mechanisms and principles.

Olsen, T. S. (1990). Arm and leg paresis as outcome predictors in stroke rehabilitation. *Stroke, 21*(2), 247-251.

Ovbiagele, B., Goldstein, L. B., Higashida, R. T., Howard, V. J., Johnston, S. C., Khavjou, O. A., ... & Saver, J. L. (2013). Forecasting the future of stroke in the united states. *Stroke*, *44*(8), 2361-2375.

Proffitt, R. M., Alankus, G., Kelleher, C. L., & Engsberg, J. R. (2011). Use of computer games as an intervention for stroke. *Topics in stroke rehabilitation, 18*(4), 417-427.

Proffitt, R., & Lange, B. (2015). Considerations in the efficacy and effectiveness of virtual reality interventions for stroke rehabilitation: moving the field forward. *Physical therapy, 95*(3), 441-448.

Robinson, R. G., & Jorge, R. E. (2015). Post-stroke depression: a review. *American Journal of Psychiatry, 173*(3), 221-231.

Roby-Brami, A., Fuchs, S., Mokhtari, M., & Bussel, B. (1997). Reaching and grasping strategies in hemiparetic patients. *Motor control, 1*(1), 72-91.

Roby-Brami, A., Feydy, A., Combeaud, M., Biryukova, E. V., Bussel, B., & Levin, M. F. (2003). Motor compensation and recovery for reaching in stroke patients. *Acta neurologica scandinavica, 107*(5), 369-381.

Saposnik, G., Levin, M., & Stroke Outcome Research Canada (SORCan) Working Group. (2011). Virtual reality in stroke rehabilitation. *Stroke, 42*(5), 1380-1386.

Sathian, K., Buxbaum, L. J., Cohen, L. G., Krakauer, J. W., Lang, C. E., Corbetta, M., & Fitzpatrick, S. M. (2011). Neurological principles and rehabilitation of action disorders: common clinical deficits. *Neurorehabilitation and neural repair, 25*(5_suppl), 21S-32S.

Schmidt, A., Wellmann, J., Schilling, M., Strecker, J. K., Sommer, C., Schäbitz, W. R., ... & Minnerup, J. (2014). Meta-analysis of the efficacy of different training strategies in animal models of ischemic stroke. *Stroke, 45*(1), 239-247.

Schultheis, M. T., & Rizzo, A. A. (2001). The application of virtual reality technology in rehabilitation. *Rehabilitation psychology, 46*(3), 296.

Sevick, M., Eklund, E., Mensch, A., Foreman, M., Standeven, J., & Engsberg, J. (2016). Using free internet videogames in upper extremity motor training for children with cerebral palsy. *Behavioral Sciences*, *6*(2), 10.

Shumway-Cook, A., & Woollacott, M. H. (1995). Motor control: theory and practical applications. Lippincott Williams & Wilkins.

Suma, E. A., Krum, D. M., Lange, B., Koenig, S., Rizzo, A., & Bolas, M. (2013). Adapting user interfaces for gestural interaction with the flexible action and articulated skeleton toolkit. *Computers & Graphics, 37*(3), 193-201.

Takeuchi, N., & Izumi, S. I. (2012). Maladaptive plasticity for motor recovery after stroke: mechanisms and approaches. *Neural plasticity*, 2012.

Taub, E., Miller, N. E., Novack, T. A., Cook 3rd, E. W., Fleming, W. C., Nepomuceno, C. S., ... & Crago, J. E. (1993). Technique to improve chronic motor deficit after stroke. *Archives of physical medicine and rehabilitation, 74*(4), 347-354.

Taylor, T. N., Davis, P. H., Torner, J. C., Holmes, J., Meyer, J. W., & Jacobson, M. F. (1996). Lifetime cost of stroke in the United States. *Stroke, 27*(9), 1459-1466.

Valdés, B. A., Glegg, S. M., & Van der Loos, H. M. (2016). Trunk Compensation During Bimanual Reaching at Different Heights by Healthy and Hemiparetic Adults. *Journal of Motor Behavior*, 1-13.

Waddell, K. J., Birkenmeier, R. L., Bland, M. D., & Lang, C. E. (2016). An exploratory analysis of the self-reported goals of individuals with chronic upper-extremity paresis following stroke. *Disability and rehabilitation, 38*(9), 853-857.

Wagner, J. M., Dromerick, A. W., Sahrmann, S. A., & Lang, C. E. (2007). Upper extremity muscle activation during recovery of reaching in subjects with post-stroke hemiparesis. *Clinical neurophysiology, 118*(1), 164-176.

Wang, G., Zhang, Z., Ayala, C., Dunet, D. O., Fang, J., & George, M. G. (2014). Costs of hospitalization for stroke patients aged 18-64 years in the United States. *Journal of Stroke and Cerebrovascular Diseases, 23*(5), 861-868.

Winstein, C. J., Stein, J., Arena, R., Bates, B., Cherney, L. R., Cramer, S. C., ... & Lang, C. E. (2016). Guidelines for adult stroke rehabilitation and recovery. *Stroke*, *47*(6), e98-e169.

Wolf, S. L., Winstein, C. J., Miller, J. P., Taub, E., Uswatte, G., Morris, D., ... & Excite Investigators. (2006). Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: the EXCITE randomized clinical trial. *Jama, 296*(17), 2095-2104.

Chapter 2: The Validity and Reliability of the Microsoft Kinect for Measuring Trunk Compensations during Reaching

This chapter is in preparation:

Foreman M.H., Engsberg J.R. (In Preparation). The validity and reliability of the Microsoft

Kinect for measuring trunk compensations during reaching.

Abstract

Background: Compensatory movements at the trunk are commonly utilized by persons with stroke during reaching. Recent low-cost motion sensors may be able to measure trunk compensation, but their validity and reliability for this application are unknown. The purpose of this study was to compare the first (K1) and second (K2) generations of the Microsoft Kinect to a video motion capture system (VMC) for measuring trunk compensations during reaching.

Methods: Healthy participants (n = 5) performed non-extended and extended reaching movements in three different directions and on two different days while being measured by all three sensors simultaneously. Kinematic variables related to reaching range of motion (ROM), planar reach distance, trunk flexion and lateral flexion, shoulder flexion and lateral flexion, and elbow flexion were calculated. Variables were analyzed using Pearson's correlations for validity and intra-class correlations and Bland-Altman plots for reliability.

Results: Results show that the K2 was closer in magnitude to the VMC, more valid, and more reliable for measuring trunk flexion and lateral flexion during extended reaches than was the K1. Both sensors were highly valid and reliable for reaching ROM, planar reach distance, and elbow flexion for all conditions. Results for shoulder flexion and abduction were mixed, but generally all three sensors performed better for extended reaches.

Conclusion: The K2 was more valid and reliable for measuring trunk compensations during reaching and therefore should be prioritized for future development in assessment and virtual reality applications. Future analyses should include a more heterogeneous clinical population such as persons with chronic hemiparetic stroke.

2.1 Introduction

Upper extremity (UE) motor impairments are highly prevalent in many clinical populations such as stroke (Olsen et al, 1990). Impaired UE movement is frequently accompanied by compensatory strategies that help a person adapt to limitations in motor function but may impact recovery and cause negative effects if used long-term (Alaverdashvili et al., 2008; Levin et al., 2009; Roby-Brami et al., 2003;). There are numerous well-researched, standardized assessments that measure UE abilities according to factors such as speed, strength, range of motion (ROM), and movement quality, but few that directly measure the amount of compensation utilized during task performance (Fugl-Meyer et al., 1974; Lyle, 1981; Wolf et al., 2001). Objective assessment of targeted and compensatory UE movements often relies on video motion capture cameras (VMC) or electromagnetic sensors that, while extremely accurate, are typically expensive and not feasible for application in a clinical setting. Because the amount of motor recovery achieved, and inversely the amount of compensation used, is highly predictive of participation and quality of life in persons living with long-term UE impairments, a clinically-feasible, affordable, accurate, and objective measure of movement compensation may be an important innovation in rehabilitation science (Desrosiers et al., 2006).

The Microsoft Kinect (Microsoft Corp., Redmond, WA) is a low-cost, off-the-shelf motion sensor originally designed for video games that can be adapted for quantitative assessment of UE clinical movements (Bonnechere et al., 2014; Clark et al., 2012; Clark et al., 2015; Reither et al., 2017). The measurement abilities of the first generation Kinect (K1) have been established for UE movements, spatiotemporal gait variables, standing balance, postural control, and even static foot posture (Bonnechere et al., 2014; Huber et al., 2015; Mentiplay et al., 2013; Yeung et al., 2014). The abilities of the second generation Kinect (K2) are not as robustly established, but have been investigated for some UE, gait, and postural movements

(Clark et al., 2015; Dehbandi et al., 2017; Kuster et al., 2016; Mentiplay et al., 2015; Reither et al., 2017). A recent study within our laboratory found both sensors to be valid relative to the gold standard of a VMC system when measuring reaching (forward and side) and angular shoulder movements (frontal, transverse, sagittal) (Reither, et al., 2017). Both sensors have also been frequently used within our laboratory for virtual reality (VR)-based motor rehabilitation aimed at improving UE motor abilities of persons with various impairments (Behar et al., 2016; Lauterbach et al., 2013; Mraz et al., 2016; Sevick et al., 2016;).

Reaching is one of the most rigorously researched UE movements due to its involvement in many activities of daily living (ADLs). The kinematics of reaching in populations such as chronic stroke have been investigated in many different studies that often rely on VMC systems (Cirstea & Levin, 2000; Levin et al., 2002). Not only do persons with stroke reach less accurately, slower, and with less motor control, they also utilize trunk flexion earlier and to a greater degree compared to the healthy population (Cirstea & Levin, 2000). Placing objects beyond the arm's length of healthy participants has been found to elicit trunk movement similar to that used by hemiparetic stroke patients reaching to objects within arm's length (Levin et al., 2002). To our knowledge, no previous studies have examined the abilities of both generations of the Kinect sensor for measuring trunk compensation during reaching, and only one existing study has compared their measurement abilities from simultaneous motion capture (Reither et al., 2017). The purpose of this investigation was to establish the validity and reliability of two versions of the Microsoft Kinect for measuring UE and trunk kinematics during different reaching conditions.

2.2 Methods

2.2.1 Participants, Settings, and Procedure

Five healthy participants (3 women and 2 men, mean age 24.8 years) were recruited from the Human Performance Laboratory at the Washington University School of Medicine. All participants gave informed written consent and the study protocol was approved by the university's Institutional Review Board.

Both the K1 and K2 combine standard red-green-blue (RGB) video and an infrared (IR) depth sensor with advanced pattern recognition algorithms to provide full-body, three-dimensional (3D) skeletal motion capture without the use of wearable trackers. Both sensors provide data at approximately 30 frames per second (fps), but the K2 generally boasts improved hardware compared to the K1 (Pagliari & Pinto, 2015) (Table 2.1). The VMC system was considered the gold standard for comparison in this case and consisted of eight IR motion capture cameras (MAC Eagle Digital Cameras, Motion Analysis Corp., Santa Rosa, CA) measuring at 60 fps with a 3D resolution accurate to within one millimeter.

Table 2.1. Comparison of the first generation Microsoft Kinect V1 (K1) and the second generation Kinect V2 (K2). The K2 boasts improved motion sensing hardware.

	Kinect V1	Kinect V2
RGB Camera (pixels)	640 x 480	1920 x 1080
Depth camera (pixels)	640 x 480	512 x 424
Max depth distance (m)	4.0	4.5
Min depth distance (m)	0.8	0.5
Horizontal Field of View (deg)	57	70
Vertical Field of View (deg)	43	60
Skeletal markers	20	26
Possible skeletons tracked	2	6
USB capability	2.0	3.0

Note: RGB = red-green-blue, USB = universal serial bus

Participants performed a set of targeted reaching movements similar to the reaching performance task (Wagner et al., 2008) while simultaneously being measured by the K1, the K2, and an 8-camera VMC system. Each participant was seated on a stool in the center of the VMC capture volume with the K1 and K2 positioned at a midline distance of approximately 2.0m and a height of 1.2m (Reither et al., 2017). Each movement set involved reaching towards a target in the sagittal (forward), scaption (45 degree angle), or frontal (lateral) planes at either a non-extended or extended distance. The non-extended distance was defined relative to each participant's anthropometrics as shoulder height and arm's length, while the extended distance was moved 20cm beyond arm's length (Figure 2.1). This extended reach required a healthy participant to flex the trunk and displace the shoulder to meet the target, similar to compensatory movements employed for reaching by persons with hemiparetic stroke (Levin et al,. 2002). On two different testing days, five repetitions were performed within each of four sets for the three directions and two conditions, resulting in a total of 240 repetitions for each of five participants.

Figure 2.1. An example of a participant reaching towards the target (T) during an extended scaption reach while wearing retroreflective markers.

2.2.2 Analysis Procedure and Statistical Approach

Kinematic data were collected for the K1 and K2 using the Microsoft Kinect for Windows Software Development Kit (SDK v1.8 and v2.0) (Microsoft, 2016), a virtual reality peripheral network (VRPN) server (Suma et al., 2013), and custom software designed in MATLAB (r2012a, Mathworks Inc., Natick, MA). The 3D positions of 11 upper body landmarks for the K1 and K2 were measured relative to each sensor's origin (Figure 2.2). Common landmarks were head, neck, shoulders, elbows, wrists, and hands. The K1 defined torso as the body centroid, while the K2 defined the torso as a mid-spine landmark. Similar data were simultaneously collected for the VMC system using Motion Analysis software (Cortex, Motion Analysis Corp. Santa Rosa, CA) to measure the positions of 25 retroreflective markers placed on bony landmarks on the participant's upper body. Markers were placed on the top of the head (vertex); C7, T10, L5, and S4 vertebrae; sternal notch; xiphoid process; acromions; medial and lateral epicondyles; ulnar and radial styloids; anterior superior iliac spines; dorsal hands; and index fingers. Two redundant markers were placed on the humerus and forearm.
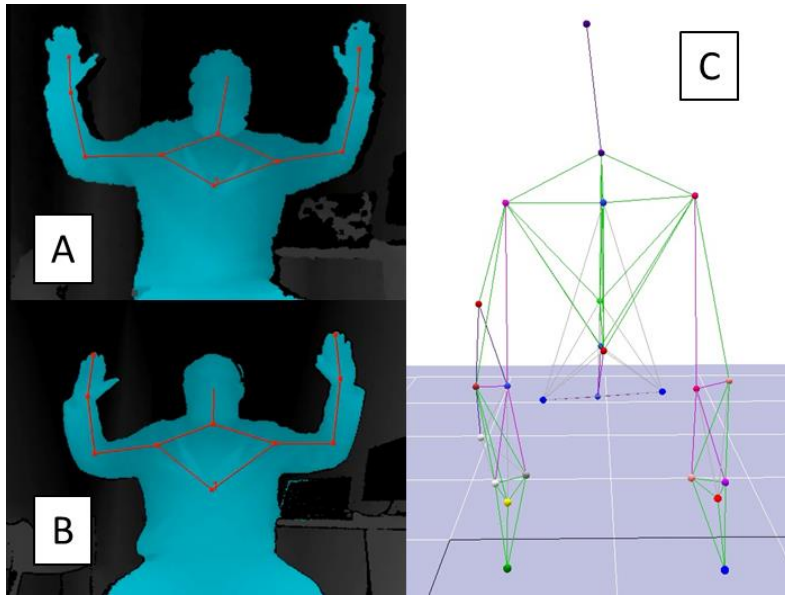
Figure 2.2. Examples of the kinematic body landmarks measured by the K1 (A), K2 (B), and VMC (C). The K1 and K2 measured 11 body landmarks. The VMC measured the position of 25 body landmarks.

Once collected, Kinect data were filtered (6th order, 6Hz Butterworth) and used to create body segment vectors including spine (torso-neck), humerus (shoulder-elbow), and forearm (elbow-wrist/hand). VMC data were similarly filtered (6th order, 6Hz Butterworth), imported into MATLAB, and used to create analogous body landmarks with marker midpoints and biomechanical conventions (Wu et al., 2002). Clinically relevant variables were calculated including reaching range of motion (ROM), planar reaching distance (sagittal and frontal), shoulder flexion and abduction, trunk flexion and lateral flexion, and elbow flexion. Reaching ROM was defined as the Euclidean distance between the shoulder and the hand, while planar reaching distance was defined as the distance traveled by the hand in the sagittal or frontal plane. Shoulder flexion and abduction were defined as the angle between the humerus and spine in the sagittal and frontal planes, respectively. Trunk flexion and lateral flexion were similarly defined as the angle between the spine and the vertical coordinate axis in the sagittal and frontal planes,

32

respectively. Finally, elbow flexion was defined as the angle between the forearm and the humerus.

A peak detection algorithm was used to determine the start and stop of each reach in terms of the maximum and minimum distance of the hand from the target. The target's position was not inherently available from the Kinect data, therefore an estimation was calculated as the average hand position at its maximum Euclidean distance from neutral. The first repetition of each trial was disregarded due to variable starting positions of the arm and hand. Validity was investigated using data from the first testing day to calculate magnitude differences, Pearson's correlations (r), and an analysis of variance (ANOVA) with Bonferroni corrections across sensors. Reliability was investigated using averages within each testing day to calculate magnitude differences, intraclass correlations (ICC), Bland-Altman plots with 95% limits of agreement (LOA), and paired t-tests between days (Berchtold, 2016; Bland & Altman, 1986). Estimates of correlations in terms of r and ICC were evaluated as excellent (0.75-1), modest (0.4-0.74), or poor (0-0.39) (Fleiss, 2011).

2.3 Results

For trunk flexion and trunk lateral flexion, the K2 was closer in magnitude to the VMC than was the K1 in all directions and for both non-extended and extended reaches (Figure 2.3 and Figure 2.4). For trunk flexion, on average, the K2 was within 3.7° and the K1 was within 9.5° of the VMC. For lateral flexion, the K2 was within 2.8° and the K1 was within 7.8° of the VMC (Table 2.2).

Figure 2.3. Trunk flexion differences between the K1 and VMC (K1-VMC) and K2 and VMC (K2-VMC) for each reaching direction and extent. The K2 is closer in magnitude to the VMC than is the K1 when measuring trunk flexion for all reaching conditions.

Figure 2.4. Trunk lateral flexion differences between the K1 and VMC (K1-VMC) and K2 and VMC (K2-VMC) for each reaching direction and extent. The K2 is closer in magnitude to the VMC than is the K1 when measuring trunk lateral flexion for all reaching conditions.
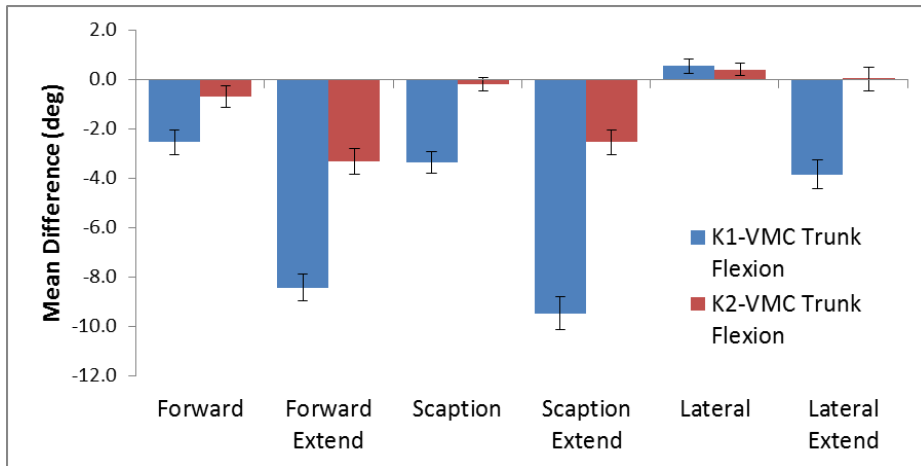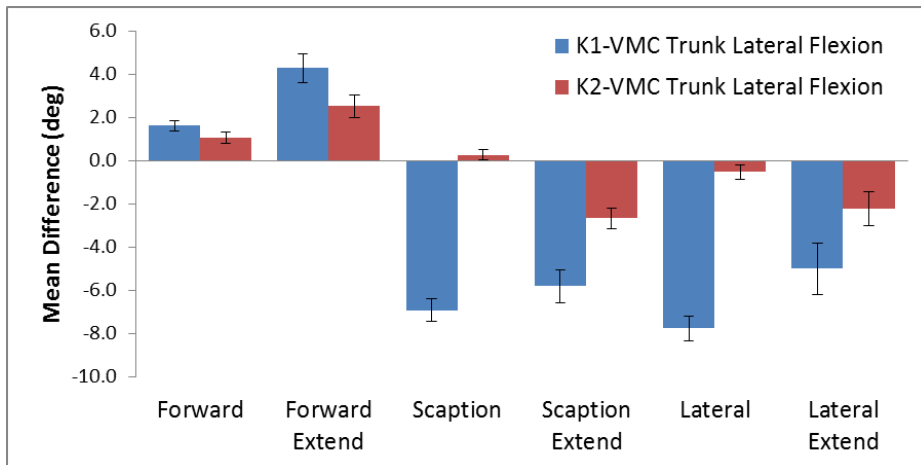
34

Table 2.2. Mean (± SD) magnitudes for the K1, K2, and VMC for all movements on the two different testing days.

	Day 1			Day 2		
	K1	K2	VMC	K1	K2	VMC
Forward						
Reaching ROM (cm)	43.9 ± 11.6*	49.2 ± 15.7*	32.7 ± 14.0	36.3 ± 13.2	42.1 ± 19.6	25.4 ± 17.3
Sagittal reach distance (cm)	49.2 ± 4.4	54.0 ± 12.2	42.0 ± 6.1	45.4 ± 6.5	49.5 ± 14.9	41.1 ± 6.6
Shoulder flexion (deg)	77.7 ± 7.5*	77.6 ± 6.9*	60.8 ± 6.1	83.0 ± 10.7	74.7 ± 9.0	62.9 ± 5.3
Trunk flexion (deg)	-2.2 ± 0.9	-0.4 ± 0.8	0.4 ± 1.3	-2.7 ± 1.2	-0.2 ± 0.6	0.2 ± 1.5
Trunk lateral flexion (deg)	0.6 ± 0.5*	0.0 ± 0.4	-1.1 ± 0.7	0.6 ± 0.5	-0.1 ± 0.4	-1.2 ± 1.2
Elbow flexion (deg)	110.1 ± 43.6	104.4 ± 38.1	86.9 ± 29.5	93.2 ± 45.8	86.0 ± 43.8	69.0 ± 33.0
Forward Extend						
Reaching ROM (cm)	37.5 ± 18.3	52.2 ± 19.4*	30.3 ± 13.7	34.5 ± 16.5	51.5 ± 16.8	26.7 ± 15.4
Sagittal reach distance (cm)	58.6 ± 12.8	72.7 ± 14.2	62.6 ± 6.9	57.7 ± 12.3	72.2 ± 15.9	61.0 ± 9.4
Shoulder flexion (deg)	88.5 ± 9.5	102.3 ± 9.0*	81.7 ± 7.2	87.8 ± 15.4	96.1 ± 17.2	78.8 ± 9.0
Trunk flexion (deg)	10.3 ± 2.7*	15.0 ± 3.5	18.7 ± 3.0	11.7 ± 1.6	17.9 ± 2.9	21.7 ± 3.5
Trunk lateral flexion (deg)	0.9 ± 1.8*	-0.9 ± 1.4	-3.7 ± 2.5	1.0 ± 2.1	-0.9 ± 2.3	-4.2 ± 5.7
Elbow flexion (deg)	109.3 ± 44.7	111.3 ± 45.2	87.9 ± 29.3	99.4 ± 42.0	97.2 ± 43.0	73.9 ± 32.1
Scaption						
Reaching ROM (cm)	39.1 ± 14.4	37.3 ± 16.7	33.3 ± 15.5	34.5 ± 13.4	30.6 ± 17.8	27.8 ± 17.3
Sagittal reach distance (cm)	25.0 ± 5.9	26.8 ± 11.6	24.0 ± 6.0	25.9 ± 5.1	23.4 ± 11.6	24.0 ± 5.0
Frontal reach distance (cm)	42.9 ± 7.5*	45.2 ± 10.4	37.8 ± 6.5	37.9 ± 7.5	39.2 ± 10.2	34.3 ± 5.5
Shoulder flexion (deg)	65.9 ± 12.3*	57.7 ± 9.9*	41.4 ± 11.6	67.4 ± 7.9	61.1 ± 6.5	46.3 ± 5.4
Shoulder abduction (deg)	52.8 ± 17.2*	55.2 ± 13.5*	36.1 ± 11.4	57.7 ± 11.1	60.1 ± 9.9	37.0 ± 6.8
Trunk flexion (deg)	-3.4 ± 1.0*	-0.2 ± 0.7	0.0 ± 0.8	-3.7 ± 1.2	-0.2 ± 0.6	0.3 ± 1.1
Trunk lateral flexion (deg)	-7.3 ± 1.5*	-0.1 ± 0.5	-0.4 ± 0.8	-6.6 ± 1.8	-0.1 ± 0.5	-0.3 ± 0.9
Elbow flexion (deg)	112.1 ± 44.7	101.1 ± 42.4	88.2 ± 33.3	95.0 ± 46.4	82.9 ± 41.6	74.4 ± 34.0
Scaption Extend						
Reaching ROM (cm)	36.6 ± 14.6	40.5 ± 17.8*	31.8 ± 14.5	28.3 ± 16.8	31.5 ± 19.3	24.7 ± 17.8
Sagittal reach distance (cm)	30.4 ± 6.3	37.3 ± 11.2	37.8 ± 7.3	31.3 ± 6.5	34.3 ± 11.6	38.8 ± 5.3
Frontal reach distance (cm)	47.4 ± 14.2	54.6 ± 14.9	51.2 ± 9.3	42.7 ± 11.0	48.6 ± 13.5	46.1 ± 7.4
Shoulder flexion (deg)	72.0 ± 8.7	88.9 ± 7.6*	62.1 ± 7.5	72.2 ± 8.1	87.8 ± 5.0	65.1 ± 6.9
Shoulder abduction (deg)	66.7 ± 11.0*	86.3 ± 8.9*	58.5 ± 7.3	68.2 ± 4.8	87.6 ± 7.4	57.5 ± 7.2
Trunk flexion (deg)	5.5 ± 1.4*	12.5 ± 2.5	15.0 ± 2.8	6.2 ± 1.8	13.1 ± 2.5	15.1 ± 4.9
Trunk lateral flexion (deg)	10.2 ± 1.7*	13.4 ± 2.4*	16.0 ± 3.5	10.8 ± 3.1	13.3 ± 3.5	15.9 ± 3.9
Elbow flexion (deg)	107.4 ± 44.9	108.8 ± 42.7	88.6 ± 32.6	85.7 ± 48.6	86.4 ± 46.5	72.0 ± 36.6
Lateral						
Reaching ROM (cm)	25.6 ± 16.0	27.7 ± 16.8	29.0 ± 16.7	23.3 ± 14.0	22.6 ± 16.5	27.4 ± 17.9
Frontal hand distance (cm)	49.7 ± 10.8	57.8 ± 12.6	51.6 ± 5.4	44.6 ± 10.2**	50.9 ± 14.9**	47.1 ± 7.5
Shoulder abduction (deg)	51.3 ± 12.2	53.1 ± 10.5*	42.6 ± 10.3	49.3 ± 12.0	49.5 ± 12.7	39.2 ± 9.6
Trunk flexion (deg)	0.3 ± 0.9	0.2 ± 0.7	-0.2 ± 0.7	0.4 ± 0.9	0.0 ± 0.3**	0.0 ± 0.6
Trunk lateral flexion (deg)	-7.8 ± 1.3*	-0.6 ± 0.9	0.0 ± 1.4	-7.7 ± 2.5	-0.5 ± 0.6	-0.5 ± 0.9
Elbow flexion (deg)	91.1 ± 48.4	91.6 ± 44.5	79.2 ± 35.9	84.8 ± 48.8	80.2 ± 42.9	72.9 ± 36.6
Lateral Extend						
Reaching ROM (cm)	13.1 ± 14.8*	23.7 ± 16.1	25.2 ± 15.4	13.8 ± 17.3	20.5 ± 18.2	24.5 ± 18.1
Frontal hand distance (cm)	55.7 ± 13.1*	69.9 ± 14.9	69.4 ± 7.6	52.6 ± 15.2	65.2 ± 19.6	65.5 ± 11.8
Shoulder abduction (deg)	77.4 ± 8.5	88.5 ± 9.2*	72.9 ± 9.4	72.1 ± 10.3	81.0 ± 11.4	67.4 ± 11.5
Trunk flexion (deg)	0.0 ± 2.2*	3.8 ± 3.0	3.8 ± 3.1	-0.8 ± 1.3	2.5 ± 2.7	2.9 ± 2.8
Trunk lateral flexion (deg)	18.9 ± 3.9	21.7 ± 3.4	23.9 ± 4.6	18.4 ± 4.9	20.5 ± 3.8	22.1 ± 6.4
Elbow flexion (deg)	87.5 ± 48.4	93.6 ± 42.6	77.3 ± 32.4	81.3 ± 51.6	86.9 ± 46.6	73.2 ± 36.3

*p < 0.05 for Bonferonni-corrected pairwise t-test between Kinect and VMC

**p < 0.05 for paired t-test between testing days

The K2 was more valid than the K1 for measuring trunk movements during extended reaches (Table 2.3). The K2 showed excellent agreement with the VMC for measuring trunk flexion (r = 0.77-0.88) and lateral flexion (r = 0.77-0.89) during extended reaches. The K1 showed moderate-excellent agreement with the VMC for trunk flexion (r = 0.52-0.78) and moderate agreement for lateral flexion (r = 0.50-0.60) during extended reaches. For non-extended reaches, the K2 showed only moderate agreement (r = 0.43) for measuring trunk flexion during lateral reaching. All other correlations were poor for both the K1 and K2.

Table 2.3. Validity measured by Pearson's correlations (r) between the K1 and VMC and the K2 and VMC.

	Forward		Scaption		Lateral	
	K1	K2	K1	K2	K1	K2
Non-Extended						
Reaching ROM (cm)	0.93*	0.95*	0.94*	0.94*	0.94*	0.94*
Sagittal reach distance (cm)	0.60*	0.79*	0.75*	0.81*	-	-
Frontal reach distance (cm)	-	-	0.93*	0.97*	0.92*	0.94*
Shoulder flexion (deg)	0.19	0.31*	0.82*	0.82*	-	-
Shoulder abduction (deg)	-	-	0.97*	0.97*	0.88*	0.96*
Trunk flexion (deg)	-0.19	0.11	-0.44*	0.17	-0.3	0.21
Trunk lateral flexion (deg)	0.25*	0.10	-0.36*	0.20	-0.23*	0.43*
Elbow flexion (deg)	0.95*	0.94*	0.97*	0.99*	0.96*	0.99*
Extended						
Reaching ROM (cm)	0.95*	0.88*	0.90*	0.98*	0.90*	0.95*
Sagittal reach distance (cm)	0.91*	0.82*	0.67*	0.84*	-	-
Frontal reach distance (cm)	-	-	0.97*	0.96*	0.94*	0.95*
Shoulder flexion (deg)	0.23*	0.23	0.43*	0.74*	-	-
Shoulder abduction (deg)	-	-	0.92*	0.94*	0.72*	0.89*
Trunk flexion (deg)	0.78*	0.88*	0.52*	0.77*	0.72*	0.83*
Trunk lateral flexion (deg)	0.51*	0.77*	0.60*	0.89*	0.50*	0.78*
Elbow flexion (deg)	0.98***	0.97*	0.96*	0.98*	0.99*	0.99*

p < 0.05 for Pearson's correlation between Kinect and VMC

Reliability results were mixed for all three sensors when measuring the trunk (Table 2.4). The K2 showed excellent reliability for measuring trunk flexion during lateral reaching (ICC = 0.83), but poor-modest reliability for trunk flexion and lateral flexion in all other reach directions

(ICC = -0.67-0.71). The K1 showed modest-excellent reliability (ICC = 0.45-0.79) for trunk

measurements during all reaches except forward. The VMC showed mixed results similar to K2,

with poor-excellent reliability in the forward direction (ICC = -0.38-0.87), poor-excellent

reliability in the scaption direction (ICC = 0.04-0.80), and modest reliability in the lateral

direction (ICC = 0.54-0.69). Bland-Altman plots mirrored these results with small mean

differences between days for all three sensors, with the K1 generally showing wider variability

between days (Figures 2.5-2.7).

Table 2.4. Reliability values measured by intra-class correlation coefficients (ICC) between testing days
for each of the sensors.

	Forward			Scaption			Lateral		
	K1	K2	VMC	K1	K2	VMC	K1	K2	VMC
Non-Extended									
Reaching ROM (cm)	0.40	0.78	0.64	0.78	0.69	0.72	0.97	0.93	0.99
Sagittal reach distance (cm)	0.36	0.86	0.70	0.41	0.58	0.59	-	-	-
Frontal reach distance (cm)	-	-	-	0.59	0.63	0.62	0.87	0.88	0.73
Shoulder flexion (deg)	0.18	-0.46	-0.13	0.33	-0.20	-0.08	-	-	-
Shoulder abduction (deg)	-	-	-	0.39	0.39	0.72	0.98	0.87	0.92
Trunk flexion (deg)	0.16	0.04	0.87	0.60	0.26	0.80	0.75	0.54	0.54
Trunk lateral flexion (deg)	0.21	0.06	0.63	0.54	0.62	0.22	0.75	0.70	0.68
Elbow flexion (deg)	0.60	0.70	0.58	0.62	0.57	0.67	0.99	0.94	0.97
Extended									
Reaching ROM (cm)	0.90	0.96	0.89	0.74	0.62	0.70	0.94	0.92	0.97
Sagittal reach distance (cm)	0.81	0.97	0.66	0.48	0.50	0.64	-	-	-
Frontal reach distance (cm)	-	-	-	0.85	0.77	0.54	0.94	0.94	0.85
Shoulder flexion (deg)	-0.39	0.08	-0.48	0.09	-0.83	-0.88	-	-	-
Shoulder abduction (deg)	-	-	-	-0.29	-0.30	0.19	0.35	0.50	0.79
Trunk flexion (deg)	0.59	-0.67	-0.38	0.59	0.49	0.59	0.46	0.83	0.69
Trunk lateral flexion (deg)	0.77	0.71	0.48	0.45	0.11	0.04	0.79	0.67	0.56
Elbow flexion (deg)	0.89	0.84	0.84	0.69	0.60	0.69	0.95	0.96	0.94
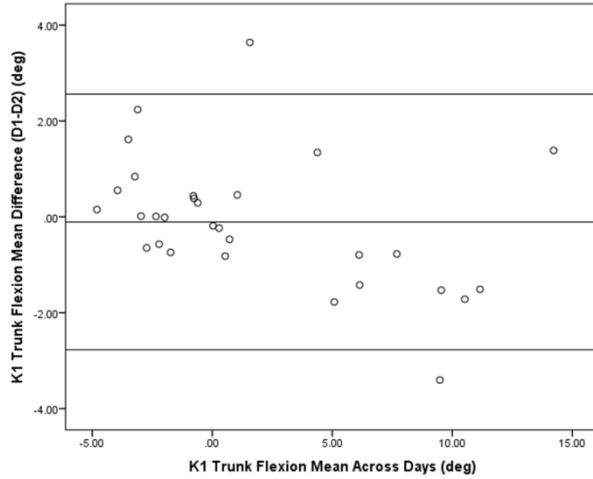
Figure 2.5. Bland-Altman plot for K1 trunk flexion including both non-extended and extended reaches across both testing days.
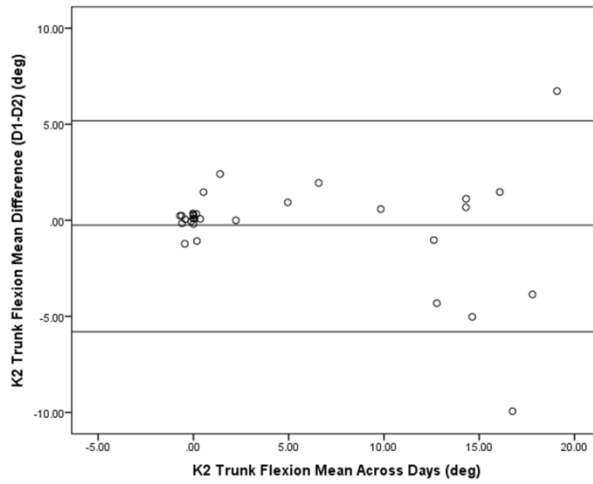
Figure 2.6. Bland-Altman plot for K2 trunk flexion including both non-extended and extended reaches across both testing days.
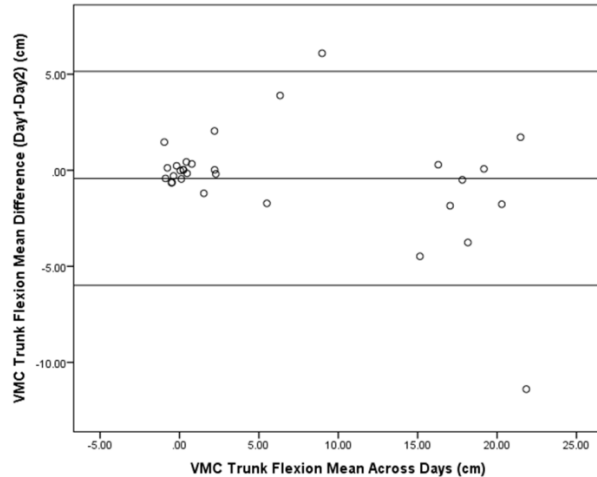
Figure 2.7. Bland-Altman plot for VMC trunk
flexion including both non-extended and extended
reaches across both testing days.

The movement signals for the three planar reaching conditions (i.e., sagittal, scaption,

frontal) illustrate the abilities of the Kinects to match the VMC (gold standard) results (Figure

2.8). Magnitude discrepancies between sensors for reaching ROM and planar distance were

largest during forward, reduced during scaption, and least during lateral reaching (Table 2.2).

Reaching ROM, planar reach distance, and elbow flexion measurements consistently showed

excellent validity for the K2 (r = 0.79-0.99) and moderate-excellent validity for the K1 (r = 0.60-

0.95) (Table 2.4). Reliability of these measurements was moderate-excellent for all three

sensors, with the exception of the K1 measuring planar reach distance in the forward direction

(ICC = 0.36) (Table 2.5). Shoulder flexion and abduction showed moderate-excellent validity

for the K2 (r = 0.74-0.96) and K1 (r = 0.43-0.97) in all directions but forward. Reliability of

shoulder measurements ranged from poor-excellent for all sensors.

39
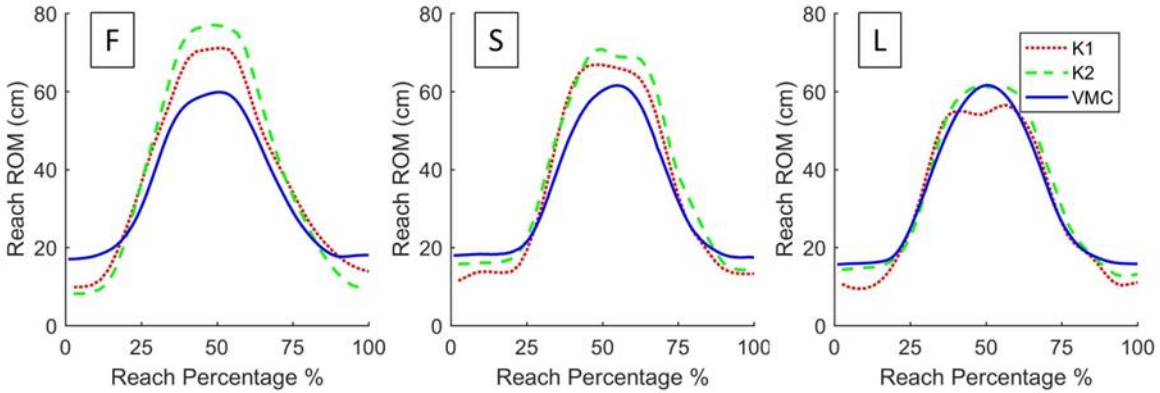
Figure 2.8. Three sets of curves showing reach ROM from start to stop of a typical reaching movement. The left curve (F) represents a forward reach, the middle curve (S) represents a scaption reach, and the right curve (L) represents a lateral reach. Curves for the K1, K2, and VMC are shown separately (see legend). The mean difference in reaching ROM between K1-VMC and K2-VMC is greatest during forward movements, reduced during scaption movements, and least during lateral movements.

2.4 Discussion

The purpose of this investigation was to establish the validity and reliability of two versions of the Microsoft Kinect for measuring upper extremity and trunk kinematics during various reaching conditions. Specifically, participants were asked to perform both a standard and extended reach in each of three directions (forward, scaption, lateral) while their movements were recorded by the K1, K2, and the gold-standard VMC simultaneously. The K2 measured the trunk more similarly to the VMC as shown by smaller average magnitude differences in trunk flexion and lateral flexion. Validity results for trunk measurement were excellent for the K2 and modest-excellent for the K1 during extended reaching conditions intended to mimic movements that might be used by persons with chronic stroke. Reliability for trunk measurement was modest-excellent for extended reaching with the K1, with the exception of the forward direction, but varied from poor-excellent for the K2. Results for both sensors were generally excellent for measuring arm and hand displacement, excellent for measuring elbow flexion, and adequate for shoulder measurement, especially when reaching in the scaption or lateral directions.

40

The results of this study are supported by previous research that examines the K1 and K2 in terms of functional movements. Bonnechere and colleagues (2013) found similar validity results when comparing the K1 to a VMC system during the performance of four functional movements including shoulder abduction (similar to lateral reaching) and elbow flexion (similar to forward reaching) (Bonnechere et al., 2013). Clark and colleagues (2015) found the K2 to have excellent concurrent validity for measuring trunk movements during dynamic balance tasks and anterior-posterior movements, but poor-moderate validity for static tasks and medial-lateral movements. In the current investigation, the K2 similarly shows the greatest validity for measuring trunk flexion during an extended movement in the anterior-posterior direction (Clark et al., 2015). Reither et al., (2017) found similar results while measuring the K1, K2, and VMC simultaneously with a single participant reaching forward, reaching to the side, and performing shoulder movements in various planes, but did not investigate trunk kinematics during such movements (Reither et al., 2017).

We found several low and negative reliability (ICC) values (Table 2.2), particularly for shoulder flexion, shoulder abduction, trunk flexion, and trunk lateral flexion during non-extended reaching in the forward and scaption directions for all sensors including VMC. Negative ICC values are not ideal and can often be attributed to low between-subjects variance in the phenomenon being measured (McGraw & Wong, 1996). Accordingly, these results might be due to small between-day variance in the kinematic variables being tested. For example, during extended forward reaching, the mean difference for shoulder flexion between days is only 0.7 degrees for K1, 6.2 degrees for K2, and 3.0 degrees for VMC. While repeatability of movement and measurement within 6.2 degrees is satisfactorily accurate, the small and nonsystematic variance may drive the ICC statistic to spuriously low and negative values. A

more heterogeneous clinical population may also improve correlation results by increasing variance in the sample.

Other variations in results might be attributed to various study limitations. First, the Kinect SDK uses a tracking algorithm that does not rely on the specific placement of markers on palpable bony landmarks as does the VMC. While this is convenient for users, it has been previously noted as a limitation in the Kinect's ability to accurately measure kinematics of movement due to variable body segment lengths; however, previous studies have developed algorithms through regression that may be able to correct for this during real-time tracking (Bonnechere et al., 2014). Second, it was clear through both observation and the relatively high standard deviations attributed to each movement (Table 2.2) that different strategies were used for reaching by participants. No neutral starting point was defined a priori, and some participants returned their arm to their lap between repetitions while others remained in a flexed position. This resulted in large variations in range of motion, namely elbow flexion. Finally, reliability results varied inconsistently for all three sensors, and it should be noted that, on top of statistical limitations, there are inter-individual differences across trials and across days in each participant's kinematics of reaching. Participants were given similar instructions on both testing days, but differences in the repeatability of human movement yet exist and may be attributable to the slight variance in between-day correlation and significance testing.

This study shows that the K1 and K2 may serve as useful tools for objectively measuring upper extremity and trunk kinematics, but application may depend on the body segment, joint, and movement plane of interest. Very few studies have investigated their measurement properties, but both sensors are widely employed as the basis for virtual reality (VR)-based interventions for persons with motor impairments including stroke and cerebral palsy

42

(Lauterbach et al., 2013; Sevick et al., 2016). Use of such interventions continues to grow along with client interest, professional knowledge, and technological accessibility (Laver et al., 2015). The current investigation may inform future VR development, namely the inclusion of real-time measurement of trunk compensations using the K2.

2.5 Conclusions

In conclusion, the K1 and K2 have been shown to be valid and reliable for measurement of some aspects of upper extremity kinematics during reaching. In particular, the K2 exhibited slightly better characteristics for measuring the trunk during standard and extended reaching in different directions, and may be recommended over the K1 in future development for purposes of measuring trunk compensation in clinical populations.

2.6 References

Alaverdashvili, M., Foroud, A., Lim, D. H., & Whishaw, I. Q. (2008). "Learned baduse" limits recovery of skilled reaching for food after forelimb motor cortex stroke in rats: a new analysis of the effect of gestures on success. *Behavioural brain research*, 188(2), 281-290.

Behar, C., Lustick, M., Foreman, M. H., Webb, J., & Engsberg, J. R. (2016). Personalized Virtual Reality for Upper Extremity Rehabilitation: Moving from the Clinic to a Home Exercise Program. *Journal of Intellectual Disability-Diagnosis and Treatment*, *4*(3), 160-169.

Berchtold, A. (2016). Test–retest: Agreement or reliability?. Methodological Innovations, 9, 2059799116672875.

Bland, J. M., & Altman, D. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *The lancet*, *327*(8476), 307-310.

Bonnechère, B., Jansen, B., Salvia, P., Bouzahouene, H., Omelina, L., Cornelis, J., ... & Jan, S. V. S. (2013). Can the kinectTM sensors be used for motion analysis?. *Transaction on Electrical and Electronic Circuits and Systems*, 4(1).

Bonnechere, B., Jansen, B., Salvia, P., Bouzahouene, H., Omelina, L., Moiseev, F., ... & Jan, S. V. S. (2014). Validity and reliability of the Kinect within functional assessment activities: comparison with standard stereophotogrammetry. *Gait & posture, 39*(1), 593-598.

Cirstea, M. C., & Levin, M. F. (2000). Compensatory strategies for reaching in stroke. *Brain*, *123*(5), 940-953.

Clark, R. A., Pua, Y. H., Fortin, K., Ritchie, C., Webster, K. E., Denehy, L., & Bryant, A. L. (2012). Validity of the Microsoft Kinect for assessment of postural control. Gait & posture, 36(3), 372-377.

Clark, R. A., Pua, Y. H., Oliveira, C. C., Bower, K. J., Thilarajah, S., McGaw, R., ... & Mentiplay, B. F. (2015). Reliability and concurrent validity of the Microsoft Xbox One Kinect for assessment of standing balance and postural control. *Gait & posture*, *42*(2),

Dehbandi, B., Barachant, A., Smeragliuolo, A. H., Long, J. D., Bumanlag, S. J., He, V., ... & Putrino, D. (2017). Using data from the Microsoft Kinect 2 to determine postural stability in healthy subjects: A feasibility trial. *PloS one, 12*(2), e0170890.

Desrosiers, J., Noreau, L., Rochette, A., Bourbonnais, D., Bravo, G., & Bourget, A. (2006). Predictors of long-term participation after stroke. Disability and rehabilitation, 28(4), 221-230.

Fleiss, J. L. (2011). *Design and analysis of clinical experiments* (Vol. 73). John Wiley & Sons.

Fugl-Meyer, A. R., Jääskö, L., Leyman, I., Olsson, S., & Steglind, S. (1974). The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. *Scandinavian journal of rehabilitation medicine*, *7*(1), 13-31.

Galna, B., Barry, G., Jackson, D., Mhiripiri, D., Olivier, P., & Rochester, L. (2014). Accuracy of the Microsoft Kinect sensor for measuring movement in people with Parkinson's disease. *Gait & posture*, *39*(4), 1062-1068.

Huber, M. E., Seitz, A. L., Leeser, M., & Sternad, D. (2015). Validity and reliability of Kinect skeleton for measuring shoulder joint angles: a feasibility study. *Physiotherapy*, 101(4), 389-393.

Kuster, R. P., Heinlein, B., Bauer, C. M., & Graf, E. S. (2016). Accuracy of KinectOne to quantify kinematics of the upper body. *Gait & posture*, 47, 80-85.

Lauterbach, S. A., Foreman, M. H., & Engsberg, J. R. (2013). Computer games as therapy for persons with stroke. *Games for Health: Research, Development, and Clinical Applications*, *2*(1), 24-28.

Laver, K. E., George, S., Thomas, S., Deutsch, J. E., & Crotty, M. (2015). Virtual reality for stroke rehabilitation. *The Cochrane Library*.

Levin, M. F., Michaelsen, S. M., Cirstea, C. M., & Roby-Brami, A. (2002). Use of the trunk for reaching targets placed within and beyond the reach in adult hemiparesis. *Experimental brain research*, *143*(2), 171-180.

Levin, M. F., Kleim, J. A., & Wolf, S. L. (2009). What do motor "recovery" and "compensation" mean in patients following stroke?. *Neurorehabilitation and neural repair*, *23*(4), 313-319.

Lyle, R. C. (1981). A performance test for assessment of upper limb function in physical rehabilitation treatment and research. *International Journal of Rehabilitation Research*, *4*(4), 483-492.

McGraw, K. O., & Wong, S. P. (1996). Forming inferences about some intraclass correlation coefficients. *Psychological methods*, *1*(1), 30.

Mentiplay, B. F., Clark, R. A., Mullins, A., Bryant, A. L., Bartold, S., & Paterson, K. (2013). Reliability and validity of the Microsoft Kinect for evaluating static foot posture. Journal of foot and ankle research, 6(1), 14.

Microsoft Corporation (2016). The Microsoft Kinect Software Development Kit SDK v2.0, Redmond, WA; 2015. http://www.microsoft.com/en-us/download/details.aspx?id=

Mraz, K., Eisenberg, G., Diener, P., Amadio, G., Foreman, M. H., & Engsberg, J. R. (2016). The Effects of Virtual Reality on the Upper Extremity Skills of Girls with Rett Syndrome: A Single Case Study. *Journal of Intellectual Disability-Diagnosis and Treatment*, *4*(3), 152-159.

Olsen, T. S. (1990). Arm and leg paresis as outcome predictors in stroke rehabilitation. *Stroke, 21*(2), 247-251.

Pagliari, D., & Pinto, L. (2015). Calibration of kinect for xbox one and comparison between the two generations of Microsoft sensors. *Sensors*, *15*(11), 27569-27589.

Reither, L. R., Foreman, M. H., Migotsky, N., Haddix, C., & Engsberg, J. R. (2017). Upper extremity movement reliability and validity of the Kinect version 2. *Disability and Rehabilitation: Assistive Technology*, 1-9.

Roby-Brami, A., Feydy, A., Combeaud, M., Biryukova, E. V., Bussel, B., & Levin, M. F. (2003). Motor compensation and recovery for reaching in stroke patients. *Acta neurologica scandinavica*, *107*(5), 369-381.

Sevick, M., Eklund, E., Mensch, A., Foreman, M., Standeven, J., & Engsberg, J. (2016). Using free internet videogames in upper extremity motor training for children with cerebral palsy. *Behavioral Sciences*, *6*(2), 10.

Suma, E. A., Krum, D. M., Lange, B., Koenig, S., Rizzo, A., & Bolas, M. (2013). Adapting user interfaces for gestural interaction with the flexible action and articulated skeleton toolkit. *Computers & Graphics*, *37*(3), 193-201.

Wagner, J. M., Rhodes, J. A., & Patten, C. (2008). Reproducibility and minimal detectable change of three-dimensional kinematic analysis of reaching tasks in people with hemiparesis after stroke. *Physical therapy*, *88*(5), 652.

Wolf, S. L., Catlin, P. A., Ellis, M., Archer, A. L., Morgan, B., & Piacentino, A. (2001). Assessing Wolf motor function test as outcome measure for research in patients after stroke. *Stroke*, *32*(7), 1635-1639.

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., ... & Schmid, O. (2002). ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip, and spine. *Journal of biomechanics*, *35*(4), 543-548.

Yeung, L. F., Cheng, K. C., Fong, C. H., Lee, W. C., & Tong, K. Y. (2014). Evaluation of the Microsoft Kinect as a clinical assessment tool of body sway. *Gait & posture*, *40*(4), 532-538.

Chapter 3: A Virtual Reality System for Measuring and Shaping Trunk Compensation for Persons with Stroke: Design and Initial Feasibility Testing

This chapter is in preparation:

Abstract

Background: Hemiparesis is a prevalent post-stroke disorder, and yet few existing interventions achieve the amount of repetitive task practice required for motor improvement with the upper extremity (UE). Compensatory movement, such as flexing the trunk during reaching, may negatively affect gains that can be made as a result of intervention. Shaping, or incrementally decreasing, the amount of compensation used during UE therapy may be a viable strategy that can be integrated into existing methods involving virtual reality (VR).

Methods: A VR tool, VRShape, was designed to (1) monitor movement kinematics in real time using an accessible motion sensor (Microsoft Kinect V2), (2) convert UE movements into control of numerous virtual environments (VEs) and computer games, and (3) provide feedback about trunk movements to shape compensation. This system was tested for feasibility by a small cohort of participants with chronic stroke (n=5). Participants used the system for a short 1-hour session, during which feedback was provided concerning trunk movements beyond individualized thresholds. Outcomes related to repetitions, compensation, movement kinematics, usability, motivation, and sense of presence were collected.

Results: Participants achieved a very high dose of reaching repetitions (461±184), with an average of 75% of repetition attempts involving excessive compensatory trunk flexion. Participants rated the system as highly usable, motivating, engaging, and safe, but found that it provided a moderate level of sense of presence and ecological validity.

Conclusions: VRShape is feasible to use as a tool for increasing repetition rates, measuring and shaping compensation, and enhancing motivation for UE therapy. Future research should focus on software improvements and investigation of efficacy over the course of a VR-based intervention for persons with stroke.

3.1 Background

Hemiparesis is the most common motor deficit resulting from stroke, with approximately 55% to75% of stroke survivors living with the condition and its associated reduced quality of life (Olsen et al., 1990). Resulting long-term impairments to strength, motor control, and range of motion (ROM) in the upper extremity (UE) can make it difficult for many stroke survivors to adequately perform important activities or participate in the flow of daily life (Lai et al., 2002).

Rehabilitation strategies for persons with hemiparetic stroke rely on principles of neuroplasticity that state thousands of specific, intense, task-oriented movement repetitions must be performed to drive reorganization of cortical motor function from injured to healthy areas of the brain (Kleim & Jones, 2008). Many physical and occupational therapy interventions capitalize on this tenet of motor learning to target improvements in post-stroke motor function. For example, constraint-induced movement therapy (CIMT) has been shown to improve motor function as a result of restraining the unimpaired arm and forcing large doses of repetitive practice with the paretic arm (Taub et al., 1994). However, such intense protocols are often impossible in typical rehabilitation settings due to time constraints, funding limitations, and client noncompliance (Jutai et al., 2003); this is reflected in recent research that suggests typical outpatient therapy sessions achieve very few movement repetitions relative to the dose required for salient motor learning (Lang et al., 2007).

Furthermore, few current interventions acknowledge that two competing mechanisms of functional motor improvement may be occurring simultaneously: motor recovery and compensation. True motor recovery refers to the reacquisition of pre-stroke movement patterns and motor skills, while compensation refers to the substitution of novel movement patterns or skills to complete tasks (Levin et al., 2009). Common compensatory strategies involve excessive

flexion and rotation at the trunk to move the hand into position during reaching (Cirstea & Levin, 2000; Levin et al., 2002). The extreme case of maladaptive compensation is "learned non-use," defined when a person learns to solely perform tasks with the unimpaired arm (Taub et al., 1994). While motor recovery is the ideal goal of most post-stroke treatments, in fact, compensatory strategies are often prescribed in lieu of normal motor functioning. It is hypothesized that frequent use of such compensations, or "learned bad-use," may lead to long-term chronic pain in overused joints and suboptimal motor recovery in the impaired arm due to limited repetitive practice (Alaverdashvili et al., 2008; Allred et al., 2010; Levin et al., 2009). While a paucity of evidence exists, many interventions, including CIMT, are suspected of inadvertently teaching compensatory strategies instead of promoting true motor recovery in persons with stroke (Kitago et al., 2013).

Virtual reality (VR) has emerged as a prominent tool for addressing some shortcomings in current motor rehabilitation strategies. VR is defined as a human-computer interface that allows a user to interact with a virtual environment (VE) through physical movement (Holden, 2005). Contemporary research has shown that VR-based therapy can elicit very large doses of movement repetitions and similar, sometimes superior, improvements in UE motor impairment, function, and activity performance relative to no therapy or conventional therapy (Henderson et al., 2007; Laver et al., 2015; Lohse et al., 2014). The most recent Cochrane review included 37 randomized controlled trials involving over 1,000 participants with stroke and concluded that VR use can significantly improve UE motor function and performance of activities of daily living (ADLs) in persons with chronic stroke (Laver et al., 2015). VR has also been found efficacious for improving mobility, gait, and balance for persons with stroke (Corbetta et al., 2015; Darekar et al., 2015). The primary advantages of VR are related to objective measurement, immediate

feedback, and high user motivation that may improve aspects of motor learning and subsequent true motor recovery when combined with principles of neuroplasticity (Levin et al., 2015). Importantly, VR systems may also be able to capitalize on advancements in motion capture technology to measure compensation during repetitive practice with the impaired arm in the hopes of further enhancing motor outcomes for persons with stroke.

We have previously successfully applied a VR-based motor therapy strategy that incorporates the Microsoft Kinect sensor (Microsoft Corp., Redmond, WA), customizable software, and freely available virtual environments (VEs) and computer games to different populations with motor deficits including chronic stroke, children with cerebral palsy (CP), and children with Rett syndrome. In a small observational study of persons with stroke (n=5), we found that the first generation Kinect (V1) and the Flexible and Articulated Skeleton Toolkit (FAAST) can be used to create intense and motivating motor therapy (Lauterbach et al., 2013; Suma et al., 2013). In case studies involving persons with stroke (n=2), we found that this strategy was feasible and capable of improving functional and occupational performance through use in a clinical setting and as a home exercise program (Behar et al., 2016). In a case series of children with CP (n=5), we found that this same strategy could be transitioned from in-laboratory to in-home therapy over the course of 12 weeks, was highly customizable and usable with as many as 26 different VEs, and was capable of facilitating improvement in some aspects of UE movement kinematics and function (Sevick et al., 2016). In a case study of a single person with Rett syndrome, we found that this strategy could improve performance of self-care activities and decrease stereotypical hand movements by facilitating an increase in the number of targeted reaches performed during therapy (Mraz et al., 2016).

None of our previous work has investigated the use of compensation during repetitive practice of UE tasks, and yet the excessive use of compensation may affect the amount of motor recovery that can be achieved. Those existing interventions that do address compensation typically restrain it completely through the use of physical restraints or static feedback (Michaelsen et al., 2006; Subramanian et al., 2013; Thielman et al., 2008; Woodbury et al., 2009). Shaping, or the incremental adjustment of task difficulty, is used often in occupational therapy and interventions such as CIMT (Taub et al., 1994), may be a more useful technique for reducing compensation, and can be integrated into existing VR methods. The purposes of this study were to design and assess the feasibility of a VR tool capable of measuring and shaping compensatory movements during repetitive UE practice for persons with chronic stroke.

3.2 Methods

3.2.1 System Design

We developed a VR tool called VRShape that (1) monitors movement kinematics in real time using an affordable, off-the-shelf motion sensor; (2) recognizes a variety of customizable, targeted UE movements; (3) converts these UE movements into control of nearly any freely available VE or computer game; (4) records and reports clinically-relevant performance metrics; and (5) provides feedback about compensatory trunk movements in real-time. Each of these elements combine to create a VR-based therapy that is client-centered, motivating, and designed to encourage clients to perform large doses of high-quality movement repetitions with incrementally decreased compensation (Figure 3.1).
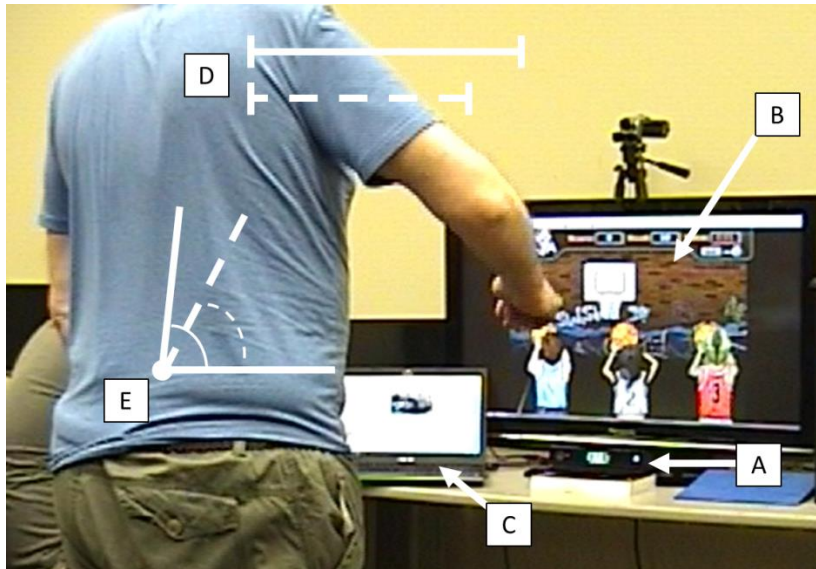
Figure 3.1. Example of experimental setup using VRShape involving
(A) the Microsoft Kinect V2, (B) a client-chosen computer game
(Hoops Mania), and (C) host computer providing feedback. A simple
representation of reaching ROM (solid) and customized reaching
threshold (dotted) is shown (D). A simple representation of trunk
flexion (solid) and trunk flexion threshold (dotted) is also shown (E).

VRShape uses the second generation (V2) of the Microsoft Kinect sensor to identify

bodily movement. The Kinect V2 combines a typical camera and an infrared depth sensor to

capture the movement of up to 25 joints and body segments in real-time without the use of

wearable trackers. The sensor connects to a host computer via a USB 3.0 connection and driver

software, namely the Kinect Software Development Kit (SDK) (v2.0). Several studies have

established the Kinect v2 to be adequately valid and reliable for measuring UE and postural

movements relative to more expensive and accurate motion capture systems (Clark et al., 2015;

Kuster et al., 2015). In a previous investigation, we found both the Kinect V1 and V2 to have

good validity and reliability for measuring arm displacements and shoulder angles relative to an

8-camera video motion capture system (VMC), but found the Kinect V2 to be closer in

magnitude to VMC for the majority of kinematic variables (Reither et al., 2017). In another

53

investigation, we found that the K2 was closer in magnitude and more valid relative to VMC for measuring trunk movements, particularly during extended reaches that simulated compensatory movements, than was the K1 for reaches in the sagittal, scaption (45º), and frontal planes.

VRShape was developed primarily within the MATLAB programming environment utilizing an interface for the Kinect V2 (r2016a, Mathworks Inc., Natick, MA).   Relevant information is defined and passed through a series of graphical user interfaces (GUIs) including a login page, a main dashboard, a calibration screen, and several performance reports to make up the general workflow of the software (Figure 3.2). These GUIs are the main interface for the person controlling an intervention session, whether it be a researcher, a therapist, or the user him- or herself. Each user can define a personalized login name, under which all subsequent setup and performance data will be saved. The user's experience can be customized according to the movement that is targeted for practice, the ROM threshold for the movement, and the desired VE or computer game. Performance metrics related to time played, number of repetitions achieved, movement used, game used, and ROM achieved can be displayed in numerical or graphical form in a series of optional GUIs. These data can also be shown longitudinally to track progress over the course of several sessions.
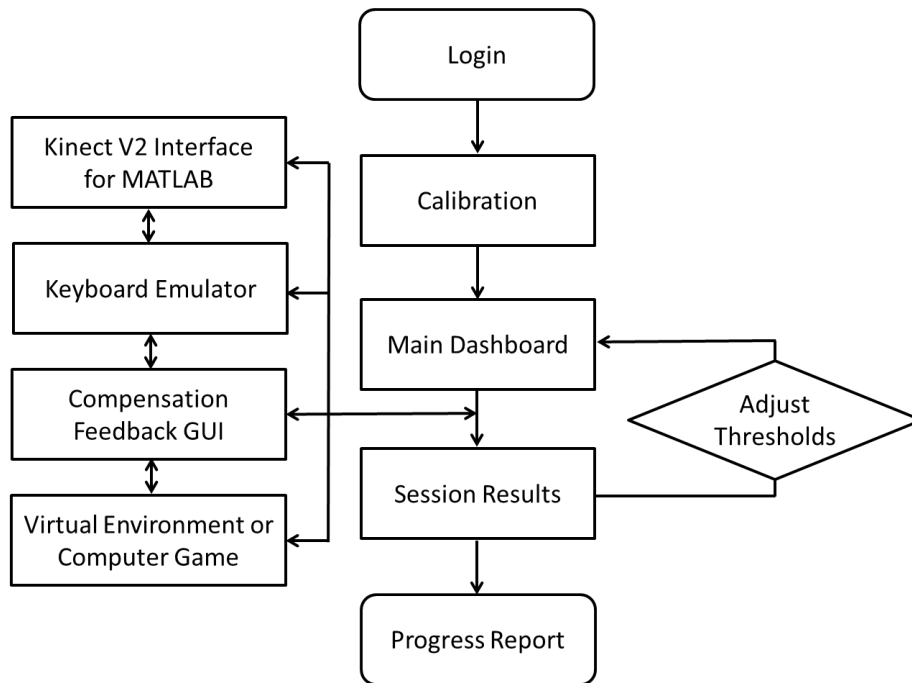
Figure 3.2. Flow diagram of VRShape processes and interfaces. Once logged in, the system is calibrated for reaching and compensation thresholds. The main dashboard allows setting of all parameters and display of the Kinect V2 data feed. Once a session is started, parallel processes use Kinect data to control a VE through a keyboard emulator. Compensation feedback is provided in a separate GUI. Results are provided and thresholds can be adjusted before transitioning to another VE. At the end of a session, a progress report is presented and saved.

VRShape has the built-in capability to recognize a variety of therapy-relevant UE movements that are common targets of repetitive training including forward, side, and vertical reaching; shoulder flexion, abduction, and internal rotation; elbow flexion; and wrist flexion and deviation. These movements are commonly affected by damage to the corticospinal tract due to stoke and resulting hemiparesis (Lang et al., 2013). The software also has the capability to recognize trunk flexion, lateral flexion, and axial rotation simultaneously during the performance of UE movements. Post-stroke deficits during functional reaching are well researched and often defined by decreased endpoint precision, increased time (slower reaches), disrupted fractionation of movement, and reduced ROM (Cirstea & Levin, 2000; Levin et al., 2002; Roby-Brami et al.,

2003). Research in post-stroke reaching also provides most robust evidence for the nature of compensatory movements post-stroke, identifying trunk movements as the most common (Cirstea & Levin, 2000; Levin et al., 2002; Roby-Brami et al., 2003). Our previous investigations have identified that the Kinect V2 is highly reliable and valid for measuring reaching (Reither et al., 2017). For these reasons, the remainder of this investigation focuses on repetitive training involve reaching and the associated trunk flexion compensations.

To interact with the system, the user either stands or sits in a chair facing the Kinect sensor at a distance of approximately 2.0m with the sensor situated at a height of approximately 1.2m above the ground (Figure 3.1). The software recognizes a movement repetition as completed when it surpasses a defined threshold, most commonly the user's targeted ROM in terms of linear or angular displacement (Figure 3.3). For reaching movements, this threshold is defined as a minimum Euclidean distance of the hand relative to the shoulder, which can be defined by an automatic calibration algorithm (maximum ROM during a preliminary set of reaches) or manually by the supervising researcher or therapist. A keyboard emulator activates when this threshold is met, allowing for the control of nearly any VE or computer game (Figure 3.4). The keyboard emulator can be programmed with any key press or mouse movement required for a specific application. For example, VRShape can be calibrated to press the spacebar when the user reaches in the sagittal plane with his or her right arm by a distance of 40cm in order to activate a virtual action requiring the spacebar in a specific computer game. This algorithm is similar to FAAST that has been used in other research performed within our laboratory for persons with a variety of motor impairments (Behar et al., 2016; Lauterbach et al., 2013; Mraz et al., 2016; Sevick et al., 2016; Suma et al., 2013).
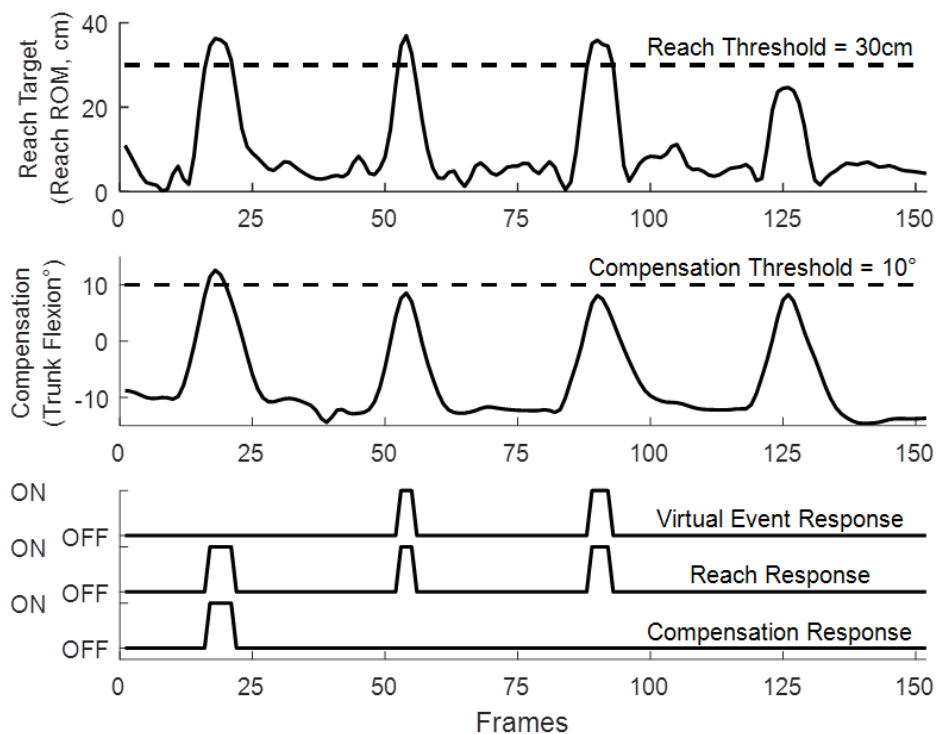
Figure 3.3. Examples of signals for reaching movement (top axes), compensatory movement (middle axes), and the response of the VRShape software. During the first attempt, the participant exceeded the compensation threshold (middle). Because virtual events only occur when reaching without compensation, there was no output for the first attempt. The subsequent two attempts resulted in a virtual event, while the last did not because the participant failed to reach far enough.
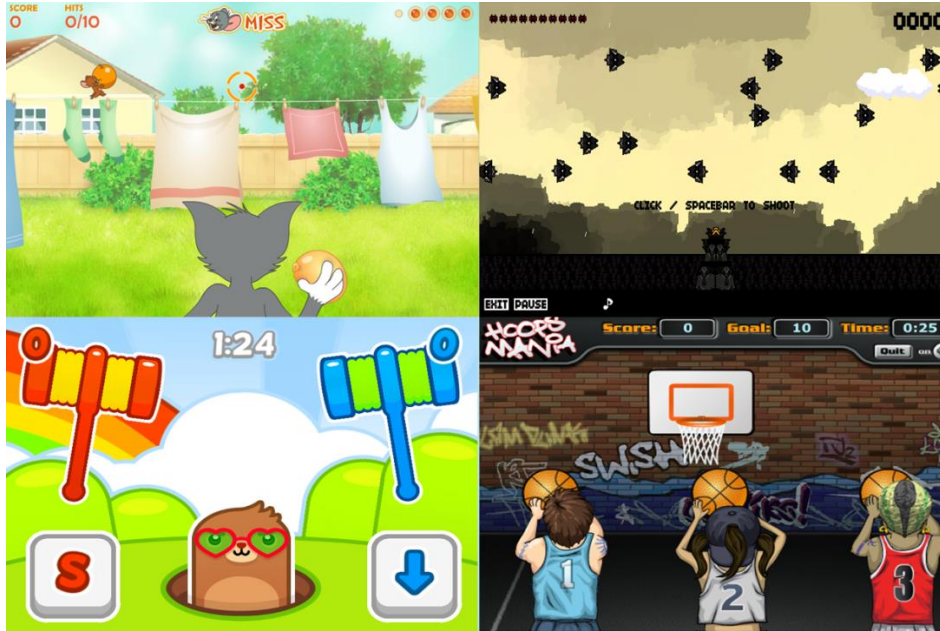
Figure 3.4. Examples of the four most common VEs used during this investigation. Tom and Jerry (top left) requires the client to reach to trigger Tom to throw a water balloon at Jerry. Ten Bullets (top right) requires the client to reach to shoot at spaceship across the sky. Mole Hammers (bottom left) requires the client to reach to slam a hammer on a mole's head. Hoops Mania (bottom right) requires the client to reach to shoot at a moving basketball hoop.

The most novel design feature of VRShape is its ability to "shape" compensatory trunk movements. Shaping is a technique founded in behavioral science and utilized as a key component of CIMT to incrementally match the difficulty of tasks to the abilities and characteristics of the client (Taub et al., 1994). Our software has the ability to shape compensations by incrementally decreasing the allowable amount of trunk flexion over the course of an intervention based on the client's movements. An automatic calibration algorithm for defining a compensation threshold can be employed before a session. This algorithm measures the average trunk flexion employed during the performance of multiple unconstrained UE movements over the course of a small timespan, and uses 90% of this average as the trigger for providing feedback during subsequent therapy. This threshold can be manually adjusted at

58

the discretion of the researcher in order to provide the best experience for the user and avoid frustration, but the value of 90% is intended to keep the user at an adequate level of challenge similar to existing rules for task grading in CIMT and task-oriented training (Birkenmeier et al., 2010; Taub et al,. 2006; Uswatte et al, 2006).

Feedback about compensatory movement is provided in three different ways. Once a compensation threshold is defined, feedback is provided during gameplay by means of audio, visual, or virtual event suppression. Audio feedback can be provided in the form of a loud alarm that triggers when the user moves his or her trunk past the threshold. Visual feedback can be provided in the form of a graphical movement trace with a prominent line representing the maximum allowable trunk movement. Finally, virtual event suppression cancels the outcome of a completed movement repetition if the user has compensated; in the above example, this would mean that the spacebar would not be pressed even if the user flexed their trunk too far even while reaching beyond the 40cm threshold. The combination of a customizable reaching trigger for interacting with a VE and a customizable compensation threshold beyond which multimodal feedback is provided are theory-based design features intended to encourage simultaneous increases in ROM and decreases in compensation utilization.

3.2.2 Feasibility Testing

Five participants with chronic stroke (4 male, 1 female; mean age 63.2 years) were recruited for this study from the greater St. Louis area. Participants were eligible for inclusion if they (1) were aged 40-80 years, (2) experienced an ischemic stroke greater than six months prior, (3) exhibited persistent hemiparesis as noted by a score of 1-3 on the motor arm subscale of the National Institutes of Health Stroke Scale (NIHSS) (Goldstein & Samsa, 1997), (4) displayed some voluntary activity in proximal or distal UE joints when asked to reach for an item in their

immediate space, and (5) utilized noticeable trunk compensation (>20 deg) when performing

these reaching movements with the impaired arm. Participants were excluded if they had any

medical conditions that would impair their ability to play computer games, such as significant

comprehension difficulties, attentional disorders, or visual field deficits (Table 3.1). All

participants provided written consent and the Institutional Review Board (IRB) of the

Washington University School of Medicine approved all study activities.

Table 3.1. Participant characteristics. Basic demographic data is shown along with the NIHSS
arm/motor subscale, data about computer knowledge and usage, and data about VR knowledge
and usage obtained from the Sense of Presence Inventory (ITC-SOPI).

	Participants				
	P1	P2	P3	P4	P5
Age	62	63	44	69	78
Gender	M	M	M	F	M
Race	White	White	Afr. Amer.	White	Afr. Amer.
Years Post-Stroke	2	1	4	6	1
Affected Side	R	R	R	L	L
NIHSS Arm/Motor	1	1	1	2	1
Computer Experience	None	Expert	Intermediate	None	Expert
Computer Game Use	Never	Often	Every Day	Never	Every Day
VR Knowledge	None	Intermediate	None	None	None
VR Use	No	Yes	No	No	No

Note: Afr. Amer. = African American, NIHSS = National Institutes of Health Stroke
Scale, VR = Virtual reality, Often = < 50% of days

Each participant took part in a one-hour session at the Human Performance Laboratory at

the Washington University School of Medicine. During this session, VRShape was used to

control four separate computer games by means of reaching movements calibrated to each

participant's abilities and ROM. Two of these games were used consistently across individuals

and two were chosen by each individual from a previously defined list of games known be

compatible with the VRShape software. Each game was played for approximately 10 minutes

and 2-3 minutes were allowed for transition between games. The remaining session time was

allotted for outcomes measures. The primary outcome measures for this feasibility study were related to usability, motivation for use, and sense of presence during use of the VRShape software.

The System Usability Scale (SUS) is a 10-item questionnaire that uses a five-point Likert scale to assess usability, which may be defined as a technological system's appropriateness for its designated task within its intended context (Brooke, 1996). The SUS has been used in thousands of publications, demonstrating excellent reliability and validity and taking less than 10 minutes to administer (Brooke, 2013). A sum score on a scale from 0-100, also representing percentile rank, is tabulated after the evaluation of each individual item. A sum score of 68 is considered "average" (Sauro, 2011), and an adjective rating scale has been validated to describe a system as "worst imaginable" (0-20.3), "awful" (20.3-35.7), "poor" (35.7-50.9), "OK" (50.9-71.4), "good" (71.4-85.5), "excellent" (85.5-90.9), and "best imaginable" (90.9-100) (Bangor et al., 2009).

The Intrinsic Motivation Inventory (IMI) is a multidimensional assessment that has demonstrated good psychometrics for measuring subjective experience of an activity related to interest/enjoyment, perceived competence, effort/importance, and pressure/tension (McAuley et al., 1989). Specifically, the interest/enjoyment subscale takes less than 10 minutes to administer and consists of seven items measured on a seven-point Likert scale that can be summed for a total score from 0-49. This subscale has previously been used within our laboratory (Behar et al., 2016; Lauterbach et al., 2013; Sevick et al., 2016). While classification ranges have not been established for the IMI, an approximate average item score of six ("mostly agree") and a total subscale score of 42 is generally considered highly motivating in existing literature that has used the interest/enjoyment subscale for assessing VR-based rehabilitation (Colombo et al., 2007; Sampson et al., 2012).

The Independent Television Commission-Sense of Presence Inventory (ITC-SOPI) measures a user's sense of presence, or overall subjective sensation of "being there," across domains related to spatial presence, engagement, ecological validity, and negative effects (Lessiter et al., 2001). It consists of 44 items measured on a five-point Likert scale; these ordinal responses are subsequently averaged within each of the four domains to produce summary scores. The validity of the ITC-SOPI has been well established and score ranges exist for multiple media formats including television, computer games, and VR (Lessiter et al., 2001; Schuemie et al., 2001). There are three parts to the ITC-SOPI: background information, Part A, and Part B. The background information section asks questions about prior knowledge and experience with computers, television, and VR (selected questions, Table 3.1). Part A includes 10 questions on engagement and negative experiences, and Part B contains the remaining 34 questions from all four domains. The entire assessment takes about 15 minutes to administer.

VRShape automatically collected performance metrics during each session, the most important of which being the number of repetitions and ROM achieved with the UE during reaching. The software also collected XYZ position data for all body landmarks viewed by the Kinect during interaction with the system. These data were filtered (6th order, 6Hz Butterworth) and post-processed in MATLAB to calculate kinematic variables including reaching ROM, sagittal and frontal planar reach distance, shoulder flexion and abduction, trunk flexion and lateral flexion, and elbow flexion. A peak detection algorithm was designed and applied to find the average maximum value for each of these kinematic variables over the course of minutes of therapy and thousands of collected frames. In the event of missing data, which intermittently occurred due to technical issues the novelty of using the system with stroke participants, metrics were extrapolated to the length of the session based on repetition and compensation rates.

Finally, at the conclusion of the session, a qualitative interview was performed to identify facilitators/barriers, likes/dislikes, and suggestions for improvement for the VRShape software. Simple questions including "What would you change about the system?" and "What would encourage or stop you from using the system regularly?" were used to facilitate discussion, similar to custom usability questionnaires utilized in prior research (Cameirao, 2012).

To assess the effect of prior knowledge or experience with computers or VR, selected items from the ITC-SOPI background assessment were converted to ordinal scales and compared to SUS sum scores, IMI interest/enjoyment scores, and ITC-SOPI subdomains. Spearman's rank-order correlations (ρ) were used due to the small sample size and ordinal type data.

3.3 Results

Participants performed an average of 461 (SD = 184) repetitions in only 40 minutes of gameplay with VRShape (Table 3.2). Seven different games were successfully played with VRShape and the average number of completed repetitions varied by game (R = 21-239) (Figure 3.5). To achieve this number of successful repetitions, participants exceeded their individualized compensation thresholds (used too much trunk flexion) and triggered feedback an average of 105 (SD = 35) times per session. The result is that participants only performed "bad" repetitions involving compensation at a rate between 16-22% and achieved success at a rate between 77-84% (Figure 3.6).

Table 3.2. Results for repetitions, compensation, and kinematic variables presented for each participant and as group mean (SD). Repetitions and compensations are calculated from performance relative to individualized reach and trunk flexion thresholds within VRShape. The average percentage magnitude achieved beyond (reach) or below (compensation) is also presented.

Variable	P1	P2	P3	P4	P5	Mean (SD)
Successful Repetitions (%)*	253 (77)	311 (84)	714 (84)	520 (82)	505(78)	461 (184)
Compensations (%)*	75 (23)	61 (16)	134 (16)	113 (18)	140 (22)	105 (35)
Percent Reach Target (%)	108.7	186.0	110.5	121.6	106.6	126.7 (33.7)
Percent Compensation Limit (%)	72.0	69.0	59.9	77.0	81.0	71.8 (8.1)
Reach ROM (cm)	49.5	55.6	51.4	50.9	49.8	51.4 (2.5)
Sagittal Reach Distance cm)	32.6	46.5	43.1	38.1	42.2	40.5 (5.3)
Front Reach Distance (cm)	12.7	18.7	14.2	9.5	11.3	13.3 (3.5)
Shoulder Flexion (deg)	13.5	12.2	11.4	15.7	18.3	14.2 (2.8)
Shoulder Abduction (deg)	39.1	29.5	40.0	24.3	31.9	33.0 (6.6)
Trunk Flexion (deg)	7.2	-14.5	-16.7	-7.7	-24.7	-11.3 (12.0)
Trunk Lateral Flexion (deg)	2.3	2.6	1.9	1.4	3.1	2.3 (0.7)
Elbow Flexion (deg)	96.5	86.2	82.7	91.7	74.6	86.3 (8.4)

Note: SD = standard deviation

*Parentheticals are the percentage of succesful reps and reps with compensation relative to an estimate of the total number of repetitions attempted
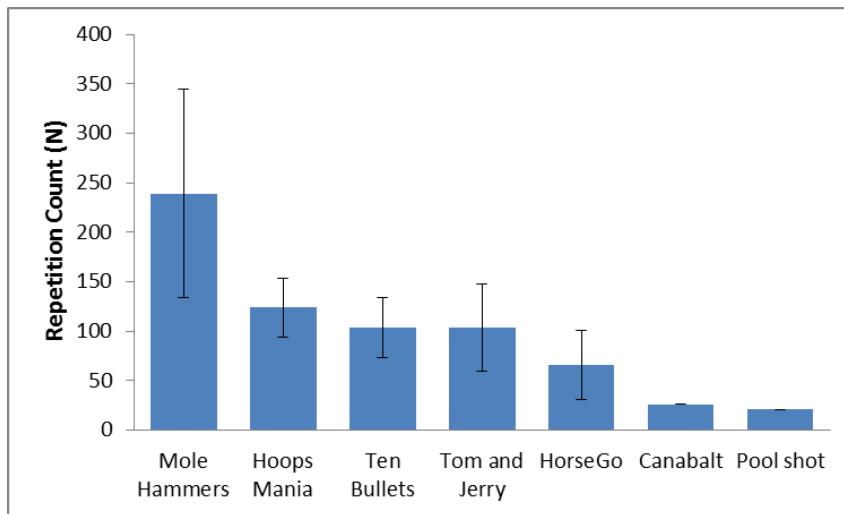
Figure 3.5. The number of repetitions performed during each of the seven games used with VRShape. Error bars represent standard deviation.
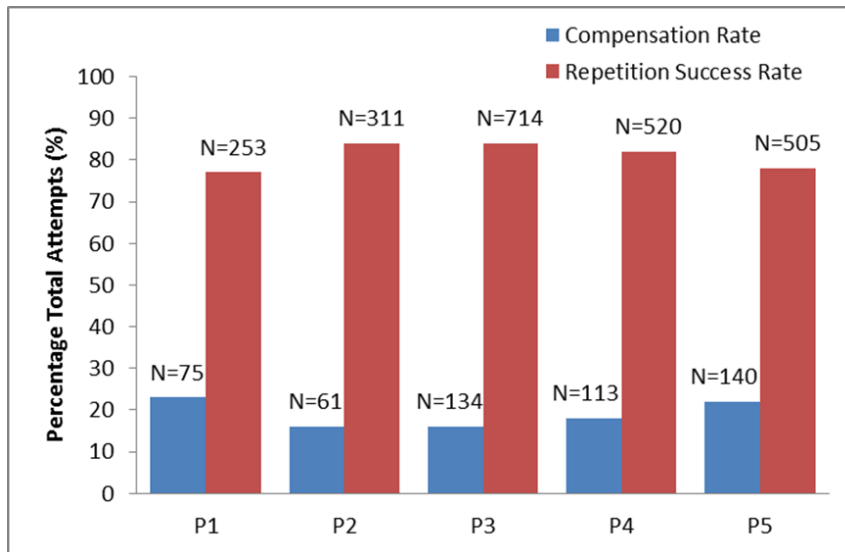
Figure 3.6. Comparison of repetition success rate and compensation rate for each participant. The raw number of successful repetitions and the number of compensations are shown above each column.

In terms of movement kinematics, participants achieved an average of approximately 126.7% (SD = 33.7) of the threshold required for reaching ROM while using only 71.8% (SD = 8.1) of the trunk flexion feedback threshold (Table 3.2). Planar reach distances, in general, show that the majority of participants were reaching more in the sagittal plane (M = 40.5cm, SD = 5.3) than in the frontal plane (M = 13.3cm, SD = 13.3) during the scaption reach. More shoulder abduction (M =3 3.0º, SD = 6.6) than flexion (M = 14.2º, SD = 2.8) was utilized to transport the arm and achieve the required reach distance. Trunk flexion varied across individuals, but remained below feedback thresholds for the majority of repetition attempts (M = -11.3º, SD = 12.0). Lateral flexion was not heavily utilized during reaches (M = 2.3º, SD = 0.7). Finally, elbow flexion remained similar across individuals during reaching (M = 86.3º, SD = 8.4).

Participants found the system's usability to be "OK" according to the average SUS sum score (M = 69.0, SD = 24.66) (Table 3.3). Individual usability ratings varied, with one participant reporting "best imaginable," one participant reporting "excellent," two participants

65

reporting "OK," and one participant reporting "poor." Participants also found the system to be

highly motivating according to the average IMI interest/enjoyment score (M = 43.2, SD = 7.66).

Individual IMI scores also varied.

Table 3.3. Results for each participant for repetition count, System Usability Scale (SUS), Intrinsic Motivation Inventory (IMI), and International Television Commission Sense of Presence Inventory (ITC-SOPI). Repetition counts are shown for the entire session (40 minutes) and each individual game used (10 minutes). Participants used two consistent games and two of their choice. Only the interest/enjoyment subscale of the IMI was utilized. ITC-SOPI scores are divided into each subscale.

Variable	P1	P2	P3	P4	P5	Mean (± SD)
SUS Sum Score	42.5	90	55	57.5	100	69.0 ± 24.7
IMI Interest/Enjoyment	44	45	48	30	49	43.2 ± 7.7
ITC-SOPI Spatial Presence	1.4	1.5	3.2	2.1	4.1	2.4 ± 1.2
ITC-SOPI Engagement	2.8	3.3	4.4	2.9	4.4	3.6 ± 0.8
ITC-SOPI Ecological Validity	1.0	1.2	5.0	1.8	4.0	2.6 ± 1.8
ITC-SOPI Negative Effects	1.7	1.8	1.0	1.8	1.0	1.5 ± 0.4

Note: SUS = System Usability Scale, IMI = Intrinsic Motivation Inventory, ITC-SOPI = Independent Television Commission Sense of Presence Inventory

ITC-SOPI scores are separated into each subscale: spatial presence, engagement,

ecological validity, and negative effects. Since the Likert scale score does not carry inherent

meaning, similar validated media forms evaluated by the creators of the ITC-SOPI are included

for reference (Lessiter et al., 2001). Participants experienced a modest sense of presence

according to the average spatial presence subscale score (M = 2.44, SD = 1.19), representing an

experience similar to that of viewing a movie at the cinema. Participants were highly engaged

during their experience with the system, exemplified by the relatively high average score on the

engagement subscale (M = 3.57, SD = 0.77), most similar to the experience of playing a

commercially-developed computer game. Ecological validity of the system was found to be

modest, exhibited by the modest ecological validity subscale score (M = 2.60, SD = 1.79). This

was most similar to the experience of viewing a movie in a group setting on a low definition

television. Finally, participants experienced very few negative effects, exemplified by the low

average negative effects subscale score (M = 1.47, SD = 0.43). This score was lower than any

media format validated with the ITC-SOPI.

Significant correlations were found between computer game use and IMI ratings (ρ = 0.95, p = 0.04) and ITC-SOPI engagement ratings (ρ = 0.97, p < 0.01) (Table 3.4). This signifies that participants that used computer games more often were also more motivated and more engaged during use of VRShape. No other significant correlations were found, but in general, prior computer knowledge or use showed greater association with outcomes than did VR knowledge or use.

Table 3.4. Spearman's rank-order correlations (ρ) between computer and VR knowledge (ITC-SOPI background) and ratings of system usability (SUS), motivation (IMI), and subdomains of spatial presence (ITC-SOPI).

	Computer Experience	Computer Game Use	VR Knowledge	VR Use
SUS Sum Score	0.79	0.47	0.35	0.35
IMI Interest/Enjoyment	0.79	0.95*	0.00	0.00
ITC-SOPI Spatial Presence	0.47	0.79	-0.35	-0.35
ITC-SOPI Engagement	0.73	0.97*	0.00	0.00
ITC-SOPI Ecological Validity	0.32	0.79	-0.35	-0.35
ITC-SOPI Negative Effects	-0.25	-0.75	0.56	0.56

Note: SUS = System Usability Scale, IMI = Intrinsic Motivation Inventory,
ITC-SOPI = Independent Television Commission Sense of Presence Inventory
*p < 0.05

Four out of five participants noted that he or she would need more time with the system to adequately comment on its positive and negative attributes. Each participant expressed excitement to continue use of VRShape in the context of an intervention. Three out of five participants, in one form or another, expressed interest for games beyond those that they used in their session, including genres like card games, board games, hunting games, and sports games. One participant (P5) stated that he felt like the system was making him do more than he was accustomed to from his previous rehabilitation experience: "I can feel it in my arm, it's making

me move more than regular therapy." Small technical issues were noted during sessions, including some difficulty viewing or hearing feedback related to trunk compensation, issues navigating game menus while motion capture was active, and delays while switching games or adjusting movement thresholds.

3.4 Discussion

The purpose of this study was to develop and test a VR tool designed to elicit high doses of UE movement repetitions while measuring and shaping compensation for persons with stroke. The resulting software, VRShape, demonstrated the ability to engage participants in an intense quantity of reaching movements while shaping success and providing feedback based on excessive trunk flexion. Participants found the software to be usable, motivating, and safe.

Relatively few limitations were directly identified following use of VRShape due to the short session length and the novelty of the system. However, some themes related to study limitations did emerge from the collected data and from observation. First, the workflow of GUIs and background data was not optimal and therefore sometimes caused brief time delays during sessions. The process for transitioning between computer games, adjusting movements, and displaying post-session data often took slightly longer than expected. Data flow and GUI layouts should be streamlined to make therapy sessions more efficient and decrease the likelihood of client disengagement. Second, a more expansive library of VEs and games must be identified; several participants gave suggestions for interesting game genres that were not yet a part of the VRShape software. These games may also include the use of a wireless mouse for gameplay and menu navigation. Along with that, it is clear that repetition rates may be bounded by the type of game being played, exemplified by the large range of repetitions (Figure 3.5). For example, a whack-a-mole game, Mole Hammers, elicited about double the repetitions (N = 242)

of a basketball game, Hoops Mania (N = 124). Finally, correlation results show that evaluation

of the system may be affected by literacy with computers and VR (Table 3.4). Due to small size

and variations in computer or VR experience within our sample, future research is needed to

generalize results and find the most appropriate users for our software within the larger stroke

population.

Contemporary motor learning research suggests that thousands of repetitions are required

to retrain the brain in order to acquire a new motor skill or make up for injured neural areas

resulting from a stroke (Kleim & Jones, 2008). Traditional physical and occupational therapy

may only involve 30-40 repetitions in a single session (Lang et al., 2007). In a study translating

research in animal dosing to persons with stroke, Birkenmeier and colleagues (2010) had

participants perform an average of 322 repetitions per 1-hour session, resulting in improvements

in motor function, activity performance, and participation (Birkenmeier et al., 2010). In a recent

large-scaled dosing study, Lang and colleagues (2016) included an individualized maximum

group that was able to achieve an average of 10,808 repetitions over an average of 36 sessions,

resulting in modest improvements in motor function (Lang et al., 2016). In our study,

participants were able to achieve an average of 461 repetitions in 40 minutes of using VRShape,

exceeding repetition rates documented for these traditionally administered task-based training

procedures. This repetition rate is similar to that seen in other VR systems (300-600 per session)

and represents an advantage of VR-based motor therapy (Behar et al., 2016; Lauterbach et al.,

2013; Mraz et al., 2016; Sevick et al., 2016). Extrapolated over the course of an intervention, it

would require only approximately 22 sessions to achieve the colloquial 10,000 repetition

threshold achieved in recent dosing studies and required for retained motor learning.

About 75% of repetitions were performed successfully by participants and the remaining 25% were performed with excessive trunk compensation (Table 3.2). Compensation thresholds were rounded to 90% of the trunk flexion used in an initial calibration trial, and VRShape was designed to increase task difficulty (restrain compensation) in these 10% increments. The process of shaping is generally defined by rules for increasing or decreasing task difficulty related to rate of success. In CIMT, a general rule is to make the task slightly more difficult if a participant achieves five successful repetitions in a row (Uswatte et al., 2006) or if performance has plateaued for as many as 10 consecutive trials (Taub et al., 2006). In task-based training protocol, it is recommended that task difficulty be graded up if a participant successfully completes more than 100 repetitions in 15 minutes, and graded down in a participant fails more than 50 repetitions in 15 minutes (Birkenmeier et al., 2010). The average repetition rate with VRShape translates to approximately 170 successful and 40 "bad" repetitions using compensation per 15 minutes. Furthermore, participants were able to achieve well over their reaching thresholds (127%) while using less than their compensation threshold (72%), signifying that most repetitions were easily completed. No participants expressed frustration or boredom in this single session, but it may be important to monitor success and failure during VRShape use in terms of both completion rate and ROM in order to keep participants engaged and challenged in future therapy.

The usability of the system was found to be "OK" and motivation for using the system was found to be high, but these values varied drastically across individuals. A mean SUS score of 69.0 is very near the global average, and is similar to other preliminary investigations of VR-based therapy systems in the literature (Brooke, 2013). In a study involving a similar customizable VR system for in-home UE therapy, Proffitt and colleagues found scores in the

same usability range that were mitigated by prior computer experience and technical issues with some participants (Proffitt et al., 2015).

An average IMI of 43.2 is considered highly motivating and is also similar to existing research in VR-based rehabilitation field. In a study involving a more immersive VR system utilizing a mechanical device and custom-built VR games, Sampson and colleagues found a similar interest/enjoyment rating (M=43.4) in a small sample of stroke participants (n=5) (Sampson et al., 2012). Wide variations in the ability and motivation to use technology may be mitigated by previous knowledge and experience with computers and VR (Table 3.1).

The subjective experience of spatial presence and ecological validity, both aspects of overall sense of presence in a virtual environment, was found to be modest following use of VRShape. Sense of presence is theoretically and empirically related to the provision of an extensive, surrounding display that vividly engages multiple senses to make the user feel included in the virtual experience (Slater & Wilbur, 1997). Recent research suggests that VR systems may be divided into two different categories: "immersive" and "non-immersive" (Henderson et al., 2007). VRShape may be considered a non-immersive system, because it does not include technology such as large screen projection, head-mounted displays, haptic feedback systems, or complex, custom-designed virtual environments that are required for immersive systems. It is therefore fitting that participants scored their sense of spatial presence and ecological validity within VRShape similarly to other validated, non-immersive systems, namely viewing a movie in a group setting either at the cinema or on a television (Lessiter et al., 2001).

There are a number of existing VR tools designed to provide a fun, engaging medium for performing UE motor therapy (Holden et al., 2007; Laver et al., 2015; Lohse et al., 2014). To our knowledge, there are very few existing tools designed specifically to shape the amount of

trunk compensation utilized over time through the provision of feedback and user-specific shaping algorithms (Alankus & Kelleher, 2012). The main ingredients of a theory-driven intervention targeting salient motor learning and associated neuroplastic change are (1) the repetitive practice of meaningful tasks, (2) progressive task difficulty matched to the person's abilities, (3) involvement of problem-solving mechanisms, (4) engagement and motivation to improve, (5) feedback about performance and results of practice (Kleim & Jones, 2008; Levin et al., 2015). In this study we have demonstrated that VRShape is designed with each of these areas in mind and is capable of providing intense, motivating, challenging motor therapy for persons with stroke. These advantages, combined with its low-cost, ease-of-use, and focus on objective compensation measurement provide tremendous potential for use as a tool for both clinical use and rehabilitation science research.

Future development with VRShape should focus on improving the efficiency of the software and increasing the number and variety of usable VEs and games. It will be important to identify aspects of each computer game and balance the repetition intensity for each participant during an intervention session. It may also be important to classify games within VRShape into different categories by age appropriateness, repetition intensity, or game genre. Future investigation should test feasibility and preliminary efficacy of VRShape for use in a VR-based intervention.

3.5 Conclusion

The present study described the development of a novel VR tool, namely VRShape, and its initial feasibility testing with a small cohort of persons with hemiparetic stroke. VRShape proved to be a capable tool for eliciting high doses of UE repetitions while providing feedback about trunk compensation during a VR-based motor therapy session. The system was found to

be usable, highly motivating, and safe while providing a modest sense of virtual presence. Areas

requiring improvement were identified and will be addressed, and future research is needed to

establish the long-term feasibility and preliminary efficacy of VRShape for use as the basis of

regular VR-based motor therapy.

3.5.1 Conflict of Interest Statement

Both Matthew Foreman and Dr. Jack Engsberg have financial interests in Accelerated

Rehabilitation Technologies (ART) and may financially benefit if the company is successful in

licensing and market software related to VRShape and this research performed at Washington

University.

3.6 References

Alankus, G., & Kelleher, C. (2012). Reducing compensatory motions in video games for stroke rehabilitation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 2049-2058). ACM.

Alaverdashvili, M., Foroud, A., Lim, D. H., & Whishaw, I. Q. (2008). "Learned baduse" limits recovery of skilled reaching for food after forelimb motor cortex stroke in rats: a new analysis of the effect of gestures on success. *Behavioural brain research*, 188(2), 281-290.

Allred, R. P., Cappellini, C. H., & Jones, T. A. (2010). The "good" limb makes the "bad" limb worse: Experience-dependent interhemispheric disruption of functional outcome after cortical infarcts in rats. *Behavioral neuroscience*, 124(1), 124.

Behar, C., Lustick, M., Foreman, M. H., Webb, J., & Engsberg, J. R. (2016). Personalized Virtual Reality for Upper Extremity Rehabilitation: Moving from the Clinic to a Home Exercise Program. *Journal of Intellectual Disability-Diagnosis and Treatment*, *4*(3), 160-169.

Birkenmeier, R. L., Prager, E. M., & Lang, C. E. (2010). Translating animal doses of task-specific training to people with chronic stroke in one hour therapy sessions: a proof-of-concept study. *Neurorehabilitation and neural repair*, *24*(7), 620.

Brooke, J. (1996). SUS-A quick and dirty usability scale. *Usability evaluation in industry*, *189*(194), 4-7.

Brooke, J. (2013). SUS: a retrospective. *Journal of usability studies*, *8*(2), 29-40.

Cameirao, M. S., i Badia, S. B., Duarte, E., Frisoli, A., & Verschure, P. F. (2012). The combined impact of virtual reality neurorehabilitation and its interfaces on upper extremity functional recovery in patients with chronic stroke. *Stroke, 43*(10), 2720-2728.

Cirstea, M. C., & Levin, M. F. (2000). Compensatory strategies for reaching in stroke. *Brain*, *123*(5), 940-953.

Clark, R. A., Pua, Y. H., Oliveira, C. C., Bower, K. J., Thilarajah, S., McGaw, R., ... & Mentiplay, B. F. (2015). Reliability and concurrent validity of the Microsoft Xbox One Kinect for assessment of standing balance and postural control. *Gait & posture*, 42(2), 210-213.

Colombo, R., Pisano, F., Mazzone, A., Delconte, C., Micera, S., Carrozza, M. C., ... & Minuco, G. (2007). Design strategies to improve patient motivation during robot-aided rehabilitation. *Journal of neuroengineering and rehabilitation*, *4*(1), 3.

Corbetta, D., Imeri, F., & Gatti, R. (2015). Rehabilitation that incorporates virtual reality is more effective than standard rehabilitation for improving walking speed, balance and mobility after stroke: a systematic review. *Journal of physiotherapy, 61*(3), 117-124.

Darekar, A., McFadyen, B. J., Lamontagne, A., & Fung, J. (2015). Efficacy of virtual reality-based intervention on balance and mobility disorders post-stroke: a scoping review. *Journal of neuroengineering and rehabilitation, 12*(1), 46.

Goldstein, L. B., & Samsa, G. P. (1997). Reliability of the national institutes of health stroke scale. *Stroke, 28*(2), 307-310.

Henderson, A., Korner-Bitensky, N., & Levin, M. (2007). Virtual reality in stroke rehabilitation: a systematic review of its effectiveness for upper limb motor recovery. *Topics in stroke rehabilitation, 14*(2), 52-61.

Jutai, J. W., & Teasell, R. W. (2003). The necessity and limitations of evidence-based practice in stroke rehabilitation. *Topics in stroke rehabilitation*, *10*(1), 71-78.

Kitago, T., Liang, J., Huang, V. S., Hayes, S., Simon, P., Tenteromano, L., ... & Krakauer, J. W. (2013). Improvement after constraint-induced movement therapy: recovery of normal motor control or task-specific compensation? *Neurorehabilitation and neural repair*, *27*(2), 99.

Kleim, J. A., & Jones, T. A. (2008). Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. *Journal of speech, language, and hearing research*, *51*(1), S225-S239.

Kuster, R. P., Heinlein, B., Bauer, C. M., & Graf, E. S. (2016). Accuracy of KinectOne to quantify kinematics of the upper body. *Gait & posture*, 47, 80-85.

Kwakkel, G., Veerbeek, J. M., van Wegen, E. E., & Wolf, S. L. (2015). Constraint-induced movement therapy after stroke. *The Lancet Neurology, 14*(2), 224-234.

Lai, S. M., Studenski, S., Duncan, P. W., & Perera, S. (2002). Persisting consequences of stroke measured by the Stroke Impact Scale. *Stroke*, 33(7), 1840-1844.

Lang, C. E., MacDonald, J. R., & Gnip, C. (2007). Counting repetitions: an observational study of outpatient therapy for people with hemiparesis post-stroke. *Journal of Neurologic Physical Therapy*, *31*(1), 3-10.

Lang, C. E., Bland, M. D., Bailey, R. R., Schaefer, S. Y., & Birkenmeier, R. L. (2013). Assessment of upper extremity impairment, function, and activity after stroke: foundations for clinical decision making. *Journal of Hand Therapy, 26*(2), 104-115.

Lang, C. E., Strube, M. J., Bland, M. D., Waddell, K. J., Cherry-Allen, K. M., Nudo, R. J., ... & Birkenmeier, R. L. (2016). Dose response of task-specific upper limb training in people

at least 6 months poststroke: A phase II, single-blind, randomized, controlled trial. *Annals of neurology, 80*(3), 342-354.

Lauterbach, S. A., Foreman, M. H., & Engsberg, J. R. (2013). Computer games as therapy for persons with stroke. *GAMES FOR HEALTH: Research, Development, and Clinical Applications*, 2(1), 24-28.

Laver, K. E., George, S., Thomas, S., Deutsch, J. E., & Crotty, M. (2015). Virtual reality for stroke rehabilitation. *The Cochrane Library*.

Lessiter, J., Freeman, J., Keogh, E., & Davidoff, J. (2001). A cross-media presence questionnaire: The ITC-Sense of Presence Inventory. *Presence: Teleoperators and virtual environments*, 10(3), 282-297.

Levin, M. F., Michaelsen, S. M., Cirstea, C. M., & Roby-Brami, A. (2002). Use of the trunk for reaching targets placed within and beyond the reach in adult hemiparesis. *Experimental brain research*, *143*(2), 171-180.

Levin, M. F., Kleim, J. A., & Wolf, S. L. (2009). What do motor "recovery" and "compensation" mean in patients following stroke?. *Neurorehabilitation and neural repair*, *23*(4), 313-319.

Lohse, K. R., Hilderman, C. G., Cheung, K. L., Tatla, S., & Van der Loos, H. M. (2014). Virtual reality therapy for adults post-stroke: a systematic review and meta-analysis exploring virtual environments and commercial games in therapy. *PloS one, 9*(3), e93318.

McAuley, E., Duncan, T., & Tammen, V. V. (1989). Psychometric properties of the Intrinsic Motivation Inventory in a competitive sport setting: A confirmatory factor analysis. *Research quarterly for exercise and sport*, *60*(1), 48-58.

Mraz, K., Eisenberg, G., Diener, P., Amadio, G., Foreman, M. H., & Engsberg, J. R. (2016). The Effects of Virtual Reality on the Upper Extremity Skills of Girls with Rett Syndrome: A Single Case Study. *Journal of Intellectual Disability-Diagnosis and Treatment*, *4*(3), 152-159.

Olsen, T. S. (1990). Arm and leg paresis as outcome predictors in stroke rehabilitation. *Stroke, 21*(2), 247-251.

Popović, M. D., Kostić, M. D., Rodić, S. Z., & Konstantinović, L. M. (2014). Feedback-mediated upper extremities exercise: increasing patient motivation in poststroke rehabilitation. *BioMed research international*, *2014*.

Proffitt, R., & Lange, B. (2015). Feasibility of a Customized, In-Home, Game-Based Stroke Exercise Program Using the Microsoft Kinect Sensor. *International Journal of Telerehabilitation*, *7*(2), 23.

Reither, L. R., Foreman, M. H., Migotsky, N., Haddix, C., & Engsberg, J. R. (2017). Upper extremity movement reliability and validity of the Kinect version 2. *Disability and Rehabilitation: Assistive Technology*, 1-9.

Sampson, M., Shau, Y. W., & James king, M. (2012). Bilateral upper limb trainer with virtual reality for post-stroke rehabilitation: case series report. *Disability and Rehabilitation: Assistive Technology, 7*(1), 55-62.

Sauro, J. (2011). *A practical guide to the system usability scale: Background, benchmarks & best practices*. Measuring Usability LLC.

Schuemie, M. J., Van Der Straaten, P., Krijn, M., & Van Der Mast, C. A. (2001). Research on presence in virtual reality: A survey. *CyberPsychology & Behavior*, *4*(2), 183-201.

Sevick, M., Eklund, E., Mensch, A., Foreman, M., Standeven, J., & Engsberg, J. (2016). Using free internet videogames in upper extremity motor training for children with cerebral palsy. *Behavioral Sciences*, *6*(2), 10.

Suma, E. A., Krum, D. M., Lange, B., Koenig, S., Rizzo, A., & Bolas, M. (2013). Adapting user interfaces for gestural interaction with the flexible action and articulated skeleton toolkit. *Computers & Graphics*, *37*(3), 193-201.

Taub, E., Crago, J. E., Burgio, L. D., Groomes, T. E., Cook, E. W., DeLuca, S. C., & Miller, N. E. (1994). An operant approach to rehabilitation medicine: overcoming learned nonuse by shaping. *Journal of the experimental analysis of behavior*, *61*(2), 281-293.

Taub, E., Uswatte, G., King, D. K., Morris, D., Crago, J. E., & Chatterjee, A. (2006). A placebo-controlled trial of constraint-induced movement therapy for upper extremity after stroke. *Stroke*, *37*(4), 1045-1049.

Thielman, G., Kaminski, T., & Gentile, A. M. (2008). Rehabilitation of reaching after stroke: comparing 2 training protocols utilizing trunk restraint. *Neurorehabilitation and neural repair*, *22*(6), 697-705.

Uswatte, G., Taub, E., Morris, D., Barman, J., & Crago, J. (2006). Contribution of the shaping and restraint components of constraint-induced movement therapy to treatment outcome. *NeuroRehabilitation*, *21*(2), 147-156.

Woodbury, M. L., Howland, D. R., McGuirk, T. E., Davis, S. B., Senesac, C. R., Kautz, S., & Richards, L. G. (2009). Effects of trunk restraint combined with intensive task practice on poststroke upper extremity reach and function: a pilot study. *Neurorehabilitation and neural repair*, *23*(1), 78-91.

Chapter 4: A Virtual Reality Tool for Shaping Trunk Compensation During Motor Therapy for Persons with Stroke: Feasibility and Preliminary Efficacy

Abstract

Background: The most common post-stroke compensation strategy is trunk flexion during reaching. Virtual reality (VR) may be able to incorporate principles of shaping to incrementally decrease compensations to enhance therapy outcomes relative to existing methods.

Methods: A small cohort (n=5) of persons with chronic stroke took part in a VR-based intervention using a novel tool designed to provide feedback concerning trunk compensation during repetitive reaching movements.   Feedback was provided based on client-specific calibrations that were reduced by an incremental amount over the course of the intervention. A standardized reach test was completed pre- and post-intervention to assess kinematic changes. Questionnaires related to usability, motivation, engagement, and safety were completed at each intervention session to assess feasibility.

Results: Compensatory trunk flexion decreased significantly during extended reaching tasks as a result of the intervention (M = 8.3º, p = 0.04). Participants were able to reach significantly farther in the sagittal (M = 4.7cm, p = 0.04) and frontal (M = 3.8cm, p = 0.04) planes while recruiting more shoulder abduction (M = 3.0º, p = 0.04) to complete those extended reaches with trunk less compensation. Participants completed large doses of movement practice and found the system to be highly usable, motivating, and engaging while experiencing very few negative effects.

Conclusions: VRShape is capable of reducing the amount of trunk compensation and improving reaching kinematics utilized during reaching movements for persons with stroke. It is feasible for use as VR-based intervention tool and has been demonstrated as usable, motivating, and safe. Future work should focus on further improvements and the application of this therapy tool within a larger, controlled study to establish its clinical efficacy.

4.1 Introduction

Compensatory movements, particularly at the trunk, are very common for persons with post-stroke motor impairments related to hemiparesis (Cirstea & Levin, 2000; Levin et al., 2002; Roby-Brami et al., 2003). In the case of stroke, hemiparesis is caused by a lesion in the corticospinal system due to ischemia or hemorrhage and results in weakness, slower and less precise movements, disrupted coordination, and reduced range of motion (ROM) on one side of the body (Sathian et al., 2011). The effect of hemiparesis on the upper extremity (UE) makes the performance of activities of daily living (ADLs) difficult, in turn affecting long-term quality of life and participation for about two-thirds of stroke survivors (Nichols-Larsen et al., 2005; Vestling et al., 2003). To remain functional and engaged in meaningful activities, many persons with chronic stroke must adapt their task performance to compensate for their impaired arm by recruiting new degrees of freedom, additional body segments, and alternative movement strategies altogether (Levin et al., 2009). Specifically, trunk anterior displacement and flexion is common during tasks involving reaching to compensate for deficits in shoulder range of motion (ROM), reduced elbow extension, and difficulty orienting the hand for grasping (Roby-Brami et al., 2003). These compensations are considered adaptive the short-term, but evidence suggests that long-term, extensive use of compensatory movements may contribute to "learned non-use" or "learned-bad use" of the impaired limb, chronic pain in overused joints, suboptimal motor recovery, and even social withdrawal due to the stigma of abnormal movement patterns (Alaverdashvili et al., 2008; Allred et al., 2010; Levin et al., 2009; Taub et al., 1994).

Many current interventions such as constraint-induced movement therapy (CIMT) and task-based training (TBT) have demonstrated promising results for ameliorating impairments related to hemiparesis and improving UE motor function and performance, but some researchers have noted that it is unclear whether these interventions promote true motor recovery or further

encourage the use of compensations (Kitago et al,. 2013; Krakauer, 2006; Levin et al., 2009).

Motor recovery, in this sense, refers to the reacquisition of typical, premorbid movement patterns

in the affected limb (Levin et al., 2009). Both of these techniques rely on the repetitive practice

of task-based, goal-oriented movements with the impaired arm that engage mechanisms of

neuroplasticity and retrain healthy portions of the brain to take on functions that were lost due to

the lesion (Kleim & Jones, 2008).

A number of studies have integrated methods for affecting trunk compensation into the

procedure for CIMT or TBT. The most common technique is complete restraint of the trunk by

physical means using tools like belts, harnesses, or feedback devices. A recent meta-analysis

involving six randomized controlled trials and 187 subjects found that trunk restraint had a

moderate, statistically significant effect for improving motor impairment, increasing active

shoulder flexion range of motion, and decreasing trunk displacement during reaching (Wee et al.,

2014). One of these studies by Michaelsen and colleagues (2006) found that restraining the

trunk to a chair using body and shoulder belts during TBT actually decreased the amount of

trunk compensation during reach-to-grasp tasks in those with moderate to severe stroke, while

TBT without trunk restraint increased the use of trunk compensation (Michaelsen et al, 2006).

Woodbury and colleagues (2009) utilized a stable pad located anteriorly to the subject to limit

trunk compensation and provide tactile cueing during CIMT, and found improved reaching

kinematics and decreased trunk compensation in the restrained group compared to non-restrained

CIMT (Woodbury et al., 2009). Thielman (2008) investigated the use of a pressure sensor fixed

to the back of the chair that provided auditory feedback when the trunk moved anteriorly, and

found similar improvements in reaching kinematics and decreased trunk compensation when

using a trunk harness during reaching for near and far targets (Thielman, 2010).

In addition to belts, harnesses, and pressure sensors, virtual reality (VR) may be a uniquely capable tool for addressing trunk compensation. VR has many advantages toward application in the rehabilitation field, including an inherently engaging and immersive environment, the ability to provide instant and pervasive feedback, customizability relative to a client's needs and goals, and objective motion capture for performance monitoring (Levin et al., 2015). In a comprehensive review, VR-based motor interventions for persons with stroke were found to be beneficial for improving UE motor function and the performance of ADLs when compared with traditional therapy or when used as an adjunct to conventional care (Laver et al., 2015). The excessive use of compensatory movements is a notorious issue with previous VR tools: even commercial gaming systems have been classified based on their ability to address compensation (Anderson et al., 2015). Only a few current tools have been designed to provide extrinsic feedback concerning trunk displacement or flexion. Subramanian and colleagues (2013) used a tool that provided auditory feedback in the form of a "whoosh" sound when participants moved their trunk more than 5cm from a neutral position during virtual TBT. Cameirao and colleagues (2012) compared the same VR system with and without a compensation-restraining robotic device, and found similar improvements in motor performance but mixed results relative to the use of compensatory movements. Alankus and colleagues used custom algorithms with off-the-shelf motion sensors including the Nintendo Wiimote (Nintendo Corp., Redmond, WA) to measure and provide feedback about trunk compensation during repetitive VR-based movements with the shoulder and elbow (Alankus & Kelleher, 2012).

While research in CIMT, TBT, and VR shows that certain tools may be beneficial for reducing compensation, the zero-tolerance restraint of movement may lead to frustration, discomfort, and lack of therapy adherence for persons with stroke. Shaping, or incrementally

decreasing, compensation may be a viable alternative. To our knowledge, few existing VR tools have been designed to incorporate methods of shaping to specifically target trunk compensation during repetitive UE training. The purpose of this study was to establish the feasibility and preliminary efficacy of a novel VR tool for shaping trunk compensation during UE reaching practice for persons with stroke. Our primary hypotheses were that compensatory movement at the trunk would decrease and reaching kinematics would improve during a standardized reach test by participants with chronic stroke as a result of using VRShape. Our secondary hypotheses were that participants would improve motor function, perform large doses of repetitions, and find the system usable, motivating, engaging, and safe.

4.2 Methods

4.2.1 Participants

Five participants with chronic stroke (4 male, 1 female; age 63.2 years) were recruited for this study from the greater St. Louis area (Table 4.1). Participants were eligible for inclusion if they (1) were aged 40-80 years, (2) experienced an ischemic stroke greater than six months prior, (3) exhibited persistent hemiparesis as noted by a score of 1-3 on the motor arm subscale of the National Institutes of Health Stroke Scale (NIHSS) (Goldstein & Samsa, 1997), (4) displayed some voluntary activity in proximal or distal UE joints when asked to reach for an item in their immediate space, and (5) utilized noticeable trunk compensation (>20 deg) when performing these reaching movements with the impaired arm. Participants were excluded if they had any medical conditions that would impair their ability to play computer games, such as significant comprehension difficulties, attentional disorders, or visual field deficits. All participants provided written consent and the Institutional Review Board (IRB) of the Washington University School of Medicine approved all study activities.

Table 4.1. Participant demographics. Basic demographic data was obtained upon enrollment. Initial motor impairment and function were measured using the NIHSS arm/motor subscale and the ARAT. Experience with television, computers, 3D images, and VR were obtained from Part A of the ITC-SOPI.

	Participants				
	P1	P2	P3	P4	P5
Age	62	63	44	69	78
Gender	M	M	M	F	M
Race	White	White	Afr. Amer.	White	Afr. Amer.
Education Level	HS Diploma	Degree	HS Diploma	Degree	Degree
Years Post-Stroke	2	1	4	6	1
Affected Side	R	R	R	L	L
NIHSS Arm/Motor	1	1	1	2	1
ARAT Score	20	10	5	3	11
Computer Experience	None	Expert	Intermediate	None	Expert
Weekly TV Viewing	41+ hours	41+ hours	33-40 hours	0-8 hours	17-24 hours
TV Size Used	Large	Large	Large	Large	Large
3D Glasses Used	No	Yes	No	Yes	Yes
3D Image Knowledge	None	Intermediate	None	None	Basic
Computer Game Use	Never	Often	Every day	Never	Every day
TV Knowledge	None	Basic	Basic	None	Intermedate
VR Usage	No	Yes	No	No	No
VR Knowledge	None	Intermediate	None	None	None

Note: M = male, f = female, R = right, L = left, Afr. Amer. = African American, HS = high school, NIHSS = National Institutes of Health Stroke Scale, ARAT = Action Research Arm Test, ITC-SOPI = Independent Television Commission Sense of Presence Inventory

4.2.2 Virtual Environment

The basis of this intervention is VRShape, a custom-built computer interface designed to shape trunk compensations during the repetitive practice of UE movements. This software builds on previous VR-based strategies that use off-the-shelf sensors to convert motion into the control of a variety of freely available virtual environments (VEs) or computer games, such as the Flexible Action and Articulated Skeleton Toolkit (FAAST) (Suma et al., 2013). In small-scale studies, we have demonstrated that the first (V1) and second (V2) generations of the Microsoft Kinect (Microsoft Corp., Redmond, WA) in combination with FAAST is feasible for use, motivating and engaging, capable of eliciting large doses of repetitions, and capable of

improving aspects of motor function and performance in persons with stroke, children with cerebral palsy, and children with Rett syndrome (Behar et al., 2016; Lauterbach et al., 2013; Mraz et al., 2016; Proffitt et al., 2011; Sevick et al., 2016).

The Kinect V2 is a consumer-ready, affordable (~$150) sensor that has been shown to be satisfactorily valid and reliable relative to the gold standard of video motion capture (VMC) systems for UE movement, postural movement, and various functional movements (Clark et al., 2015; Kuster et al., 2015; Reither et al., 2017). Specifically, the Kinect V2 more closely matches VMC than the Kinect V1 in terms of reaching ROM, planar hand movement, trunk flexion, and trunk lateral flexion for reaching movements in the frontal and scaption (45° between the sagittal and frontal) planes.

VRShape is novel because it incorporates feedback about compensatory movements in the form of visual and auditory virtual events. For the purposes of this study, compensatory trunk flexion was monitored in real-time during repetitive reaching in the scaption plane. A calibration process took place at the beginning of each week during which the participant performed repetitions for approximately two minutes. The average maximum trunk flexion was calculated from this calibration session, and the initial compensation limit was set at 90% of this value. This limit was chosen to keep the participant ideally challenged and was based on existing rules in CIMT and TBT for task grading (Birkenmeier et al., 2010; Taub et al., 1994; Uswatte et al., 2006). During training, if trunk flexion in excess of this defined threshold was detected, feedback was provided in three different ways: (1) a large image of a red stoplight would appear within a highly visible GUI, (2) a "buzzer" sound would be heard, and (3) all conversion of reaching movement into control of VE would be cancelled. These feedback modes would persist until the person moved his or her trunk under the compensation limit.

85

4.2.3 Intervention

Participants took part in 18 intervention sessions over the course of six weeks (3x/week). Each session lasted one hour and consisted of approximately 40 minutes for VR-based therapy, 10 minutes for feasibility outcome assessment, and 10 minutes for technical manipulation and participant rest. The first (pre) and last (post) intervention sessions were longer due to the assessment of efficacy outcomes. The 1-hour session length was chosen based on previously calculated repetitions rates with similar VR systems (Lauterbach et al., 2013; Sevick et al., 2016) and motor interventions that translated large repetition doses from animal studies (Birkenmeier et al., 2010; Lang et al., 2016).

During each session, participants repetitively performed reaching movements in the scaption plane to interact with different VEs. This movement direction was chosen because it is a more common plane of motion than purely sagittal or frontal. The Kinect V2 also has improved measurement capabilities in the scaption and frontal planes, particularly in terms of trunk flexion, trunk lateral flexion, and planar hand displacement. Participants were instructed to start at a neutral position, most commonly with their hand in their lap, and reach as far as possible in the scaption plane. When the hand exceeded a predefined movement threshold relative to the starting position, defined during the aforementioned calibration period, a virtual event specific to the VE in use would be triggered. If the trunk was flexed beyond the predefined limitation, feedback would be instantly provided in the forms described above. Participants were only instructed on the operation of VRShape and the meaning of its feedback modes: no verbal cueing or training was provided by the researcher.

Four different VEs were used during each session. Three of these VEs were freely chosen by each individual based on their goals and preferences, and one was used consistently across all sessions. Participant selected from a previously established list of compatible

computer games, virtual activities of daily living, and other VEs. Some of these VEs had been used in previous investigations and some had been added to a library based on suggestions from participants during an initial session.

4.2.4 Primary Outcomes

Primary outcomes were related to trunk compensation and UE kinematics during a standardized functional reach task (Wagner et al., 2008). This task is a simple targeted reaching assessment that is designed to measure changes in UE reaching kinematics. Participants were seated on a chair within the capture volume of an 8-camera VMC and markers were placed on 25 bony landmarks on the trunk and UE. A target was set at shoulder height and placed in positions corresponding to different reaching conditions. For the purposes of this study, two conditions were tested; in the first, the target was placed at arm's length in the scaption plane. In the second, the target was placed 20cm beyond arm's length in the scaption plane. The participant reached towards each target a total of four times in each of three trials. The kinematics of each movement were analyzed using motion capture software (Motion Analysis Corp., Santa Rosa, CA) and custom analysis software written in MATLAB (Mathworks Inc., Natick, MA). The primary kinematic measures were reaching ROM, planar hand distance, trunk flexion and lateral flexion, shoulder flexion and abduction, and elbow flexion.

4.2.5 Secondary Outcomes

Secondary outcomes included feasibility in the form of usability, motivation, engagement, and safety. The System Usability Scale (SUS) is a short, 10-item questionnaire that uses Likert style questions to evaluate usability following interaction with a technology. Usability in this case may be defined as "appropriateness for its designated task" and can be evaluated along the lines of effectiveness, efficiency, and satisfaction in use (Brooke, 1996). The

87

reliability of the SUS has been evaluated as excellent ($\alpha=0.91$) and it has been validated with an easily interpreted adjective scale (Bangor et al., 2008; Bangor et al., 2009).

The Intrinsic Motivation Inventory (IMI) involves 45-items that make up seven subscales. The subscales include interest/enjoyment, perceived competence, effort, value/usefulness, felt pressure and tension, perceived choice, and experiences of relatedness. Only the interest/enjoyment subscale was used for this study. This IMI subscale has demonstrated good internal consistency ($\alpha = 0.78$) for a variety of applications in sports and rehabilitation (McAuley et al., 1989). This measure has been used in previous investigations into VR-based therapy, requires little training, and can be administered quickly (<10 minutes) (Behar et al., 2016; Lauterbach et al., 2013; Sevick et al., 2016).

The Independent Television Company Sense of Presence Inventory (ITC-SOPI) is a measure of subjective feelings of immersion and presence within VEs and other media forms (Lessiter et al, 2001). The assessment is divided into two parts: Part A consists of six items and refers to the participants' impressions/feelings that follow the virtual experience. Part B consists of 38 items and refers to the subjects' impressions/feelings during the virtual experience. Only Part A was used for this investigation due to time constraints. The ITC-SOPI employs Likert scales and overall the assessment has been shown to measure (1) spatial presence, or how physically present users feel in the VE; (2) engagement, or how involved users feel toward the content of the VE; and (3), ecological validity, or the level of realism and naturalness of the environment. The ITC-SOPI has been established as reliable ($\alpha > 0.76$) and has been validated with various media forms including movies, television, and computer games (Lessiter et al., 2001).

Secondary motor outcomes included measures of repetitions and movement thresholds directly from VRShape. The Action Research Arm Test (ARAT) was also assessed. The ARAT is a highly standardized, quick (<15 minutes) assessment of proximal and distal motor function in the UE that showed strong clinical utility (Connell et al., 2012; Yozbatiran et al., 2008). The assessment uses 19 tests in the subdomains of grasp, grip, pinch, and gross movement. Each subtest is used to rate motor function on a scale of 0 (no movement) to 3 (normal movement). The assessment has excellent test-retest reliability (ICC = 0.97, r = 0.97) and inter-rater reliability (ICC = 0.99, r = 0.99) and is well-validated against other established measures of UE function such as the Fugl-Meyer assessment (r = 0.93) (van der Lee et al., 2001; Platz et al., 2005; Yozbatiran et al., 2008). The minimally clinically important difference (MCID) has been established for persons with chronic stroke and is considered to be 5.7 points or 10% of the assessment's total range (van der Lee et al., 2001).

4.2.6 Statistical Analysis

Non-parametric statistics were used for all analyses due to the small sample size. Wilcoxon signed-rank tests were used to evaluate change in reach test kinematics and ARAT outcomes from pre-intervention to post-intervention ($\alpha = 0.05$). For assessments with multiple domains (ARAT), individual domains were analyzed along with sum scores to evaluate changes in underlying constructs. Individual ARAT scores were compared to existing standards for MCID to determine the resulting clinical significance.

4.3 Results

4.3.1 Primary Outcomes

In terms of preliminary efficacy, trunk flexion used during extended reaches within the standardized reach test decreased significantly from pre- to post-intervention (Figure 4.1) (mean

difference, MD = 8.3°, p = 0.04). There were no significant differences between measurement

periods for other trunk variables during non-extended or extended reaches; however, group

averages for trunk flexion and lateral flexion did slightly decrease for non-extended reaches

(Table 4.2). Trunk lateral flexion was greater during extended reaches than non-extended,

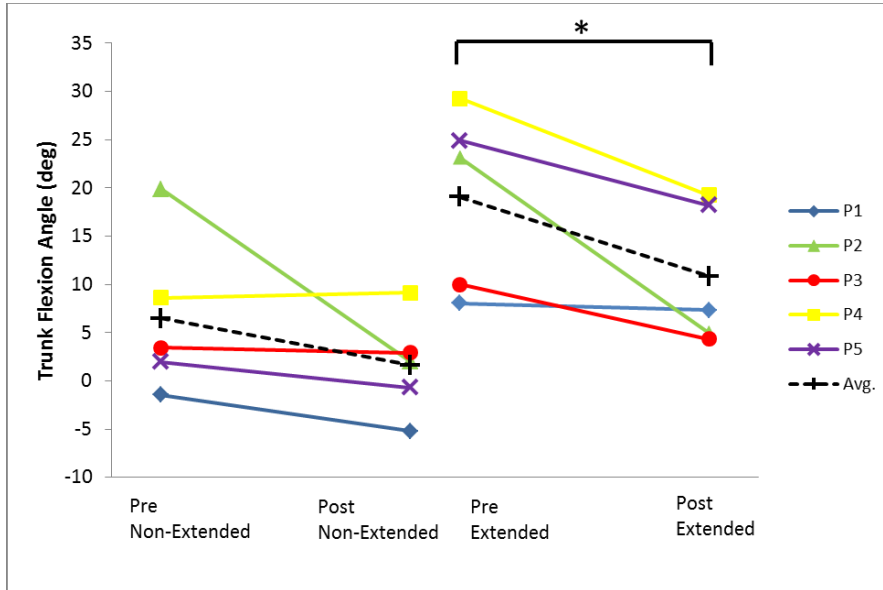signifying more of a tendency to lean towards the target.

Figure 4.1. Change in compensatory trunk flexion during the standardized
reach test from pre- to post-intervention for all participants. Non-extended
reaches are shown in the left curves, and extended reaches are shown in the
right.
* Significant difference from pre- to post (p < 0.05)

Table 4.2. Group means and standard deviations (M ± SD) from pre- to post-intervention for non-extended and extended reaches within the standardized functional reach test. Two separate Wilcoxon Sign-Rank tests were used to compare non-extended reaches from pre- to post-intervention and extended reaches from pre- to post-intervention.

Variable	Non-Extended		Extended	
	Pre	Post	Pre	Post
Reach ROM (cm)	42.3 ± 5.8	45.4 ± 8.4	42.3 ± 7.8	43.8 ± 9.1
Sagittal Reach Distance (cm)	26.3 ± 4.2	30.4 ± 5.8	22.2 ± 7.0	26.9 ± 7.3*
Frontal Reach Distance (cm)	15.3 ± 9.5	16.1 ± 7.8	13.6 ± 9.1	17.4 ± 10.4*
Trunk Flexion (deg)	6.5 ± 8.3	1.6 ± 5.2	19.1 ± 9.5	10.8 ± 7.3*
Trunk Lateral Flexion (deg)	-2.7 ± 4.8	-3.7 ± 5.7	6.2 ± 9.2	5.7 ± 7.3
Shoulder Flexion (deg)	-0.6 ± 6.6	1.2 ± 9.7	5.3 ± 7.4	5.9 ± 10.5
Shoulder Abduction (deg)	26.0 ± 1.2	26.0 ± 3.5	33.1 ± 5.5	36.1 ± 4.1*
Elbow Flexion (deg)	99.4 ± 11.9	92.4 ± 19.3	98.5 ± 17.6	95.6 ± 21.2

* $p < 0.05$ for pre to post, comparing non-extended or extended reaches

Significant differences were also found for the distance reached in the sagittal (MD = 4.7cm, p = 0.04) and frontal (MD = 3.8cm, p = 0.04) planes during extended reaches (Figure 4.2 and Figure 4.3). While overall reaching ROM did not change significantly, it did increase as a result of the intervention during both non-extended and extended reaches. Very little shoulder flexion was utilized for reaching performance, but the amount of shoulder abduction was large and increased significantly from pre- to post-intervention (MD = 3.0º, p = 0.04). Elbow flexion did not change significantly, but did decrease for both reaching types signifying a trend toward greater extension.

Figure 4.2. Change in sagittal plane reach distance during the standardized reach test from pre- to post-intervention for all participants. Non-extended reaches are shown in the left curves, and extended reaches are shown in the right.
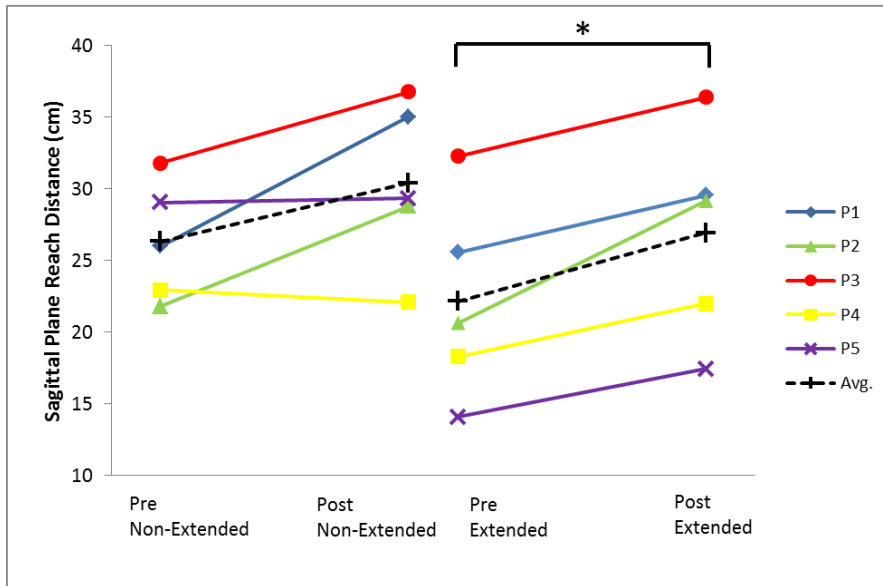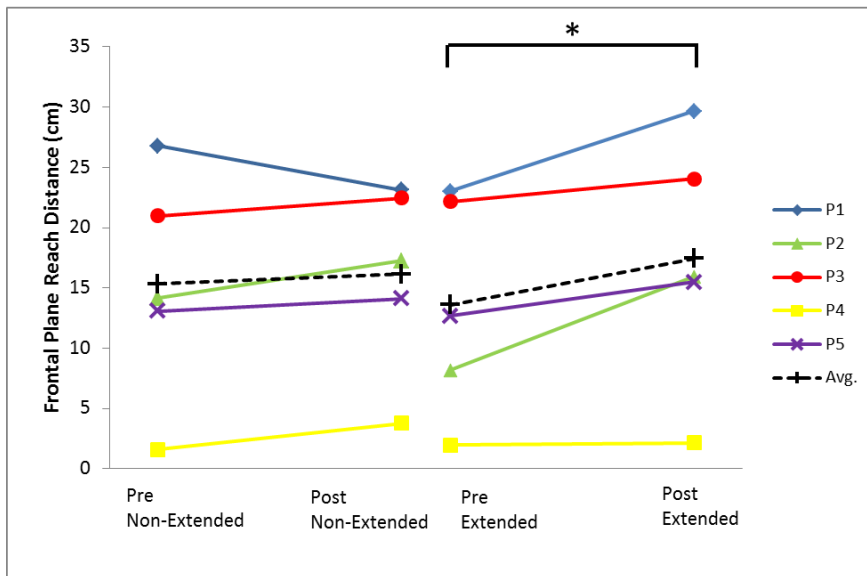 * Significant difference from pre- to post (p < 0.05)

Figure 4.3. Change in frontal plane reach distance during the standardized reach test from pre- to post-intervention for all participants. Non-extended reaches are shown in the left curves, and extended reaches are shown in the right.
 * Significant difference from pre- to post (p < 0.05)

In terms of individual results (Table 4.3), we can see that the majority of participants improved their reaching distances during both non-extended and extended reaches. All participants decreased trunk flexion during extended reaches and four out of five decreased trunk flexion during non-extended. Trunk lateral flexion angles decreased for the majority of participants, signifying less of a trend for leaning towards the target. Shoulder flexion changes varied, but shoulder abduction increased for all participants. Elbow flexion decreased slightly for most participants, representing a trend towards greater extension.

Table 4.3. Individual changes (Post-Pre) in kinematic variables resulting from the intervention.

Variable	P1	P2	P3	P4	P5	Mean
Non-Extended						
Reach ROM (cm)	7.55	5.14	3.22	-0.53	0.12	3.10
Sagittal Reach Distance (cm)	9.03	6.99	4.96	-0.85	0.29	4.09
Frontal Reach Distance (cm)	-3.67	3.11	1.47	2.19	1.01	0.82
Trunk Flexion (deg)	-3.76	-17.83	-0.52	0.51	-2.66	-4.85
Trunk Lateral Flexion (deg)	-3.48	-0.04	2.36	-3.05	-1.10	-1.06
Shoulder Flexion (deg)	10.45	-8.57	15.01	2.49	-10.22	1.83
Shoulder Abduction (deg)	-0.80	5.87	1.51	-4.10	-2.31	0.03
Elbow Flexion (deg)	-22.90	-1.20	-14.45	0.02	3.31	-7.04
Extended						
Reach ROM (cm)	2.35	5.10	2.51	0.38	-2.54	1.56
Sagittal Reach Distance (cm)	4.02	8.52	4.12	3.73	3.38	4.75
Frontal Reach Distance (cm)	6.62	7.76	1.88	0.21	2.81	3.86
Trunk Flexion (deg)	-0.71	-18.16	-5.61	-10.05	-6.70	-8.24
Trunk Lateral Flexion (deg)	-8.43	-9.15	-6.77	9.13	12.58	-0.53
Shoulder Flexion (deg)	8.32	-6.53	8.11	1.49	-8.46	0.58
Shoulder Abduction (deg)	5.41	0.58	0.57	3.51	5.29	3.07
Elbow Flexion (deg)	-9.27	1.03	-9.86	-1.95	5.81	-2.85

Note: Positive values represent an increase from pre- to post-intervention, and positive values represent an increase from pre- to post.

4.3.2 Secondary Outcomes

In terms of feasibility, all participants were able to complete the intervention for a total of 90 sessions without significant technical difficulty. The average number of repetitions achieved with 40 minutes of interaction with VRShape within each intervention session was 512 (SD =

95) (Table 4.4). Participants used 15 different VEs, ranging in average repetitions from 24 to

242 repetitions (Figure 4.4). Over the course of the entire intervention, participants completed

an average of 9,678 repetitions (SD = 1561). The average compensation threshold measured by

VRShape prior to each session decreased by approximately 12.8º and plateaued towards the

second half of the intervention (Figure 4.5). The average reaching threshold defined by

VRShape increased by approximately 11.2cm (Figure 4.6).

Table 4.4. Feasibility outcomes (Mean ± SD) for each participant. Repetitions, usability (SUS), motivation (IMI), engagement (ITC-SOPI), and negative effects (ITC-SOPI) were collected at each intervention session.

	P1	P2	P3	P4	P5	Mean
Total Repetitions	427.4 ± 67.2	467.0 ± 70.1	630.8 ± 154.6	527.9 ± 65.6	507.5 ± 87.5	512.1 ± 95.2
SUS Sum Score	92.9 ± 15.3	92.9 ± 6.01	87.8 ± 11.2	53.3 ± 5.4	99.0 ± 2.9	85.2 ± 18.8
IMI Interest/Enjoyment	46.8 ± 3.2	44 ± 0.0	49 ± 0.0	26.9 ± 5.5	49 ± 0.0	43.2 ± 8.8
ITC-SOPI Engagement	3.7 ± 0.4	3.7 ± 0.2	4.9 ± 0.2	2.3 ± 0.4	5.0 ± 0.2	3.9 ± 1.0
ITC-SOPI Negative Effects	1.0 ± 0.0	1.0 ± 0.0	1.0 ± 0.0	2.4 ± 0.7	1.0 ± 0.0	1.3 ± 0.7

Note: SUS = System Usability Scale, IMI = Intrinsic Motivation Inventory, ITC-SOPI = Independent Television
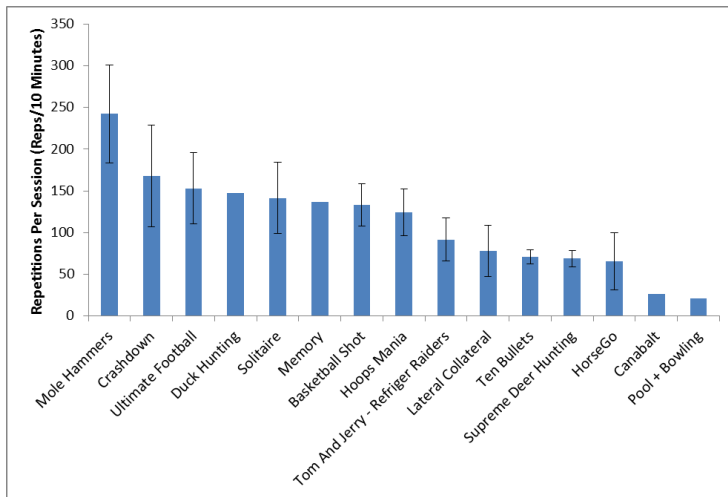
Figure 4.4. Repetitions achieved per 10 minutes with each of the 15 games used during the VR-based intervention using VRShape.
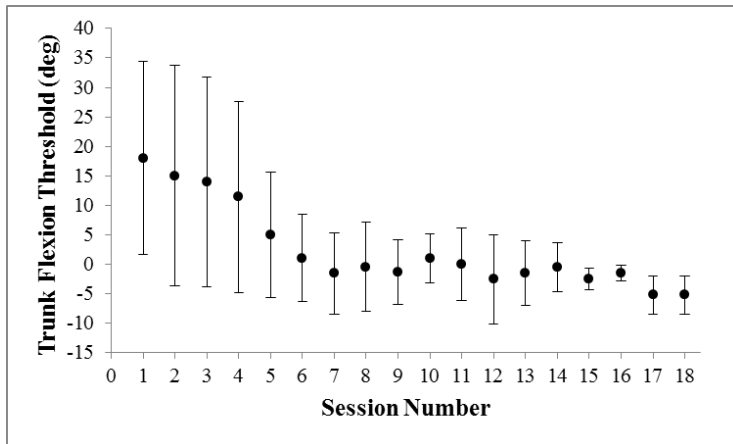
Figure 4.5. Average trunk flexion compensation threshold automatically measured and calibrated by VRShape over the course of 18 intervention sessions.
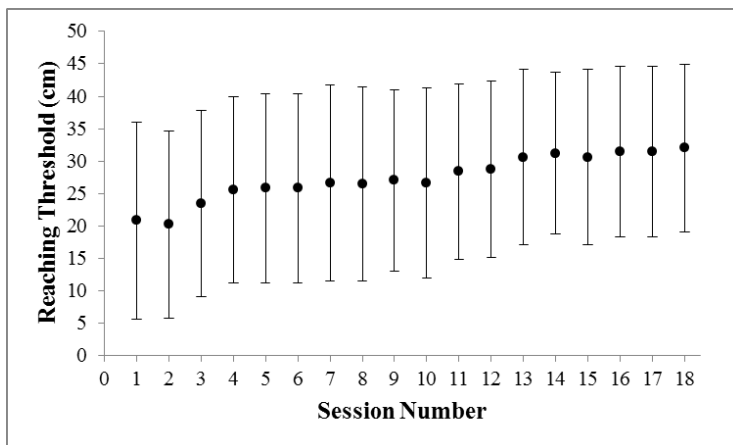
Figure 4.6. Average reaching threshold automatically measured and calibrated by VRShape over the course of 18 intervention sessions.

The average SUS sum score from all interventions sessions was relatively high (M = 85.2, SD = 18.8) and represents an adjective rating of "excellent" or a letter grade average of "B" (Bangor et al., 2009). The average IMI interest/enjoyment score was also high (M = 43.16, SD = 8.80). The ITC-SOPI Part A scores are broken into subscales of engagement and negative effects: engagement was moderately high (M = 3.93, SD = 0.96) and negative effects were very low (M = 1.28, SD = 0.57). In terms of individuals, only one person tended to rate the system

95

more negatively than others (P4), showing moderate levels of usability, motivation, engagement. This was also the only individual to report a negative effect on the ITC-SOPI. Interestingly, this participant also has the least experience using computers, VR, and other digital media forms (Table 4.1).

Mean ARAT score improved from pre- to post-intervention but did not achieve statistical significance (MD = 2.4). On an individual level, three participants improved their ARAT score and two remained the same. One participant approached the MCID for the ARAT by improving the overall score by five points (MCID = 5.7). The largest subscale increase was for the gross motor portion (MD = 0.8), for which three out of five participants improved (Figure 4.7).
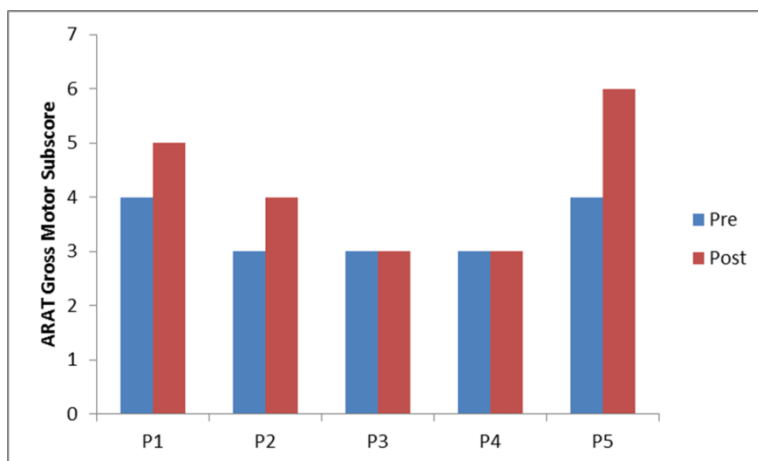
Figure 4.7. Gross motor subscale scores of the ARAT for each participant from pre- and post-intervention.

4.4 Discussion

The purpose of this study was to examine the feasibility and preliminary efficacy of using a novel VR tool (VRShape) designed to shape trunk compensation over the course of a six-week VR-based motor intervention for a small cohort of persons with stroke. Participants that used VRShape were able to decrease the amount of trunk flexion, increase their planar reaching distances, and increase their shoulder abduction when reaching to a target during a standardized

96

reach task. Participants were able to complete very large doses of UE movement practice using VRShape and found the system to be usable, motivating, and safe throughout the intervention. The majority of participants were able to improve their gross movement abilities as measured by a standardized assessment of motor function.

Over the course of 90 intervention sessions, several limitations in the software and study design arose. First, it is difficult to make definitive conclusions about the study results due to the small sample size. Further research should include a larger sample size and more advanced study design that includes a comparison group. Second, it became clear that the ARAT, while chosen as an outcome measure due to its popularity in stroke research, included many domains that were not a target of training with VRShape. The Kinect does not reliably track finger or hand movement, and therefore these finer movements are not a part of the VRShape control scheme; however, the ARAT has several domains that involve pinch, grasp, and grip that were not likely to change as a result of the intervention. The gross motor subscale was most likely to change as a result of using VRShape, and indeed, three out of five participants improved their score on this subscale. Finally, due to the nature of this investigation, all research was performed within a controlled laboratory setting and all outcomes were focused on the effect of the intervention on specific motor abilities. The transfer of training to everyday activities outside of the laboratory was not assessed. Several studies have shown that it is possible for training in VEs to affect performance of similar activities in the real world, but large review papers have noted that lack of outcomes related to activity performance, participation, and quality of life are serious shortcomings in current VR research (Laver et al., 2015; Levin et al., 2015; Lohse et al., 2014a).

Our results show a significant average decrease of 8.3º of trunk flexion during extended reaching to a target in the scaption plane by persons with chronic stroke as a result of using VRShape. Clinical significance for kinematic changes in trunk flexion is estimated at 4.8cm during a reach-to-point task to change one unit on the Fugl-Meyer Assessment, a common measure of motor impairment (Subramanian et al., 2010a). Based on our 3D kinematic model, the observed change in trunk flexion is well above this threshold and is therefore clinically significant for improving UE motor impairment. Our evidence is supported by a recent review that found trunk restraint to have a large effect for decreasing trunk displacement during TBT and CIMT (Wee et al., 2014). Woodbury and colleagues (2009) found an approximate 9% decrease in trunk displacement as measured relative to a straight-line path between the participant's hand and the reaching target (Woodbury et al., 2009). Analogously, our angular change represents an approximate average 43% reduction in the amount of trunk compensation used during reaching. Due to the novelty of our VR tool and limitations in the current study, it is impossible to directly compare our results to previous research; however, it is clear that VRShape produces results on the same level as existing techniques that utilize trunk restraint and therefore may be a more desirable alternative due to its ability to provide a more motivating and engaging environment.

The initial severity of motor impairment has been well established as the best predictor for the amount of possible motor recovery following stroke (Coupar et al., 2012). For those with greater initial impairment, the trajectory of recovery may be slower and with a lower plateau for achievable improvement (Beebe & Lang, 2009). Our results show that three out of five participants were able to increase their motor function as measured by the ARAT, most notably the gross motor subscale. The two participants that did not improve motor function (P3 and P4)

showed the lowest pre-intervention ARAT scores, while the participant that experienced the greatest improvement (P5) showed the highest pre-intervention ARAT scores. Conversely, these same two participants with the lowest initial function were able to decrease their amount of compensatory trunk flexion similarly and sometimes to a greater extent than higher functioning participants. This suggests that, even in this small sample, there exists relationships between initial severity and possible motor recovery where higher functioning individuals may improve more drastically but also may not require as much compensation intervention. It is clear that, while group results were promising from this study, not all individuals with stroke may benefit from using VRShape. It may be important in future research to further define the optimal users for VRShape in order to maximize their possible motor improvements. Based on results of this study and in order to maximize motivation, engagement, and motor recovery, optimal users might be those with prior computer experience with moderately impaired motor abilities requiring some initial trunk compensation.

Extrinsic feedback is an important aspect of motor learning and is an inherent design feature of VRShape. The learning and retention of real-world motor tasks, such as reaching and grasping for objects, is enhanced by the provision of feedback similar to that provided within VRShape (Krakauer, 2006). In particular, intermittent feedback concerning performance during reaching tasks has been shown to improve ROM, increase interjoint coordination, and facilitate impairment and functional gains associated with decreased trunk rotations relative to feedback concerning results in persons with hemiparetic stroke (Cirstea & Levin, 2007; Subramanian et al., 2010b). Common UE rehabilitation paradigms utilize such evidence to guide therapists in providing explicit and fading feedback cues depending on an individual's impairment severity, task performance, and learning progress (Muratori et al,. 2013).

99

The ability to automatically and engagingly provide salient feedback is a major advantage of VR-based motor rehabilitation and has also been shown to improve motor outcomes (Laver et al., 2015; Levin et al., 2015). For example, augmented feedback in the form of either robotic haptics or virtual visual stimuli has been shown to produce greater improvements in motor impairment as measured by the Fugl-Meyer Assessment and the Wolf Motor Function Test compared to no feedback (Abdollahi et al., 2014). VRShape was able to significantly improve movement kinematics for persons with stroke most likely due, at least in part, to the ability to provide audio and visual feedback for both knowledge of performance, or trunk kinematics during an UE movement, and knowledge of results, or the success/failure of an UE movement repetition. Knowledge of performance occurred in the form of a real-time updating graph of trunk movement as well as a "buzzer" sound and the display of a traffic light if too much trunk compensation is utilized. Knowledge of results occurred in the form of a virtual event within a VE or computer game when an UE movement is performed successfully without compensation. For the purposes of this study, each of these feedback forms was provided during therapy for all participants. However, current literature posits that more research is needed to determine the most effective mode and frequency of feedback for optimizing motor learning on a client-centered, individualized basis for persons with stroke (Subramanian et al., 2010b). VRShape may be capable of providing variable, customizable feedback in the future with the goal of optimizing recovery and providing further evidence for feedback-driven motor learning.

The most analogous VR system was tested by Subramanian and colleagues (2013) and it provided feedback about reaching performance and trunk displacement in auditory and visual form (Subramanian et al., 2013). Feedback about compensation occurred in the form of a "whoosh" sound that would be heard if the trunk was displaced by a constant threshold (5cm).

100

Participants with chronic stroke were randomized to either a VR group or a dose-matched control group that got similar feedback. A subset of participants in the VR group improved elbow extension without utilizing the trunk during a reach-to-grasp task, while participants in the control group required greater trunk movement (30mm) to achieve the same increase in elbow extension. While participants in the current study did not achieve significant changes in elbow movement, a relationship between improvements in motor performance and decreases in trunk displacement was found, in theory due to shaping and feedback provided during the intervention.

The average number of repetitions performed by each participant over the course of the intervention (n = 9,678) approached the colloquial 10,000 repetitions threshold defined by traditional motor learning theory. The average number of massed repetitions performed during each session (n = 509) was much greater than observed in typical stroke rehabilitation sessions (n=32) (Lang et al., 2007). Large doses of practice are known to excite cortical processes associated with neuroplasticity in order to produce robust motor learning; in a recent review by Lohse and colleagues (2014b), researchers found that larger repetition doses were associated with a small-moderate effect size over control groups that received smaller less dose (Lohse et al., 2014b). While this seminal research has postulated that "more is better," a recent comprehensive study performed by Lang and colleagues (2016) found that maximum tolerable repetition may not actually lead to greater improvements in UE motor function for persons with chronic impairment due to stroke. Future work involving further iterations of the VRShape software should include a comparison group to establish relative efficacy.

While many VR systems have proven efficacious in small-scale studies, and a few have provided knowledge of performance or results regarding compensation, very few have sought to incrementally decrease the amount of compensation over the course of an intervention. The

overuse of compensatory movements is hypothesized to affect the degree to which motor recovery is possible following stroke, therefore a tool that can simultaneously decrease compensation and improve UE movement abilities may help to optimize post-stroke motor outcomes moving forward. Occupational therapy clinicians often report lack of time, availability, accessibility, and difficulty in implementation as common barriers to using advances in evidence-based practice (Upton et al., 2014). In addition, compensatory movement is often addressed only through verbal cues and subjective observation in a clinical setting (Levin et al., 2009). VRShape has the potential to act as an affordable, easy-to-use, engaging, and safe tool for providing intense UE motor therapy and facilitating the delivery of evidence-based practice for rehabilitation professionals.

Future work involving VRShape should involve a larger-scale study with a comparison group to show efficacy relative to no therapy, conventional therapy, or dose-matched therapy. Assessments that are more sensitive to changes in reaching kinematics should be included in the future, along with measurements of in-laboratory improvements transferred to changes in real-world activity performance, participation, and quality of life. It is also possible for VRShape to capture and shape compensatory movements at other joints, such as the shoulder, which may be useful for future measurement and intervention purposes.

4.5 Conclusion

VRShape is a novel rehabilitation tool designed to shape compensatory trunk movements during the performance of UE reaching practice within motivating VEs. Participants found VRShape to be feasible for use as measured by excellent usability, high motivation, moderately high engagement, and very low negative effects. A preliminary effect was observed following a six-week, VR-based intervention in the form of significantly decreased compensatory trunk

flexion, increased shoulder abduction, and increased planar reaching ROM during a standardized

reach test. Future research is needed to establish the efficacy of VRShape relative to

conventional or dose-matched UE therapy, but this study shows that it has promise for future

research and development.

4.5.1 Conflict of Interest Statement

Both Matthew Foreman and Dr. Jack Engsberg have financial interests in Accelerated

Rehabilitation Technologies (ART) and may financially benefit if the company is successful in

licensing and market software related to VRShape and this research performed at Washington

University.

4.6 References

Abdollahi, F., Case Lazarro, E. D., Listenberger, M., Kenyon, R. V., Kovic, M., Bogey, R. A., ... & Patton, J. L. (2014). Error augmentation enhancing arm recovery in individuals with chronic stroke: a randomized crossover design. *Neurorehabilitation and neural repair*, *28*(2), 120-128.

Alankus, G., & Kelleher, C. (2012). Reducing compensatory motions in video games for stroke rehabilitation. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 2049-2058). ACM.

Alaverdashvili, M., Foroud, A., Lim, D. H., & Whishaw, I. Q. (2008). "Learned baduse" limits recovery of skilled reaching for food after forelimb motor cortex stroke in rats: a new analysis of the effect of gestures on success. *Behavioural brain research*, 188(2), 281-290.

Alaverdashvili, M., & Whishaw, I. Q. (2013). A behavioral method for identifying recovery and compensation: hand use in a preclinical stroke model using the single pellet reaching task. *Neuroscience & Biobehavioral Reviews*, *37*(5), 950-967.

Allred, R. P., Cappellini, C. H., & Jones, T. A. (2010). The "good" limb makes the "bad" limb worse: Experience-dependent interhemispheric disruption of functional outcome after cortical infarcts in rats. *Behavioral neuroscience*, 124(1), 124.

Anderson, K. R., Woodbury, M. L., Phillips, K., & Gauthier, L. V. (2015). Virtual reality video games to promote movement recovery in stroke rehabilitation: a guide for clinicians. *Archives of physical medicine and rehabilitation, 96*(5), 973-976.

Bangor, A., Kortum, P. T., & Miller, J. T. (2008). An empirical evaluation of the system usability scale. *Intl. Journal of Human–Computer Interaction*, *24*(6), 574-594.

Bangor, A., Kortum, P., & Miller, J. (2009). Determining what individual SUS scores mean: Adding an adjective rating scale. *Journal of usability studies*, *4*(3), 114-123.

Beebe, J. A., & Lang, C. E. (2009). Active range of motion predicts upper extremity function 3 months after stroke. *Stroke*, *40*(5), 1772-1779.

Behar, C., Lustick, M., Foreman, M. H., Webb, J., & Engsberg, J. R. (2016). Personalized Virtual Reality for Upper Extremity Rehabilitation: Moving from the Clinic to a Home Exercise Program. *Journal of Intellectual Disability-Diagnosis and Treatment*, *4*(3), 160-169.

Birkenmeier, R. L., Prager, E. M., & Lang, C. E. (2010). Translating animal doses of task-specific training to people with chronic stroke in one hour therapy sessions: a proof-of-concept study. *Neurorehabilitation and neural repair*, *24*(7), 620.

Brooke, J. (1996). SUS-A quick and dirty usability scale. *Usability evaluation in industry*, *189*(194), 4-7.

Cirstea, M. C., & Levin, M. F. (2000). Compensatory strategies for reaching in stroke. *Brain*, *123*(5), 940-953.

Cirstea, M. C., & Levin, M. F. (2007). Improvement of arm movement patterns and endpoint control depends on type of feedback during practice in stroke survivors. *Neurorehabilitation and neural repair*, *21*(5), 398-411.

Clark, R. A., Pua, Y. H., Oliveira, C. C., Bower, K. J., Thilarajah, S., McGaw, R., ... & Mentiplay, B. F. (2015). Reliability and concurrent validity of the Microsoft Xbox One Kinect for assessment of standing balance and postural control. *Gait & posture*, *42*(2), 210-213.

Connell, L. A., & Tyson, S. F. (2012). Clinical reality of measuring upper-limb ability in neurologic conditions: a systematic review. *Archives of physical medicine and rehabilitation*, *93*(2), 221-228.

Coupar, F., Pollock, A., Rowe, P., Weir, C., & Langhorne, P. (2012). Predictors of upper limb recovery after stroke: a systematic review and meta-analysis. *Clinical rehabilitation*, *26*(4), 291-313.

Csikszentmihalyi, M. (1996). Flow and the psychology of discovery and invention. *New York: Harper Collins*.

Goldstein, L. B., & Samsa, G. P. (1997). Reliability of the national institutes of health stroke scale. *Stroke, 28*(2), 307-310.

Kitago, T., Liang, J., Huang, V. S., Hayes, S., Simon, P., Tenteromano, L., ... & Krakauer, J. (2013). Improvement after constraint-induced movement therapy. *Neurorehabilitation and Neural Repair*, *27*(2), 99-109.

Kleim, J. A., & Jones, T. A. (2008). Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. *Journal of speech, language, and hearing research*, *51*(1), S225-S239.

Krakauer, J. W. (2006). Motor learning: its relevance to stroke recovery and neurorehabilitation. *Current opinion in neurology*, *19*(1), 84-90.

Kuster, R. P., Heinlein, B., Bauer, C. M., & Graf, E. S. (2016). Accuracy of KinectOne to quantify kinematics of the upper body. *Gait & posture*, 47, 80-85.

Lang, C. E., MacDonald, J. R., & Gnip, C. (2007). Counting repetitions: an observational study of outpatient therapy for people with hemiparesis post-stroke. *Journal of Neurologic Physical Therapy*, *31*(1), 3-10.

Lang, C. E., Bland, M. D., Bailey, R. R., Schaefer, S. Y., & Birkenmeier, R. L. (2013). Assessment of upper extremity impairment, function, and activity after stroke: foundations for clinical decision making. *Journal of Hand Therapy*, *26*(2), 104-115.

Lang, C. E., Strube, M. J., Bland, M. D., Waddell, K. J., Cherry-Allen, K. M., Nudo, R. J., ... & Birkenmeier, R. L. (2016). Dose response of task-specific upper limb training in people at least 6 months poststroke: A phase II, single-blind, randomized, controlled trial. *Annals of neurology*, *80*(3), 342-354.

Lauterbach, S. A., Foreman, M. H., & Engsberg, J. R. (2013). Computer games as therapy for persons with stroke. *GAMES FOR HEALTH: Research, Development, and Clinical Applications*, *2*(1), 24-28.

Laver, K. E., George, S., Thomas, S., Deutsch, J. E., & Crotty, M. (2015). Virtual reality for stroke rehabilitation. *The Cochrane Library*.

Lessiter, J., Freeman, J., Keogh, E., & Davidoff, J. (2001). A cross-media presence questionnaire: The ITC-Sense of Presence Inventory. *Presence: Teleoperators and virtual environments*, 10(3), 282-297.

Levin, M. F., Kleim, J. A., & Wolf, S. L. (2009). What do motor "recovery" and "compensation" mean in patients following stroke?. *Neurorehabilitation and neural repair*, *23*(4), 313-319.

Levin, M. F., Weiss, P. L., & Keshner, E. A. (2015). Emergence of virtual reality as a tool for upper limb rehabilitation: incorporation of motor control and motor learning principles. *Physical therapy*, *95*(3), 415.

Lohse, K. R., Hilderman, C. G., Cheung, K. L., Tatla, S., & Van der Loos, H. M. (2014a). Virtual reality therapy for adults post-stroke: a systematic review and meta-analysis exploring virtual environments and commercial games in therapy. *PloS one, 9*(3), e93318.

Lohse, K. R., Lang, C. E., & Boyd, L. A. (2014b). Is more better? Using metadata to explore dose–response relationships in stroke rehabilitation. *Stroke*, *45*(7), 2053-2058.

McAuley, E., Duncan, T., & Tammen, V. V. (1989). Psychometric properties of the Intrinsic Motivation Inventory in a competitive sport setting: A confirmatory factor analysis. *Research quarterly for exercise and sport, 60*(1), 48-58.

Michaelsen, S. M., Dannenbaum, R., & Levin, M. F. (2006). Task-specific training with trunk restraint on arm recovery in stroke. *Stroke*, *37*(1), 186-192.

Muratori, L. M., Lamberg, E. M., Quinn, L., & Duff, S. V. (2013). Applying principles of motor learning and control to upper extremity rehabilitation. *Journal of Hand Therapy, 26*(2), 94-103.

Nichols-Larsen, D. S., Clark, P. C., Zeringue, A., Greenspan, A., & Blanton, S. (2005). Factors influencing stroke survivors' quality of life during subacute recovery. *Stroke*, *36*(7), 1480-1484.

Platz, T., Pinkowski, C., van Wijck, F., Kim, I. H., Di Bella, P., & Johnson, G. (2005). Reliability and validity of arm function assessment with standardized guidelines for the Fugl-Meyer Test, Action Research Arm Test and Box and Block Test: a multicentre study. *Clinical Rehabilitation*, *19*(4), 404-411.

Proffitt, R. M., Alankus, G., Kelleher, C. L., & Engsberg, J. R. (2011). Use of computer games as an intervention for stroke. *Topics in stroke rehabilitation*, *18*(4), 417-427.

Rabadi, M. H., & Rabadi, F. M. (2006). Comparison of the action research arm test and the Fugl-Meyer assessment as measures of upper-extremity motor weakness after stroke. *Archives of physical medicine and rehabilitation*, *87*(7), 962-966.

Reither, L. R., Foreman, M. H., Migotsky, N., Haddix, C., & Engsberg, J. R. (2017). Upper extremity movement reliability and validity of the Kinect version 2. *Disability and Rehabilitation: Assistive Technology*, 1-9.

Sathian, K., Buxbaum, L. J., Cohen, L. G., Krakauer, J. W., Lang, C. E., Corbetta, M., & Fitzpatrick, S. M. (2011). Neurological principles and rehabilitation of action disorders: common clinical deficits. *Neurorehabil Neural Repair, 25*(5 Suppl), 21S-32S.

Sauro, J., & Lewis, J. R. (2011). When designing usability questionnaires, does it hurt to be positive?. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 2215-2224). ACM.

Sevick, M., Eklund, E., Mensch, A., Foreman, M., Standeven, J., & Engsberg, J. (2016). Using free internet videogames in upper extremity motor training for children with cerebral palsy. *Behavioral Sciences*, *6*(2), 10.

Subramanian, S. K., Yamanaka, J., Chilingaryan, G., & Levin, M. F. (2010a). Validity of movement pattern kinematics as measures of arm motor impairment poststroke. *Stroke*, *41*(10), 2303-2308.

Subramanian, S. K., Massie, C. L., Malcolm, M. P., & Levin, M. F. (2010b). Does provision of extrinsic feedback result in improved motor learning in the upper limb poststroke? A systematic review of the evidence. *Neurorehabilitation and neural repair*, *24*(2), 113-124.

Subramanian, S. K., Lourenço, C. B., Chilingaryan, G., Sveistrup, H., & Levin, M. F. (2013). Arm motor recovery using a virtual reality intervention in chronic stroke: randomized control trial. *Neurorehabilitation and neural repair*, *27*(1), 13-23.

Taub, E., Crago, J. E., Burgio, L. D., Groomes, T. E., Cook, E. W., DeLuca, S. C., & Miller, N. E. (1994). An operant approach to rehabilitation medicine: overcoming learned nonuse by shaping. *Journal of the experimental analysis of behavior*, *61*(2), 281-293.

Thielman, G., Kaminski, T., & Gentile, A. M. (2008). Rehabilitation of reaching after stroke: comparing 2 training protocols utilizing trunk restraint. *Neurorehabilitation and neural repair*, *22*(6), 697-705.

Upton, D., Stephens, D., Williams, B., & Scurlock-Evans, L. (2014). Occupational therapists' attitudes, knowledge, and implementation of evidence-based practice: a systematic review of published research. *The British Journal of Occupational Therapy, 77*(1), 24-38.

Uswatte, G., Taub, E., Morris, D., Barman, J., & Crago, J. (2006). Contribution of the shaping and restraint components of constraint-induced movement therapy to treatment outcome. *NeuroRehabilitation*, *21*(2), 147-156.

Van der Lee, J. H., De Groot, V., Beckerman, H., Wagenaar, R. C., Lankhorst, G. J., & Bouter, L. M. (2001). The intra-and interrater reliability of the action research arm test: a practical test of upper extremity function in patients with stroke. *Archives of physical medicine and rehabilitation*, *82*(1), 14.

Vestling, M., Tufvesson, B., & Iwarsson, S. (2003). Indicators for return to work after stroke and the importance of work for subjective well-being and life satisfaction. *Journal of rehabilitation medicine*, *35*(3), 127-131.

Wagner, J. M., Rhodes, J. A., & Patten, C. (2008). Reproducibility and minimal detectable change of three-dimensional kinematic analysis of reaching tasks in people with hemiparesis after stroke. *Physical therapy*, *88*(5), 652.

Wee, S. K., Hughes, A. M., Warner, M., & Burridge, J. H. (2014). Trunk restraint to promote upper extremity recovery in stroke patients: a systematic review and meta-analysis. *Neurorehabilitation and neural repair*, *28*(7), 660-677.

Woodbury, M. L., Howland, D. R., McGuirk, T. E., Davis, S. B., Senesac, C. R., Kautz, S., & Richards, L. G. (2009). Effects of trunk restraint combined with intensive task practice on poststroke upper extremity reach and function: a pilot study. *Neurorehabilitation and neural repair*, *23*(1), 78-91.

Yozbatiran, N., Der-Yeghiaian, L., & Cramer, S. C. (2008). A standardized approach to performing the action research arm test. *Neurorehabilitation and neural repair*, *22*(1), 78-90.

Chapter 5: Conclusion

5.1 Overall Summary

The goal of this project was to develop and test a novel technological tool for measuring and shaping trunk compensatory movement during VR-based motor therapy for persons with chronic hemiparetic stroke. To achieve this, we investigated (1) the validity and reliability of two off-the-shelf motion sensors (Microsoft Kinect V1 and V2) for measuring arm, shoulder, and trunk ROM during reaching movements, (2) the initial feasibility of a prototype software, VRShape, for measuring trunk compensation during a single session of UE reaching practice, and (3) the feasibility and preliminary efficacy of a VR-based motor intervention using VRShape. This research combined motor learning theory with engineering principles to progress through an iterative development process based on the performance of hardware components (Chapter 2), the performance of software components (Chapter 3 and 4), feedback from end-users (Chapter 3 and 4), and the treatment effect of the system as a whole (Chapter 4). Objective and subjective data were collected at three testing levels including two sessions with healthy model participants (Chapter 2), a single model session with stroke participants (Chapter 3), and multiple intervention sessions with stroke participants (Chapter 4). The end result is a robust assessment of the abilities of VRShape for its intended purpose as a rehabilitation tool. Future work is needed to address limitations in the current research.

5.1.1 Chapter 2 Summary

In the majority of VR rehabilitation applications, some type of motion sensor is typically required to measure client movement. The Microsoft Kinect is one of the most popular of these input devices due to its affordability, ability to measure skeletal motion without wearable trackers, and ease of development for kinematic motion capture (Lange et al., 2012). Several

studies have examined the tracking accuracy and reliability of the first generation Kinect (K1)

for clinically-relevant UE and trunk movements (Bonnechere et al., 2014; Clark et al., 2012).

Only a few existing studies have examined similar properties of the second generation Kinect

(K2) (Clark et al., 2015; Reither et al., 2017). The K2 boasts greatly enhanced camera and depth

resolution, an improved depth tracking algorithm, and the ability to track more skeletal

landmarks, and therefore may be an improvement for development in the VR-based

rehabilitation field moving forward (Pagliari & Pinto, 2015).

In Chapter 2, our purpose was to investigate the measurement abilities of these two off-

the-shelf motion sensors, the K1 and K2, relative to the gold standard of an 8-camera video

motion capture system (VMC). Specifically, a small cohort of healthy participants (n = 5)

performed a series of reaching movements in the forward (sagittal), scaption, and lateral (frontal)

planes under two different conditions and on two separate testing days while being

simultaneously measured by the K1, the K2, and the VMC. Kinematic variables representing

reaching ROM, planar reach distance, shoulder flexion and abduction, trunk flexion and lateral

flexion, and elbow extension were collected for a non-extended (arm's length) and an extended

(20cm beyond arm's length) reach in each direction. The extended reaching condition was used

to simulate trunk compensations that might be utilized by persons with hemiparetic stroke (Levin

et al., 2002).

Results showed that the K2 was closer in magnitude and showed greater agreement with

the gold standard than did the K1 for trunk movements during extended reaches in all directions.

No studies to date have compared the validity of these two sensors from simultaneous

measurement of trunk movement. Multiple studies have found similar validity results for the K1

during UE, postural, and full-body functional tasks for both healthy and clinical populations

(Bonnechere et al., 2013; Clark et al., 2012; Galna et al., 2014). Kuster and colleagues (2016) found similar magnitude differences between the K2 and VMC for trunk lateral flexion during seated, non-extended shoulder movements in the sagittal, scaption, and frontal planes (Kuster et al., 2016). Clark and colleagues (2015) also found similar validity results for K2 during dynamic balance tasks involving forward and lateral extended reaches and trunk bending to limits of stability (Clark et al., 2015). Both the K1 and K2 were highly correlated with the VMC for reaching ROM, planar reach distance, and elbow extension. These results are supported by previous research that shows strong agreement between the K1 and VMC during functional UE movements (Clark et al., 2012). A study performed within our laboratory found similar agreement between the K1, K2, and VMC for ROM of similar UE movements performed in the sagittal, frontal, and transverse planes from movements with a single participant on multiple days (Reither et al., 2017). Reliability results were mixed, but in general, all three sensors showed moderate to excellent reliability for measuring movement kinematics during extended reaches across testing days. In conclusion, the K2 should be prioritized for VR software development that primarily aims to measure arm kinematics and trunk compensations.

5.1.2 Chapter 3 Summary

The greatest advantages for VR in motor rehabilitation applications are its abilities to elicit large doses of movement repetitions, motivate the client, be customized to individual client goals and preferences, and provide automatic and objective feedback (Holden 2005; Levin et al., 2015; Rizzo & Kim, 2005). These are key factors for stimulating mechanisms of neuroplasticity and motor learning processes that have been shown to improve motor performance even for those in the chronic phase of stroke (Kleim & Jones, 2008). However, several barriers preventing widespread adoption of VR overshadow these advantages, including difficult-to-use

computer interfaces, disengagement of the client due to boredom or technical difficulties, and ambiguity concerning the most effective form of feedback (Levin et al., 2015).

In Chapter 3, our purpose was to investigate the feasibility of using VRShape as the basis for motor therapy. A small cohort of persons with chronic stroke (n =5) participated in a 1-hour session using VRShape during which they performed repetitive reaching movements within four different virtual environments (VEs). Outcomes related to system usability (System Usability Scale, SUS), motivation (Intrinsic Motivation Inventory, IMI), and virtual presence (Sense of Presence Inventory, ITC-SOPI) were collected following each session along with a semi-structured interview to obtain feedback about qualities of the system. Repetition counts were collected by VRShape during each session.

Participants achieved an average of 461 repetitions in just 40 minutes of directly using VRShape while compensating during approximately 25% of reaches. Participants rated the system as acceptably usable with a score representing an adjective rating of "OK." The average usability score was near the established global average from the population of assessed media devices, but informed researchers that there was room for improvement (Brooke, 2013). Motivation for using the system was high, and mirrored assessment in other similar VR devices (Behar et al., 2016; Proffitt & Lange, 2015; Sevick et al., 2016). The system was viewed as engaging and safe, but not ecologically valid and poor in creating a sense of virtual presence. Engagement was higher than existing systems that use more immersive hardware, and negative effects were very near the bottom of the possible rating scale (Lessiter et al., 2001). Altogether considering the performance of the system, subjective assessment, and qualitative user feedback from stroke participants, we concluded that, following slight changes in system efficiency and the addition of new VEs, this rehabilitation tool was feasible to use in a motor intervention.

112

5.1.3 Chapter 4 Summary

In Chapter 4, our purpose was to investigate the feasibility and preliminary efficacy of VRShape over the course of a motor intervention for persons with stroke. A small cohort of participants with chronic hemiparetic stroke (n = 5) took part in 18 intervention sessions that each lasted one hour. Repetitive reaching practice was performed at each session within four different VEs. The extent of trunk flexion was assessed at the beginning of each week, and a threshold of allowable compensation was calculated as 90% of this value. If movement beyond this threshold was detected, negative auditory and visual feedback was instantly provided. A standardized reach test was assessed before and after the intervention, during which participants performed reaching movements in the scaption plane to a non-extended (arm's length) and extended (20cm beyond arm's length) target. Motor function was also assessed using the Action Research Arm Test (ARAT) pre- and post-intervention. Similar feasibility assessments to Chapter 2 were used at the conclusion of each session. Repetitions and kinematics were measured by VRShape over the course of the intervention.

Participants used significantly less trunk flexion (8.3°) while reaching farther in the sagittal (4.7cm) and frontal (3.7cm) planes during the standardized reach test as a result of the intervention. This represents a clinically significant change in trunk flexion movement. Participants achieved an average of 9,678 repetitions over the course of 18 sessions, and an average of 509 repetitions within a single session using VRShape. Single session doses, again, greatly eclipse that seen in analogous VR therapy (~32 per 5 minutes) and typical UE therapy (32 per session) (Lang et al., 2007; Lauterbach et al., 2013). The total dose approaches the colloquial 10,000 repetitions threshold established by motor learning therapy and the optimal dose translated from animal studies in neuroplasticity (Birkenmeier et al., 2010). Average ratings of usability, motivation, engagement, and safety remained very high for the entirety of

the intervention. ARAT scores did not change significantly from pre- to post-intervention, although one participant did nearly achieve a minimally clinically important change in motor function (5 points). We concluded that, in a preliminary investigation, VRShape is a usable, motivating, safe, and efficacious tool for decreasing trunk compensations and improving aspects reaching kinematics by facilitating large doses of movement repetition in persons with chronic stroke.

5.2 Significance

There is bountiful evidence that VR devices of all types may be useful in some capacity for motor rehabilitation. The rehabilitation tool described in the presented chapters is novel and significant for both research and clinical applications in rehabilitation science because of its abilities to (1) accurately measure trunk compensatory movements, (2) establish relationships between compensation and motor recovery, and (3) act as the basis for an efficacious motor intervention for persons with stroke.

In Chapter 2, we demonstrated that the motion sensor integral to VRShape can be used to validly and reliably measure arm and trunk kinematics during reaching movements involving compensation. The competition between true motor recovery and compensation is a pervasive issue that is present throughout rehabilitation science, and yet very few commonly utilized motor assessments explicitly distinguish between the two mechanisms. Numerous studies have assessed kinematics in a variety of conditions using both healthy and stroke populations in order to define the nature of compensatory movements during reaching (Cirstea & Levin, 2000; Levin et al., 2002; Roby-Brami et al., 1997). Typically, this research has relied on VMC systems that are expensive, involve experts and long setup times for use, require participants to wear markers or trackers, necessitate large volumes of laboratory space, and are completely immobile. On the

114

other hand, the K2 is inexpensive (~$150), requires little expertise or setup time given easy-to-use software (VRShape), uses marker-less motion capture, requires little space (~1.4m from sensor), and is highly portable. A sensor with these qualities and the capability of accurately measuring trunk compensations represents a significant innovation that could be useful in a variety of research fields, especially when combined with usable software.

The measurement abilities of VRShape in conjunction with the K2 provide an opportunity to investigate relationships in motor learning that have been difficult to establish. In some of the most popular, theory-driven, effective motor interventions, it is unclear whether stroke participants are improving motor function due to the reacquisition of motor abilities or the integration of compensation strategies. Researchers hypothesize that UE gains made in constraint-induced movement therapy (CIMT) and task-based training may actually be due to learning alternative movements strategies, the most prominent of which being trunk displacement (Kitago et al., 2013). VRShape could have a significant role for objectively measuring compensation during existing therapy protocols like CIMT, task-based training, and VR-based interventions, in effect shedding light on the true nature of functional motor improvements. Even further, VRShape has the capability to provide feedback concerning compensation during these existing interventions.

In Chapters 3 and 4, we demonstrated that VRShape was able to elicit approximately 500 repetitions in a single session. In Chapter 4, we showed that VRShape can elicit nearly 10,000 repetitions over the course of an 18-session intervention. While enduring this intense practice, participants consistently rated the system as highly usable and remained motivated and engaged throughout therapy. Typical motion videogames, robotics, and similar Kinect-based solutions do not achieve this large dose of repetitions and often become boring over time due to lack of VE

variety (Burdea et al., 2013). This is especially significant because, at the moment, the cost of VRShape is defined only by the price of the K2 sensor and a computer with adequate capabilities; there are no costs associated with the development of VEs or computer games because VRShape can utilize nearly any VE freely available on the internet. Persons with stroke, when surveyed, express desire for VR systems that have more variety in games and activities and that are more affordable (Hung et al., 2015). VRShape is more affordable, elicits more repetitions, and remains more motivating than the majority of VR systems available and therefore may be more useful for widespread clinical application. Based on this evidence and the recent clinician guidelines for selecting VR systems for motor rehabilitation, it is clear that VRShape could have a significant place for future clinical use.

In Chapter 4, we showed that utilization of VRShape over the course of an intervention can significantly decrease trunk flexion and significantly increase reaching distance and shoulder flexion. VRShape is the only tool for VR-based motor therapy that has used a built-in shaping algorithm to produce such an effect. Only a handful of interventions in physical or virtual environment have shown an effect for static, zero-tolerance physical or feedback-driven trunk restraint for improving reaching abilities in persons with stroke (Wee et al., 2014). VRShape is the first to demonstrate that incrementally decreasing compensation during therapy by means of objective measurement and real-time feedback can affect the amount of compensation utilized.

5.3 Limitations

The presented research was designed, carried out, and analyzed with the highest possible care and rigor; however, it is obvious that several limitations persist. One such limitation within each of the presented chapters is limited sample size. Small samples limited study designs to small, single-cohort feasibility investigations and influenced statistical analyses. It should be

noted, however, that the main goal of the overall project was to demonstrate the accuracy, feasibility, and efficacy of a rehabilitation tool in order to gauge its potential for further development and assessment in larger scale studies.

5.3.1 Chapter 2 Limitations

Although the K2 was, in general, found to be closer in magnitude and more highly correlated with VMC, particularly for trunk movement during extended reaches, large magnitude differences between all three sensors existed for kinematic variables such as reaching ROM and elbow extension. These discrepancies may be due to different methods for identifying body landmarks, variable body landmarks positions and body segment lengths in both versions of the Kinect, and interference in Kinect motion tracking due to the presence of a physical target (Xu & McGrory, 2015). In addition, correlations performed in both validity and reliability analyses were found to be spuriously low and even negative in some cases, particularly for non-extended reaches. This is most likely due to the lack of variance between reaches and between days. For example, during non-extended reaches with healthy participants the trunk does not tend to deviate from neutral and therefore any variance in trunk kinematics is mostly likely due to measurement bias or random error. Lack of heterogeneity due to the use of healthy participants also limits the clinical utility and generalizability of results; even though extended movements were included to simulate trunk compensations, healthy participants typically tend to move quite differently than persons with chronic hemiparesis (Levin et al., 2002).

5.3.2 Chapter 3 Limitations

It is possible to describe an underlying purpose of the study performed in Chapter 3 as the identification of limitations in VRShape based on feedback from participants with stroke. Through study execution and analysis of results, two major limitations were identified: (1) time

delays during setup and transition between VEs were too long and (2) the number of reaching

repetitions varied widely depending on the VEs used. While, on average, stroke participants

rated the system as usable, motivating, and safe, it was clear from their feedback that a wider

variety of VEs and games may enhance their participation in the intervention moving forward.

Each participant mentioned that they would need more time to adequately comment on the

system's qualities, therefore an increase in the number of sessions or the amount of time with

VRShape may have enhanced the quantity and quality of feedback.

5.3.3 Chapter 4 Limitations

Several limitations were identified from the use of VRShape over the course of 90

separate intervention sessions. While the purpose of this investigation was to establish the

presence of an effect following use of VRShape, results are limited to changes in the single

cohort and are not directly comparable to conventional or no therapy.

Participants were instructed to reach as far as possible in the scaption plane during

training. The result was a reaching movement involving shoulder flexion, shoulder abduction,

elbow extension, and transportation of the hand to a generally consistent area in space. The

majority of stroke-related research for the repetitive practice of reaching for persons with stroke

involves errorful learning through the planning and movement of an end-effector, most

commonly the hand, to a defined position in space, usually a target for grasping or pointing

(Cirstea & Levin, 2000; Levin et al., 2002; Roby-Brami et al., 1997; Roby-Brami et al., 2003).

Errorful learning, or learning involving problem-solving and error detection, has been shown to

produce more robust motor skill acquisition and is often employed in the later stages of stroke

recovery. Errorless learning, or direction for task completion without deviation, is often

facilitated in the early phases of stroke recovery by means of manual therapist guidance to

maximize safety, initiate early skill acquisition with newly impaired limbs, and to assist those

with possible impairments in problem solving or error detection (Kleim & Jones, 2008;

Krakauer, 2006; Muratori et al., 2013). Feedback concerning the magnitude of error can be

provided through intrinsic mechanisms of error detection (proprioception, somatosensation,

visual detection, etc.) or the provision of extrinsic error signals such as visual, auditory, or haptic

feedback (Poole, 1991). Research has shown that, when tolerable, larger and more variable

errors with fading levels of extrinsic feedback may lead to the greatest and most generalizable

improvements in motor abilities (Muratori et al., 2013). In the case of VRShape, errorful

learning occurred through repetitive practice with extrinsic feedback in the form of

visual/auditory feedback concerning trunk compensation (knowledge of performance) and the

success/failure of virtual events corresponding to a reach (knowledge of results). Compared to

existing studies in trunk restraint that actually utilize errorless learning by means of non-

adjustable physical devices or zero-tolerance feedback, VRShape may actually provide more

robust improvements in motor control of the trunk (Michaelsen et al., 2006; Subramanian et al.,

2013; Woodbury et al., 2009). In terms of UE movements, however, motor learning principles

suggest that an identifiable target for movement planning of the end-effector, variable movement

types and target positions, and mechanisms for augmented error signals through adjustable

feedback may be important for inclusion in future work with VRShape.

It is a major limitation that Chapter 4 did not include any outcomes related to

participation or health-related quality of life (QOL) because there is an overall lack of evidence

for their relationship with motor impairment and they are the ultimate goal of any rehabilitation

strategy for persons with stroke. Several different therapy paradigms including task-based

training (TBT), CIMT, and VR-based motor therapy have been able to improve aspects of motor

impairment, function, and performance, but evidence is limited to suggest that these basic motor changes lead to more complex changes in home and community participation. In the most recent Cochrane review, a small-moderate effect size for participation related to global motor function and a small effect size for QOL was found in favor of repetitive task training such as TBT (French et al., 2016). In two different reviews of CIMT, no positive effect was found for improved participation or QOL for any dose of CIMT relative to traditional or no therapy (Kwakkel et al., 2015; Peurala et al,. 2011). One review of VR-based motor rehabilitation calculated a moderate effect size in favor of interventions involving VEs (Lohse et al., 2014). Each of these large reviews and meta-analyses across intervention types specifically noted a lack of high-quality studies that utilize outcomes within the activity and participation limitation domains of the International Classification of Functioning, Disability, and Health (French et al., 2016; Kwakkel et al., 2015; Peurala et al., 2011). Indeed, the most recent Cochrane review for VR-based rehabilitation for persons with stroke was unable to perform analyses for participation or QOL due to lack of evidence (Laver et al., 2015). Numerous analyses into VR and stroke rehabilitation have called for increased emphasis on assessing the transfer of motor performance within the laboratory or VE to everyday occupational performance, participation, and QOL for stroke survivors, and therefore future work in design, assessment, and intervention utilizing VRShape should include such measures (Henderson et al., 2007; Laver et al., 2015; Lohse et al., 2014; Saposnik et al., 2011).

5.4 Future Research

Many publications have identified key areas of future research for VR-based rehabilitation. One review study suggests areas including (1) study design involving clearly defined comparison groups, such as conventional therapy, (2) inclusion of participation

120

measurement, and (3) consideration of motivational components of VR, and (4) performance of larger scale randomized control trials using commercially available gaming equipment (Lohse et al., 2014). Future research in each of the presented chapters should involve larger and more heterogeneous samples, which would improve the rigor of study design and allow for techniques like randomization and blinding, improve the robustness of statistical analyses, and enhance the generalizability of results in terms of the larger stroke population.

5.4.1 Chapter 2 Future Research

Following the establishment of its measurement capabilities, development moved forward with the K2 as the main sensor for VRShape within the context of the current project. However, based on the results from Chapter 2 and other existing literature, there may be potential for further development with the sensor hardware itself. It may be possible to create transformation algorithms to more closely match raw data from the K2 to that of the VMC. This has been explored within similar studies, but has not been applied to UE motor intervention or the measurement of compensatory movements (Cameirao et al., 2012). These algorithms would rely on signal processing techniques related to amplitude matching, time delay measurement, and the calculation of an appropriate linear or non-linear gain. The applications of these and analogous, more complex statistical methods might also improve our understanding of sensor data in the current study. In addition, while the current project was focused on reaching in three different planes, the inclusion of more varied reaches in terms of distance, height, and speed may increase sample heterogeneity and improve the robustness of our results. Most importantly, future research would benefit from testing with persons with hemiparesis to establish measurement properties in a more heterogeneous and clinically representative sample. Additional kinematic variables such as movement speed, accuracy, and efficiency are known to

121

improve as a result of motor training in persons with stroke and therefore should be included in the future.

5.4.2 Chapter 3 Future Research

The form and function of VRShape will be the focus of continual improvement in the future. The process for defining movement thresholds, choosing VEs, and selecting compensation feedback parameters should be streamlined to decrease setup and transition time. Each of the graphical user interfaces (GUIs) could benefit from improvements in aesthetics and user-friendliness. While VRShape is capable of providing auditory and visual feedback, these forms were limited to one sound, one image, and the cancellation of virtual events in the current project. Future versions could incorporate a variety of sounds and images that could be customized to the individual client. The set of performance metrics, including repetitions and kinematic variables, should also be expanded. The presentation of these metrics could be improved for the researcher (therapist) and client; some existing technologies use separate detailed, expanded performance reports and abbreviated, easy-to-interpret performance reports. Along with the K2, it may be possible to integrate other sensors into VRShape. We have already developed software to utilize the K1, the Leap Motion (Leap Motion, San Francisco, CA), and the Thalmic Labs Myo (Thalmic Labs, Ontario, CA) for use in the same general movement threshold and keyboard emulation strategy. The K1 has been used extensively in our laboratory and in the literature (Lauterbach et al., 2013; Mraz et al., 2016; Sevick et al., 2016), but very few studies have examined the feasibility of using the Leap and the Myo. Given these multiple sources for improvement, it will be crucial to assess feasibility with physical and occupational therapists within a clinical setting in the future. Incorporating feedback from rehabilitation

professionals will maximize clinical utility and enhance the probability of VRShape being used in future clinical research.

5.4.3 Chapter 4 Future Research

The next step for research surrounding VRShape will be an efficacy trial on a larger scale that includes a comparison group in the form of no therapy, traditional therapy, or dose-matched therapy. While the purpose of this investigation was to measure the effects of applying VRShape as a tool for shaping movement compensation and improving motor function for persons with stroke, and we can compare these effects to previous studies, we do not yet know its effects relative to a control group from the same experiment. Larger and more rigorous clinical trials have been identified as a crucial goal for future research in VR-based rehabilitation (Lohse et al., 2014). More rigor may also be included in future studies by investigating additional relationships, such as (1) the difference between training in a motivating VE and the real world, (2) the effects of providing differing forms of feedback, and (3) the optimal dose of repetitions to maximize motor improvements. In terms of compensation, it may be possible to use VRShape to identify an inverse dose-response type relationship between the dose of compensation limitation applied through a shaping algorithm and the response of the motor system to achieve the defined goal. Future research should also include additional outcome measures to assess muscle strength, as it was likely to have changed due to the training in this investigation. Cognitive and psychosocial disorders related to attention, awareness, executive function, and depression are known barriers to recovery and should be assessed in future research (Cicerone et al., 2011). Finally, retention and transfer of training should be assessed through an additional measurement distal time point and the inclusion of outcome measures related to activity performance, participation, and QOL.

5.5 References

Birkenmeier, R. L., Prager, E. M., & Lang, C. E. (2010). Translating animal doses of task-specific training to people with chronic stroke in one hour therapy sessions: a proof-of-concept study. *Neurorehabilitation and neural repair*, *24*(7), 620.

Bonnechere, B., Jansen, B., Salvia, P., Bouzahouene, H., Omelina, L., Moiseev, F., ... & Jan, S. V. S. (2014). Validity and reliability of the Kinect within functional assessment activities: comparison with standard stereophotogrammetry. *Gait & posture*, 39(1), 593-598.

Brooke, J. (2013). SUS: a retrospective. *Journal of usability studies*, *8*(2), 29-40.

Burdea, G. C., Cioi, D., Kale, A., Janes, W. E., Ross, S. A., & Engsberg, J. R. (2013). Robotics and gaming to improve ankle strength, motor control, and function in children with cerebral palsy—a case study series. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, *21*(2), 165-173.

Cameirao, M. S., i Badia, S. B., Duarte, E., Frisoli, A., & Verschure, P. F. (2012). The combined impact of virtual reality neurorehabilitation and its interfaces on upper extremity functional recovery in patients with chronic stroke. *Stroke, 43*(10), 2720-2728.

Cicerone, K. D., Langenbahn, D. M., Braden, C., Malec, J. F., Kalmar, K., Fraas, M., ... & Azulay, J. (2011). Evidence-based cognitive rehabilitation: updated review of the literature from 2003 through 2008. *Archives of physical medicine and rehabilitation*, *92*(4), 519-530.

Cirstea, M. C., & Levin, M. F. (2000). Compensatory strategies for reaching in stroke. *Brain*, 123(5), 940-953.

Clark, R. A., Pua, Y. H., Fortin, K., Ritchie, C., Webster, K. E., Denehy, L., & Bryant, A. L. (2012). Validity of the Microsoft Kinect for assessment of postural control. *Gait & posture*, 36(3), 372-377.

Clark, R. A., Pua, Y. H., Oliveira, C. C., Bower, K. J., Thilarajah, S., McGaw, R., ... & Mentiplay, B. F. (2015). Reliability and concurrent validity of the Microsoft Xbox One Kinect for assessment of standing balance and postural control. *Gait & posture*, 42(2), 210-213.

French, B., Thomas, L. H., Coupe, J., McMahon, N. E., Connell, L., Harrison, J., ... & Watkins, C. L. (2016). Repetitive task training for improving functional ability after stroke. *The Cochrane Library*.

Galna, B., Barry, G., Jackson, D., Mhiripiri, D., Olivier, P., & Rochester, L. (2014). Accuracy of the Microsoft Kinect sensor for measuring movement in people with Parkinson's disease. *Gait & posture*, *39*(4), 1062-1068.

Henderson, A., Korner-Bitensky, N., & Levin, M. (2007). Virtual reality in stroke rehabilitation: a systematic review of its effectiveness for upper limb motor recovery. *Topics in stroke rehabilitation, 14*(2), 52-61.

Holden, M. K. (2005). Virtual environments for motor rehabilitation: review. *Cyberpsychology & behavior*, 8(3), 187-211.

Hung, Y. X., Huang, P. C., Chen, K. T., & Chu, W. C. (2016). What do stroke patients look for in game-based rehabilitation: a survey study. *Medicine*, 95(11).

Kitago, T., Liang, J., Huang, V. S., Hayes, S., Simon, P., Tenteromano, L., ... & Krakauer, J. W. (2013). Improvement after constraint-induced movement therapy: recovery of normal motor control or task-specific compensation? *Neurorehabilitation and neural repair*, *27*(2), 99.

Kleim, J. A., & Jones, T. A. (2008). Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. *Journal of speech, language, and hearing research*, *51*(1), S225-S239.

Krakauer, J. W. (2006). Motor learning: its relevance to stroke recovery and neurorehabilitation. *Current opinion in neurology*, *19*(1), 84-90.

Kuster, R. P., Heinlein, B., Bauer, C. M., & Graf, E. S. (2016). Accuracy of KinectOne to quantify kinematics of the upper body. *Gait & posture*, 47, 80-85.

Kwakkel, G., Veerbeek, J. M., van Wegen, E. E., & Wolf, S. L. (2015). Constraint-induced movement therapy after stroke. *The Lancet Neurology, 14*(2), 224-234.

Lang, C. E., MacDonald, J. R., & Gnip, C. (2007). Counting repetitions: an observational study of outpatient therapy for people with hemiparesis post-stroke. *Journal of Neurologic Physical Therapy*, 31(1), 3-10.

Lange, B., Koenig, S., Chang, C. Y., McConnell, E., Suma, E., Bolas, M., & Rizzo, A. (2012). Designing informed game-based rehabilitation tasks leveraging advances in virtual reality. *Disability and rehabilitation*, 34(22), 1863-1870.

Lauterbach, S. A., Foreman, M. H., & Engsberg, J. R. (2013). Computer games as therapy for persons with stroke. *GAMES FOR HEALTH: Research, Development, and Clinical Applications*, 2(1), 24-28.

Laver, K. E., George, S., Thomas, S., Deutsch, J. E., & Crotty, M. (2015). Virtual reality for stroke rehabilitation. *The Cochrane Library*.

Lessiter, J., Freeman, J., Keogh, E., & Davidoff, J. (2001). A cross-media presence questionnaire: The ITC-Sense of Presence Inventory. *Presence: Teleoperators and virtual environments*, 10(3), 282-297.

Levin, M. F., Michaelsen, S. M., Cirstea, C. M., & Roby-Brami, A. (2002). Use of the trunk for reaching targets placed within and beyond the reach in adult hemiparesis. *Experimental brain research*, 143(2), 171-180.

Levin, M. F., Weiss, P. L., & Keshner, E. A. (2015). Emergence of virtual reality as a tool for upper limb rehabilitation: incorporation of motor control and motor learning principles. *Physical therapy*, 95(3), 415.

Lohse, K. R., Hilderman, C. G., Cheung, K. L., Tatla, S., & Van der Loos, H. M. (2014). Virtual reality therapy for adults post-stroke: a systematic review and meta-analysis exploring virtual environments and commercial games in therapy. *PloS one, 9*(3), e93318.

Michaelsen, S. M., Dannenbaum, R., & Levin, M. F. (2006). Task-specific training with trunk restraint on arm recovery in stroke. *Stroke*, 37(1), 186-192.

Mraz, K., Eisenberg, G., Diener, P., Amadio, G., Foreman, M. H., & Engsberg, J. R. (2016). The Effects of Virtual Reality on the Upper Extremity Skills of Girls with Rett Syndrome: A Single Case Study. *Journal of Intellectual Disability-Diagnosis and Treatment*, 4(3), 152-159.

Pagliari, D., & Pinto, L. (2015). Calibration of kinect for xbox one and comparison between the two generations of Microsoft sensors. *Sensors*, 15(11), 27569-27589.

Peurala, S. H., Kantanen, M. P., Sjögren, T., Paltamaa, J., Karhula, M., & Heinonen, A. (2012). Effectiveness of constraint-induced movement therapy on activity and participation after stroke: a systematic review and meta-analysis of randomized controlled trials. *Clinical rehabilitation*, 26(3), 209-223.

Poole, J. L. (1991). Application of motor learning principles in occupational therapy. *American Journal of Occupational Therapy*, 45(6), 531-537.

Proffitt, R., & Lange, B. (2015). Feasibility of a Customized, In-Home, Game-Based Stroke Exercise Program Using the Microsoft Kinect® Sensor. *International Journal of Telerehabilitation*, 7(2), 23.

Reither, L. R., Foreman, M. H., Migotsky, N., Haddix, C., & Engsberg, J. R. (2017). Upper extremity movement reliability and validity of the Kinect version 2. *Disability and Rehabilitation: Assistive Technology*, 1-9.

Rizzo, A., & Kim, G. J. (2005). A SWOT analysis of the field of virtual reality rehabilitation and therapy. *Presence: Teleoperators and Virtual Environments*, 14(2), 119-146.

Roby-Brami, A., Fuchs, S., Mokhtari, M., & Bussel, B. (1997). Reaching and grasping strategies in hemiparetic patients. *Motor control, 1*(1), 72-91.

Roby-Brami, A., Feydy, A., Combeaud, M., Biryukova, E. V., Bussel, B., & Levin, M. F. (2003). Motor compensation and recovery for reaching in stroke patients. *Acta neurologica scandinavica*, 107(5), 369-381.

Saposnik, G., Levin, M., & Stroke Outcome Research Canada (SORCan) Working Group. (2011). Virtual reality in stroke rehabilitation. *Stroke, 42*(5), 1380-1386.

Sevick, M., Eklund, E., Mensch, A., Foreman, M., Standeven, J., & Engsberg, J. (2016). Using free internet videogames in upper extremity motor training for children with cerebral palsy. *Behavioral Sciences*, *6*(2), 10.

Subramanian, S. K., Lourenço, C. B., Chilingaryan, G., Sveistrup, H., & Levin, M. F. (2013). Arm motor recovery using a virtual reality intervention in chronic stroke: randomized control trial. *Neurorehabilitation and neural repair*, 27(1), 13-23.

Wee, S. K., Hughes, A. M., Warner, M., & Burridge, J. H. (2014). Trunk restraint to promote upper extremity recovery in stroke patients: a systematic review and meta-analysis. *Neurorehabilitation and neural repair*, *28*(7), 660-677.

Woodbury, M. L., Howland, D. R., McGuirk, T. E., Davis, S. B., Senesac, C. R., Kautz, S., & Richards, L. G. (2009). Effects of trunk restraint combined with intensive task practice on poststroke upper extremity reach and function: a pilot study. *Neurorehabilitation and neural repair*, *23*(1), 78-91.

Xu, X., & McGorry, R. W. (2015). The validity of the first and second generation Microsoft Kinect™ for identifying joint center locations during static postures. *Applied ergonomics*, 49, 47-54.