UPPER EXTREMITY KINEMATIC IN INDIVIDUALS WITH STROKE UNDER VARIED TASK CONSTRAINTS

By

TARA SUE PATTERSON

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2009

To Mom and Dad

ACKNOWLEDGMENTS

Every great manuscript is the culmination of hard work and dedication, and cannot be accomplished without the assistance and support of various individuals. I have been fortunate to have had the support of many during my graduate career at the University of Florida, and to express sufficient gratitude to each individual separately is nearly impossible. Therefore, I would like to extend my sincere appreciation to everyone that has played a part of this research project as well as those that have supported me during my graduate career.

First and foremost, I would like to thank my family for their incredible support not only through my dissertation, but in everything that I have pursued. It is hard to express in words my gratitude, and a simple “thank-you” does not describe the magnitude of appreciation I have. My parents have never allowed me to give up and always provided unconditional love and support regardless of the circumstances. These past few years have been exceptionally challenging, but the support was always felt over the miles through phone calls, emails, and care packages. I know I will never be able to fully comprehend the emotions they experienced during some of my toughest days, but they were always there to stand by me and listen to my frustrations, share in my joys, and offer encouragement. I would like to thank my Mom and Dad for allowing me to pursue my goals and supporting my decisions. You both are truly the "wind beneath my wings."

My brothers have always looked out for their “little sister” and I thank them for always being there for me. Scott is a source of comic relief and surprises me with short one line emails to see how I am doing or sending a message of encouragement. Todd has always taken the time to proofread my writing, call to check in on me, and give me the “tough love” and words of wisdom that I needed when I doubted myself. I also would like to thank my “surrogate” family, Aunt Rita and Aunt Barbara, for their encouragement, and always offering their home as a place to visit. Finally, I would like to thank Larissa for being my best friend and “twin” for the past twelve years, and for always believing in me.

I would like to thank my Chair and mentor, Dr. Lorie Richards, for her support, insight and encouragement over the past three years. Dr. Richards has provided me with a sense of confidence in my research ideas, which was quite crucial to the completion of this dissertation, and has given me encouragement and guidance when the end product seemed unattainable. I have learned a great deal through her mentoring and I am grateful that we have developed not only such a strong professional relationship, but a friendship as well. I would also like to thank my other committee members: Dr. Andrea Behrman, Dr. Mark Bishop, and Dr. Mark Tillman. I am grateful to have such a diverse group of individuals to work with, and their unique perspectives and contributions have added to the strength of this dissertation. Additionally, Dr. Mark Bishop has provided outstanding support throughout my academic career. I appreciate his patience with my never-ending questions, for being my statistical “guru,” allowing me to vent my frustrations when I had reached my maximal stress threshold, and supporting me through several funded studies. Finally, I would like to thank Dr. Kathye Light for providing me with the opportunities to work on numerous research projects with participants living with stroke.

I would like to thank all of the faculty, staff, and students at the Veterans Affairs (VA) Brain Rehabilitation Research Center (BRRC) for their assistance with participant recruitment and Institutional Review Board (IRB) and VA-related paperwork, for always providing a great sense of support, and for being willing consumers of my baked goods. I would like to thank Sandy Davis and Dr. Carolyn Hanson, in particular, for all of their help with participant recruitment and for checking to see how I was doing. Their optimism and warm heartedness made the days much more bearable. I also would like to thank my fellow “RSD UE” students,

Amit Sethi and Heather Tweedie, for their help with data collection and feedback on my dissertation. Although I have only known Heather for a short while, I am so grateful to have formed a great friendship with her. She has reminded me of the importance of laughter, that a little time in the outdoors is truly good for the soul, and peppermint espresso truffles are a necessity in graduate school. Finally, I would like to Erin Carr for her friendship and support during our late night work sessions at the VA, and to Mark Bowden for his insight and willingness to pair up on data collection so that I would be able to graduate more timely.

I would like to express enormous gratitude to the Human Motor Performance Lab (HMPL) engineers: Ryan Knight, Kelly Rooney, and Theresa McGuirk. Theresa particularly needs recognition for her unending patience and assistance. Theresa managed to teach someone with very little skills in motion analysis how to conduct, test, analyze and process data, and more importantly spark an interest to continue to examine kinematics in future research. I have great respect for Theresa and am grateful for her friendship and insightful words of encouragement, as well as cooking recipes. I would like to thank Dr. Steven Kautz for his assistance with the motion analysis lab, and Dr. Carolyn Patten for offering insight into the reliability component of this project. I would like to thank Betsy Cathey, Diana Saunders, Nicole Prieto-Lewis, Randy Huntzberry, and Todd Dietrich in the Gait and Balance Clinic for their help with my dissertation and encouragement during some of my more challenging days.

Finally, I would like to thank Laurie Bialosky, Maggie Horn, Patty Hovis, and Vicky Buckles for being such great friends and co-workers over the past few years. Patty and her family are like a second family to me, and I truly admire her ability to persevere under the toughest of times and still manage to enjoy life and make time to have a little fun. I am so

appreciative of Patty's optimistic and "I am over it" attitude and her willingness to talk statistics at any time of the day.

I have had the opportunity to become friends with numerous individuals that have crossed the "threshold" from student to PhD status. I would like to thank each of these individuals for their friendship and support, and for showing me that there indeed is life after the PhD: Dr. Joel Bialosky, Dr. Yi Po Chiu, Dr. Preeti Nair, Dr. Sergio Romero, Dr. Claudia Senesac, and Dr. Michelle Woodbury.

I cannot end this section without including my most loyal friend, my cat Teko. Even though he has behavioral quirks, he is still my family and reminds me of that daily.

Finally, I would like to thank all participants living with stroke with which I have had the honor of working and knowing throughout the years, as well as those that volunteered to be a part of this research study. I admire the strength and perseverance of each participant. Their desire to help as much as possible so that others may benefit from their experiences reminds me of why I chose research as my career path and decided to keep taking the necessary steps forward to complete this degree.

This material is based upon work supported by the Office of Rehabilitation Research and Development, Department of Veterans Affairs and the Office of Academic Affairs, Department of Veterans Affairs: Rehabilitation Research and Development Center, grant F2182C (Leslie J. Gonzalez Rothi), a Career Development Award – II, B5033W (Lorie Richards), and an RO3 grant from the National Institute of Health, grant 1 RO3 HD051624-01A1 (Lorie Richards).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

UPPER EXTREMITY KINEMATICS IN INDIVIDUALS WITH STROKE UNDER VARIED TASK CONSTRAINTS

By

Tara Sue Patterson

May 2009

Chair: Lorie Richards
Major: Rehabilitation Science

Approximately 780,000 cases of new or recurrent incidents of stroke are reported yearly, and about 2/3 of individuals surviving stroke have residual impairments within the upper extremity. Numerous outcome measures exist to evaluate movement execution post-stroke, yet these measures are very subjective and lack the ability to quantify movement composition. Additionally, there is a paucity of research examining movement kinematic changes due to differences in parameters by severity of impairment after stroke.

This research study examined reliability and consistency of five movement parameters of healthy controls, and individuals with mild and moderate impairment due to stroke. Kinematic analysis was used to analyze reaching to touch and reaching to grasp tasks. Kinematic variables included: movement time, peak velocity, index of curvature, trunk displacement, maximum aperture and percent of movement cycle where peak aperture occurs.

Individuals with mild impairments demonstrated excellent reliability for all variables, while individuals with moderate impairment were slightly less reliable. In contrast, controls were highly variable. Variables producing lower reliability values (low ICC) included movement time, peak velocity, and maximum aperture.

The control group performed movements all task conditions more quickly, with higher peak velocities and straighter hand paths utilizing less trunk displacement than both groups of participants with stroke. Individuals with impairments due to stroke were able to perform the movements according to the varying task constraints. However, the two groups did not differ from each other except for peak velocity when performing reaches at different speeds and grasping different size objects. A clinically important finding is that the participants with stroke were able to increase aperture in order to grasp objects, regardless of severity of impairment. However, individuals with mild impairment had larger aperture values than both the control and moderate impairment group. These values were similar for both the average and larger size can.

This study was an attempt at establishing reliability in kinematic measures of an upper extremity model within the Human Motor Performance Laboratory. Further research is necessary in order to investigate the contribution of joint segments to movement production, additional measures such as smoothness metrics, and the inclusion of larger sample sizes.

CHAPTER 1
BACKGROUND AND SIGNIFICANCE

Introduction

Stroke is one of the most prevalent and disabling conditions observed worldwide. Approximately 780,000 cases of new or recurrent incidents of stroke are reported within the United States each year.[1] Stroke is the leading cause of serious long term disability within the United States, and although stroke is documented as the third leading cause of death, the mortality rate has declined over the past several years.[2, 3] This has lead to an increase in the number of people requiring rehabilitation.[4] About 2/3 of the individuals surviving stroke have residual deficits with one of the most common being upper extremity hemiparesis. It has been reported that 1/3-2/3 of people surviving stroke may no longer be able to use the affected upper extremity, therefore relying on primary use of the lesser affected upper extremity or substitution of alternate movement patterns within the more affected upper extremity.[3, 5] Due to this high prevalence, the impact is felt not only on the lives of those living with stroke, but also on families and society as a whole.[6-9]

One of the challenges rehabilitation professionals are faced with is what type of interventions may facilitate the recovery of movements that are as functional as possible. Because of upper limb impairment, most individuals with stroke will use alternate compensatory strategies in order to accomplish a task.[10] Therapists may tend to focus on teaching the individual to use alternate movements in order to perform activities of daily living. However, most are concerned with restoring movements that are as normal as possible.[11] The use of alternate movement patterns may promote weakness in the upper extremity muscles and may ultimately be detrimental to the recovery process by inducing secondary complications such as contractures, weakness and pain.[12]

Restoration of “normal” movement requires the ability to delineate and quantify when movement patterns deviate from normal and to measure when they are progressing towards normalcy and when they are not.[12] Providing the best intervention for promoting motor recovery requires the ability to apply targeted interventions to those areas that most strongly deviate from normal. Because movement patterns and abnormalities of movement may vary according to task, an understanding of how differing task demands impact movement patterns after stroke is necessary. The overarching initial question should be focused on examining movement characteristics of individuals with stroke while completing various tasks. This may further lead to the understanding of whether or not the completion of tasks may be performed in the same manner with the same efficiency as before the neurological insult and in which compensatory movements are used.[5, 13, 14] Then, it may be understood what parameters may be altered and what the intervention should focus on improving.

While numerous outcome measures presently exist to evaluate movement execution and production, most rely on subjective clinical assessments typically providing information regarding such things as speed of goal completion.[15-17] These outcome measures do not have the resolution to distinguish between true recovery of motor control or compensation of movement production and lack the ability to detect subtle yet potentially crucial changes in movement composition.[11, 18] Therapists may be able to better understand the mechanisms underlying the deficits post stroke by incorporating objective quantitative measurements, such as kinematic analysis. Quantification of movement may provide a more robust measure of recovery and may be used to augment clinical evaluations.[15, 19] Kinematic analysis of upper extremity function post stroke is one such measure that can provide as both an evaluative and discriminative measure.

Multiple studies have yielded information about how upper extremity movements are altered post stroke, and a few have incorporated kinematic analysis pre and post intervention.[12, 15, 16, 19-37] However, little information exists to date on the psychometric properties of three-dimensional kinematic analyses, particularly upper extremity kinematics, where there is a paucity of reliable measurement techniques for upper extremity motion analysis.[17, 18] Only two studies have been found to date that report test-re-test reliability for upper extremity kinematics.[15, 17] Reliability is particularly important to establish when using kinematics as outcome measures for intervention studies because a "change" observed in a measure may not be representative of change due to treatment, but rather measurement error if the assessment tools are not reliable.[38, 39] In order to adequately determine whether interventions are promoting motor recovery, or that change in movement production may be a result of treatment, measurement methods need to demonstrate test-retest reliability.

The purpose of this research study is to compare movement quality and composition in individuals with and without stroke while performing varied tasks. The goals of the study are to examine both consistencies of measures, as well as to compare strategy of movement used by individuals with and without stroke under varied task constraints. This will be accomplished by measuring several kinematic variables from three dimensional (3-D) motion analyses. The kinematic analysis will provide understanding regarding the quality of movement produced and if the movement strategies used by individuals with stroke in these tasks are similar to that of healthy controls or are substitutions of alternate compensatory movement strategies.[5] Two groups of individuals (mild to moderate impairment) with stroke will also be observed in order to determine how level of motor impairment also affects the consistency and types of movement used to accomplish a goal. This dissertation will provide a detailed description of the theoretical rationale for why changing task demands may alter movement patterns, reaching characteristics as it applies to healthy populations and individuals with stroke, and literature review of studies incorporating kinematic analysis of reaching as a measurement outcome.

Theoretical Framework

The human motor system is complex and highly adaptable, and has the ability to adjust movement patterns according to changes within the environment as well as task goals.[40] Motor skill acquisition has been examined from two schools of thought: the traditional approach and coordinative structure orientation. The traditional approach views skills as developing as a result of a "prescribed" program present within each individual, and motor programs are pre-structured sets of motor commands that are constructed at the highest cortical levels converging to lower levels in order to execute a movement.[41, 42] In contrast, the coordinative approach views the development of coordination and control as emergent from the interactions of various components within a system of chaos.[41, 43] This phenomena is described by the dynamical systems approach.[41, 43]

Dynamical Systems Theory

The dynamical systems theory is a framework to describe performance-orientated biomechanics. Dynamical systems approach dates back to almost a century, but has only been recently applied to the movement sciences to describe the emergence of coordination and control.[41] This theory relies on the tenet of "self-organization," referring to the ability of the human motor system to spontaneously adjust itself under certain controlled conditions. Functional movement must have four characteristics: flexibility, meaningfulness, consistency and modifiability. The action must also exhibit coordination (constraining movement into smallest amount of degrees of freedom) and control (manipulation of the coordinated pattern of movement). Movement patterns emerge through organization and interaction of subsystems, while coordination reflects effective manipulation and assembly of joints and muscles synergies into functional units of action. These units of action are based on a continuous stream of sensory information yielded by movement performance.[42]

Variability in movement, from the dynamical systems perspective, arises from the abundance of degrees of freedom comprising the human motor system. The degrees of freedom problem was first introduced by Bernstein in 1967, which simply describes coordination resulting from mastering the degrees of freedom to the minimum number required to successfully accomplish the goal of specific task.[22, 44, 45] According to Bernstein, the individual "freezes" or "unfreezes" the degrees of freedom of a particular joint to achieve a goal. Movement, according to Bernstein's conceptual ideas, is a natural phenomena resulting from the interaction of the brain, movement system and environment.[45] The individual must self organize spontaneous pattern formation between the interaction of these parts, and this self-organization is manifested as transitions between states as the individuals strives to achieve a coordinated movement pattern.[46] Changes in task or environmental demands require the motor system to be flexible in order to select the coordinative structure appropriate to meet the task demands; however, stable output must also be achieved.[46, 47] There are four essential concepts in the dynamical systems theory: constraints, self organization, patterns and stability.[41] The concept of constraints is important to study due to its influence on movement coordination and the emergence of movement patterns.

Constraints

The role of constraints and influence of behavior may be noted in such areas as psychology, recreation and leisure, and motor development. Constraints are viewed as barriers that may hinder involvement, performance or development of movement patterns, and may have profound impact on the individual. In recreation and leisure, constraints are viewed as those factors that would impede participation in an activity and have been described as structural, interpersonal and intrapersonal.[48, 49] In sports medicine and motor learning, constraints have been described as external or internal factors that influence the motor action exhibited. Individuals constantly strive to master constraints in order to produce optimal movement patterns.[50] Rehabilitation approaches must recognize that individuals have unique movement systems shaped by many constraints, and performance of tasks may be better viewed as emergent and functional due to the many influences of constraints the individuals must satisfy.[46] Many types of constraints exist that may shape the behavior of a dynamical system, and Newell categorized them as organism, task and environment.[43, 46, 51]

Newell's Model of Constraints

Newell examined stages of development in infants and children, and proposed the importance of examining constraints that may affect movement output.[43, 51-53] He proposed three variables (organism, task, and environment) that are the key source to constraint input, and the interaction of these components leads to the emergence of the optimal pattern of movement for a particular situation.[43, 51] An illustration is presented in Figure 1-1.[51]

In motor behavior, movement arises from a system surrounded by constraints, and may be examined at each level: organism, task, or environment.[41, 51] Organism characteristics, or internal constraints, may include such things as body anthropometrics, biomechanical characteristics, cognitive and emotional attributes, and other structural and neural components.[51, 54] The second group of constraints is viewed as external constraints, and these are the limitations imposed by the environment in which the action is performed as well as the tasks to be accomplished. Environmental constraints may include factors external to the individual such as gravity, temperature, and cultural factors. Finally, task constraints may include the goals, rules and machines influencing the performance of the action.[51] Motor control in an individual is explained by the interaction of the external and internal constraints, and the objective of motor rehabilitation is to understand the how the nervous system responds to these constraints in individuals with neurologic dysfunction.[54] Dynamical systems theory views coordination and control developing by mastering the numerous degrees of freedom so that the desired inter-joint coordination pattern is selected to reach a goal.[22] However, numerous strategies may be selected leading to movement variability, and it is important to analyze the manner of movement execution of simple motor tasks.[23]

Understanding variability in movement has been a challenge for researchers and clinicians. Variability of movement may occur due to fluctuations within the system, and maybe measured by variance of motor output. However, within the dynamical systems perspective, variability may be viewed as a result of exploratory behavior of the motor system adapting responses to changing environmental or task demands, with the latter providing a better understanding of variability.[41, 55] Task constraints dictate the specific response dynamic, affect the final shape of the movement and marshal the system into the behavior we observe.[41, 51] Changing task demands or constraints may provide further insight into understanding functional movement solutions in healthy individuals as well as those individuals with altered nervous systems. The nature of variability of movement driven by the interaction of various constraints on actions can provide insight into the system dynamics for a particular performer, under a specified set of task constraints.[55] From this perspective, intra and inter variability in movement performance may have a positive role and maybe viewed as a function of learning and development.[46]

Constraints Application to Alternate Populations

While the application of the constraints model has primarily focused on infants and children, and much research has been conducted on motor performance of healthy individuals, it is important to examine how the nervous system reacts to various constraints to produce motor behavior after neurologic insult.[54] After neurological insult, the system is thrown in to more chaos and it is not clearly understood how mechanisms interact to produce functional movements. It is also not clear as to whether or not the individual is able to build off of previous motor programs, or if he must "re learn " the movement pattern.

Researchers note that constraints present both internally and externally interact and may be potential contributors to movement production; however, a paucity of research exists on how this may affect clinical populations.[54] Learning or adapting motor behavior to produce a functional movement relies on the mutual influence of the task, environment and organism, with the latter component being drastically altered due neurologic insult, such as stroke.[16] It is likely the individual may have adapted a new coordinative after experiencing a neurologic insult, or that the individual may not be able to adapt the movement according to the demands of the task. It is crucial to examine this pattern and how it changes by altering the constraints placed on the goal.

Individuals with stroke at varied levels of disability performing various tasks under different constraints may produce different patterns of movement that may have emerged due to the organism constraints as compared to healthy controls. Alteration of the goal of the action, or change in task demands, may yield an emergence of a specific motor pattern to satisfy those task constraints.[56] Examination through the constraints model may ultimately assist in developing therapeutic interventions aimed at improving coordinative patterns to become more functional. Since coordination and control patterns emerge due to the interaction of the organism and task constraints, these properties should be taken into account when making clinical decisions regarding movement performance and evaluations.[54, 57] This dissertation will now examine the concept of constraints and application to a common everyday action: reaching.

Characteristics of Reaching

Reaching is referred to as the voluntary positioning of the arm and hand by an individual near a location so that it may interact with the surrounding environment.[26] Reaching is a very complex motion that requires the integration of visual information about the intrinsic and extrinsic properties of the object that is being reached for, as well as the ability to coordinate the large number of degrees of freedom across multiple joints to complete the reach task.[21-23, 26, 58-61] The human arm contains seven degrees of freedom, and performance of everyday activities requires coordination among the muscles and joints of the upper extremity and mastering the degrees of freedom so that a coordinated motion produces a desired trajectory to accomplish a goal.[22, 36] Before understanding the alterations in movement production for the reach to grasp task in individuals living with stroke, it is crucial to examine the characteristics of the reach to grasp task in healthy individuals.

The reach to grasp action has been examined in numerous studies.[3, 25, 56, 61-69] Movement planning requires the integration of several aspects: task specific properties, grasp strategy, and hand opening and location.[59] Reaching to a target within arms length involves the wrist, elbow, and shoulder, while further targets also require the movement of the trunk. In healthy people, the joint motion during reaching is similar for any given start and end position.[26, 56, 59] In order to reach for a particular object in a particular space, neural processing allows for the transformation of visuospatial information about the location of the object into motor commands which specify the type of force and motion needed by the joints in muscles in order to bring the hand to the location.[70]

Reaches are produced using both feedforward and feedback control depending on the accuracy requirements of the given task.[26] Reaches are initiated (the transport phase) under feedforward control.[26] Under feedforward control, sensory information concerning the spatial relationship between the upper extremity and object are used to plan the action to determine the spatial-temporal characteristics of the movement trajectory prior to movement initiation.[26, 71, 72] Information is used to anticipate disturbances to limb dynamics in order to plan the appropriate activation of muscles to produce this continuous ballistic movement.[24, 26] The movement is typically performed without additional sensory information altering the movement. The open loop, feedforward control system is responsible for the execution of quick skilled movements, and the movements may not be modified if an error occurs once they are initiated.

Feedforward control is characterized by one acceleration and one deceleration phase in a continuous movement. This results in a smooth bell shaped velocity profile with one major peak in the endpoint tangential velocity trace occurring halfway between the start and end of the movement.[26] Fast velocity is noted during the initial phase of the movement, and fingers should become outstretched as the hand approaches the object. Lower velocity values are presented consistently after 75% of the movement time has elapsed, and this is correlated with closure of the fingers at the end of transport.[73] The hand paths during typical reach to grasp are straight or slightly curved. They result from coordinated movements between the shoulder and elbow joints, with slight trunk displacement.[26]

Grasping, the second phase of the reach cycle, occurs under feedback control. The transport phase usually is produced with some error, such that targets, unless they are very large, are seldom contacted with this first feedforward movement.[24, 26] Therefore, sensory information from the proprioceptors and visual system are used to make corrective movements to hone in on the object in order to grasp it. Feedback control allows the individual to correct discrepancies of how and where to place the arm and hand in order to achieve the task goal.[24, 26] Feedback control is characterized by multiple accelerations and decelerations, and the velocity profile has several peaks.[26]

The aperture, or opening, of the hand is scaled according to the object size.[74] Grasping patterns will differ depending on such things as weight and size of the intended object.[32, 35, 59, 61, 75, 76] Larger sized objects require greater aperture and will affect transport and hand orientation.[10, 26, 30] Larger size objects may lead to an increase in average velocity as well as aperture.[10, 59, 61, 75, 77, 78] Peak aperture tends to occur between 55 and 75% of the movement time.[73] Movement kinematics will alter as a result of changes in not only target size, but also shape and location, whether or not the reach is unimanual or bimanual and the speed of performance.[3, 25, 32, 56, 62-69, 73, 79, 80] The individuals must perceive the task specific properties (intrinsic and extrinsic) in order to select and plan proper hand location and orientation.[59] It has also been demonstrated that the intention of what will occur after the object is grasped may alter movement strategies.[59]

Post Stroke Reaching Changes

The hemispheric damage with stroke results in deficits in the ability to produce smooth and accurate arm movements, and the individual typically exhibits movements that are characterized by weakness, abnormal muscle tone and movement synergies, abnormal postural adjustments, and restricted active moments at the joint segments of the affected upper extremity.[10, 25, 28] Damage post stroke produces movements that are not controlled and coordinated, and may be relational to the area where the stroke has occurred.[81] For example, the basal ganglia is crucial for scaling specific movement parameters such as amplitude and velocity; the cerebellum is important in error detection and correction; and the motor cortex is crucial for the planning and execution of motor actions. Lesions within these areas will lead to motor deficits; for example, a lesion within the cerebellum will lead to limb ataxia such as dysdiadochokinesia and dysmetria.[81] Examination of these movements in relation to level of impairment may yield insight into movement production strategy.

While reaching deficits post stroke vary according to motor impairment, there are some generalities to these movements after stroke.[82] Generally, the reaching movement post stroke is less precise, slower, and more variable in movement time.[22, 26, 67, 83] There are smaller joint excursions and coordination patterns are disrupted; muscular forces are generally decreased.[21-23, 25, 31, 75, 84]

Movement trajectories are also altered, and movement paths are more variable and less smooth.[19] In order for the hand path to be straight, as demonstrated in healthy individuals, there has to be simultaneous rotation of the shoulder and elbow and a near constant ratio of shoulder and elbow velocities. A deviation from a linear hand path trajectory may demonstrate decreased coordination which is characteristic for an individual with stroke.[26] Research has also demonstrated that individuals with stroke have difficulty decelerating elbow flexion and lack coordination between maximal shoulder velocity and the change in elbow movement from flexion to extension. Often the movements exhibited by individuals living with stroke are dominated by one of two gross movement patterns.[21, 25] Flexor synergy consists of shoulder flexion and abduction combined with elbow flexion, wrist extension, and forearm supination. Extensor synergy consists of shoulder extension and adduction with elbow extension, wrist flexion and forearm pronation.[21, 25]

Changes in velocity and acceleration during movement execution are typically altered after stroke. The hand contralateral to the lesion typically produces a much lower velocity than in healthy individuals and peak velocity occurs within the first 50% of the movement cycle.[32] Changes in the smoothness of movement are also apparent for individuals living with stroke, and there may be several peaks in the speed profile indicating many periods of acceleration and deceleration.[19] The deficits exhibited may limit or prevent the individual from using the more affected arm and hand in activities of daily living, and primarily relying on the lesser impaired arm and hand.

While healthy individuals may incorporate movement at the trunk to lean toward an object, individuals living with stroke tend to produce a much greater amount of trunk movement during the transport phase of reaching.[20-23, 25-27, 29, 56, 58, 60, 65, 69, 82, 85-89] Unlike healthy individuals, the trunk is recruited even during the execution of a reach that is well within the arm's length.[20-23, 25-27, 29, 56, 58, 60, 65, 69, 82, 85-90] When performing a reaching movement, healthy individuals typically accomplish the goal by initially flexing the elbow and shoulder to raise the arm. They then adduct the arm across the body and extend the elbow in order to reach the target. There is minimal trunk involvement of approximately 37.5 mm.[21] However, individuals with stroke were observed initially flexing the elbow and shoulder and moving the trunk to reach for the target, rather than adducting the shoulder and extending the elbow producing approximately 110.2 mm of trunk displacement.[21] This may be due to the central nervous system's accounting for the biomechanical restrictions of the affected limb in motor planning and execution, and the development of a new coordinative structure which relies on the trunk.[10, 27-29] A decrease in trunk displacement may be indicative of improved coordination of the shoulder and elbow.

Changes in the size and location of targeted objects also results in greater alterations in the movement produced by individuals living with stroke compared to those of healthy adults.[54, 59, 61, 74, 80, 91] Velocity and transport time are altered as well as angular and linear displacement values and finger aperture. Decreasing the size of an object increases accuracy demands altering movement execution, while transport time increases with increasing object size. Grasp aperture also changes: individuals with stroke increase aperture size with larger targets to a larger extent than healthy adults and the maximum aperture also occurs earlier in the movement than is observed in healthy adults.[32, 35, 75, 92-94] However, while a majority of studies have examined the reach component; only a few have analyzed the grasp component or have done so independent of the reach.[10, 75]

Michaelson and colleagues examined grasping parameters in individuals with stroke to a 35mm can, and the results showed that the major characteristics of reach and grasp were preserved, but that there was heavier reliance on incorporating the trunk to complete the goal.[10] Lang and colleagues also found differences for individuals with acute hemiparesis due to stroke as compared to healthy controls for reaching to grasp a 38mm diameter object. These researchers examined reaching and grasping at movements made as fast as possible, and individuals with stroke had greater impairments for grasping as compared to reaching.[75] Examination of reach to grasp, and particularly the grasp component has generally produced alterations in movement patterns, but the research has been limited and stressed the need for further investigation into such parameters as alterations of object size.

Jeannerod and colleagues (1994) demonstrated that grasp aperture was grossly exaggerated for smaller objects as compared to larger sized objects in an individual with a stroke located in the posterior parietal lobe. These investigators suggested that individuals with stroke, particularly within the parietal lobe, have impaired ability to calibrate the grip size as a function of object size.[92]

Nowak (2007) found that individuals with stroke possessed deficits with timing and scaling aperture size to object size in bimanual reach to grasp conditions, and severity of impairment was independent of the hemisphere affected. These researchers also found that peak aperture occurs earlier in the movement for individuals with stroke.[94]

Van Vliet and Sheridan (2007) observed changes in reaching and aperture as a result of changing both speed of movement to complete the task as well as object size in individuals with stroke.[32] The instructions were to pick up a cup of water and take a drink at a comfortable speed, and as fast as possible without spilling water in 2 different sized cups (6 and 7 cm diameter) of differing height and weight. The results showed larger aperture sizes for movements occurring at faster speeds and grasping larger objects; however, these investigators stressed the need for examining objects of larger size difference (other than 1 cm). [32]

The effect of adding a grasping component to reaching has been shown to produce faster reaches in healthy individuals but more variable movements in individuals with stroke.[75] Peak aperture in healthy individuals occurs after maximum transport speed, and within 55-75% of the total movement time, however, people living with stroke demonstrate altered timing sequences even for average size objects.[75, 91] Changing the task demand by increasing the size of the object to be grasped may produce further alterations in movement strategies in order to accomplish the goal.

Finally, movement may be affected by changing the difficulty of the task. Difficulty may be altered in many ways, including changing location, size, and speed of movement required to complete the action.[95] Performance at faster speeds may demonstrate more pronounced deficits in spatial errors and lower peak velocity in individuals with stroke. This may be due to the increase in accuracy demands of moving at a fast pace, which may be more pronounced in the reach tasks, particularly when reaching to touch a target of a specific size.[75, 91] This may also be due to increased stiffness in the joints and spasticity leading to more difficulty in completing a task quickly.[31, 75]

In summary, the reach to grasp action in individuals living with stroke demonstrates many alterations in movement profiles. Changes occur in velocity and smoothness of motion. Kinematic variables provide greater detail about the movement pattern than observation alone and have been widely studied to assess post stroke-changes; however, these variables have not been systematically examined in relation to changes in task constraints and their relation to severity of impairment due to stroke.[10, 12, 21, 22, 25, 30, 54, 62, 69, 78, 84, 93, 96, 97] Studies of reaching post stroke have incorporated a broad range of experimental designs in order to assess both reaching and grasping movements post stroke. There has not been a consistent methodology present within the literature to demonstrate what happens to movement composition after alteration of task constraints. The majority of studies to date have focused on reaching to targets in the ipsilateral verses contralateral workspace, reaching with a trunk restraint, and few have examined prehension; few studies that examined reach to grasp at differing speeds for different shaped objects,[17, 32, 34, 54, 75, 92] Previous studies also have examined the influence of speed and accuracy on outcome measures and had a broader range of task goals which may have a more profound effect on the movement parameters exhibited. Additionally, few studies incorporated healthy participants as controls. The use of kinematic assessment of movement composition has recently gained increased interest,[18] but almost no studies have examined these variables for test-re-test reliability.[17] This is important for accurate descriptions of movements post stroke and critical for using such measures as outcomes in clinical trials.

While recovery from a neurological insult, such as stroke, may be clinically observed, the extent of the recovery is highly variable and individualistic.[2, 98] There is an increase in the application of kinematic analysis to identify movement patterns post stroke as well as to demonstrate changes post intervention, yet little to no studies report the reliability of these measures.[17] Establishing reliability of the metrics used in motion analysis is the first crucial step to support or negate the use of kinematics as an evaluative tool to assess change in upper extremity performance pre and post intervention.[17] Kinematics of lower limb function and production has established validity, but upper extremity analysis in stroke is still fairly new. There are many evaluation tools available to researchers and therapists, yet there is a crucial need to implement evaluation methods that provide more accurate and reliable analysis of upper extremity motion.[15, 17]

Additionally, it is also imperative to examine separate groups based on level of deficit, because treating a heterogeneous group as a homogenous group will conceal a lot of information about movement kinematic patterns.[36, 99] Examining kinematic measures may lead to better understanding of movement production and strategy in populations with stroke of different severity of impairment performing tasks of varying constraints. This initial step is crucial and future studies may begin to incorporate these measures to understand more concretely rehabilitation outcomes and whether or not improvement in performance is resulting in more "normal" coordinative patterns, or substitution of a compensatory new pattern.[12, 19, 30, 100-102]

Summary

The ability to perform purposeful movements, such as reaching, is clearly disrupted post stroke, and the degree of ability to perform such tasks may be different for those individuals with mild to moderate deficits from stroke. Movement kinematics may provide detailed, structured quantification of movement performed by these populations. However, research incorporating these outcome measures has failed to include measures of reliability; a crucial factor to examine before incorporating this methodology pre and post therapeutic intervention. Changes in upper extremity motor performance may not be due to treatment, but rather due to measurement error. Establishing reliability prior to inclusion in intervention studies will allow the researcher to support the use of kinematic analysis as a method determining change as a result of the intervention. Knowledge of lower extremity motion analysis has been widely studied and validated, while upper extremity motion analysis still remains unreliable and questionable.

Movement production during reaching and grasping tasks varies according to severity of impairment. Examination of the movement parameters while completing tasks of varied task constraints may provide understanding of the movement components utilized to accomplish a goal. Furthermore, this understanding must extend to each group independently rather than examining the group as a homogenous sample, since it is well known that stroke is widely individualistic. Understanding these parameters may then assist with the development of particular interventions for each deficit so that functional gains may be attained. Examining these parameters before intervention will help in designing and implementing the most appropriate strategy by focusing on those movement deficits characterized by movement analysis. Therefore, the purpose of this dissertation is to examine the reliability of kinematic measures of individuals with stroke across two severity levels and healthy controls, as well as provide detailed description of the movement components utilized during reaching and reaching to grasp of varied task constraints. By altering the task constraints, particular response dynamics may emerge and it is important to examine the effect of changing the task constraint has on motor behavior while varying the organism constraints.[41, 51]

Specific Aims and Hypothesis

Specific Aim 1: The first aim of this dissertation is to examine the test-retest reliability of kinematic measures of both individuals with stroke and a healthy control group.

Hypothesis 1: Kinematic measures of movement time, peak velocity, index of curvature, trunk displacement, thumb/index finger aperture, and time to maximum aperture will produce high reliability across Time 1 (T1) and Time 2 (T2).

Hypothesis 2: Performance at T1 and T2 will not be significantly different.

Specific Aim 2: The second aim of this dissertation is to test the hypothesis that kinematics of reach to point will be different depending on speed of task completion and severity. Healthy controls and individuals with mild stroke performing reach to touch at a fast verses comfortable speed will display:

Hypothesis 1: Shorter movement times than the more moderately compared group.

Hypothesis 2: Higher peak velocity values than the more moderately impaired group.

Hypothesis 3: Straighter hand paths than the more moderately impaired group.

Hypothesis 4: Less trunk displacement than the more moderately impaired group.

Specific aim 3: The third aim is to test the hypothesis that test the hypothesis that kinematics of reach to grasp will be different depending on size of the object and severity. Reaching to grasp a larger can will display:

Hypothesis 1: Longer movement times especially for the moderately impaired group.

Hypothesis 2: Lower peak velocity values especially for the moderately impaired group.

Hypothesis 3: Less straight hand paths especially for the moderately impaired group.

Hypothesis 4: More trunk displacement especially for the more moderately impaired group.

Hypothesis 5: Larger peak aperture values occurring later in the movement cycle.

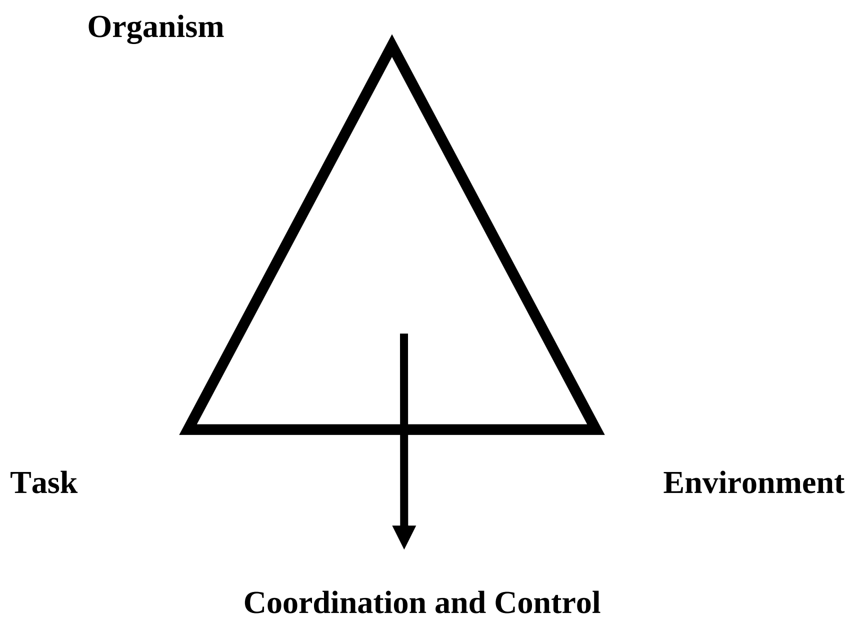

Figure 1-1 Newell' s model of constraints (Newell, 1986)

CHAPTER 2
METHODOLOGY

Experimental Design

This study utilized a repeated measures cross sectional design of two groups of participants; those diagnosed with stroke and healthy controls. The participants with stroke were separated into two subgroups by a median split of the Upper Extremity Fugl Meyer score: those with minimal (mild) and moderate motor impairment.[103]

Participants

The participants in this study were 18 individuals diagnosed with stroke and nine healthy controls. Individuals were recruited through inclusion in studies examining stroke as well as selection from a stroke database. A table of demographics is presented in Table 2-1 for the healthy controls, Table 2-2 for the participants with mild impairments after stroke, and Table 2-3 for the participants with moderate impairment after stroke. This sample size was estimated through a power analysis conducted a priori utilizing data from a previous study examining the index of curvature variable (a robust measure of smoothness) and changes occurring pre- to post-therapy in individuals with stroke. It was determined that with alpha set at 0.05, and a sigma (standard deviation) value of 0.83, a one-paired t-test yielded 18 participants with stroke for a power of 0.80.[104, 105]

The inclusion criteria for this study for individuals with stroke included: (1) a diagnosis of a single unilateral ischemic stroke occurring at least 6 months prior, (2) between the ages of 18-90 years of age, (3) ability to follow a two-step command, (4) and have no other condition or active drug or alcohol use that would interfere with participation in this research study. Individuals within this study were grouped according the mean of Upper Extremity Fugl Meyer scores.[103] Therefore, 9 individuals were considered to be “mildly impaired” with their Fugl Meyer score greater than 39 and the “moderately impaired” group consisted of 9 individuals with scores of 39 and below.

The healthy control group included a sample of convenience of nine aged matched individuals (within 10 years to 9 participants with stroke) that were neurologically and orthopedically intact, so that no alternate condition affected upper extremity performance.[15, 75] The participants in the control group included staff at the Malcom Randall Veteran’s Hospital (VA) in Gainesville, Florida. The study protocol was part of two larger studies (IRB# 286-2005; 469-2007; PI Lorie Richards), and was approved by the University of Florida (UF) Institutional Review Board and the Veteran’s Affairs Subcommittee for Clinical Investigations.

Procedures

Participants meeting eligibility criteria read and signed an informed consent. Each participant was evaluated in the Human Motor Performance Laboratory located within the Malcom Randall VA Center. Each participant with stroke completed the upper extremity subscale of the Fugl-Meyer Motor Assessment.[103] The participants were tested through kinematic analysis twice, at approximately 24 hours up to one week apart (T1 and T2). All participants received the same testing procedures at the two test sessions. Clinical measurements and kinematic data were recorded on data collection documents stored in a locked cabinet in the VA Brain Rehabilitation Research Center.

Kinematic Testing

The participants were evaluated through kinematic testing at each of the two test periods using three-dimensional (3-D) motion analysis and two analog video cameras. A 12 MX camera set-up was used to collect the motion analysis data (Vicon 612; Oxford Metrics Inc., Oxford, UK) at a sampling frequency of 100 Hz.[106] Infrared light emitting diodes were used to capture the movements. An example of the set up for Vicon Workstation is shown in Figure 2-1.

Markers maybe occluded during a movement by being blocked or covered by a body segment. Numerous cameras assisted in preventing the disappearance of markers even when the upper extremity performed irregular movements. Additionally, in order to obtain valid 3-D motion data, a marker must be seen by a minimum of three cameras throughout the entire motion. Multiple cameras also allowed for the capture of more discrete fine movements, such as aperture.

Prior to testing, the workspace and surrounding areas were checked for any reflections that may interfere with the collection, and all reflective objects were removed or covered. The cameras were then calibrated for two separate recordings: static and dynamic. A static calibration was performed by placing an L-frame on the right edge of the table, which determines the 0,0,0, (or x,y,z origin), and the trial is recorded for approximately five seconds. Dynamic calibration is then performed by sweeping the space with a wand that had five markers secured to it. Camera calibration is crucial and is done so that the cameras may be orientated to each other as well as the entire space where the movement will occur.

Midway through the study, the motion analysis system was changed to Vicon Nexus 1.3 (Oxford, UK). This system allowed for higher efficiency, better resolution and faster sampling frequency (Nexus 1.3; Oxford, UK). Data within this system is sampled at 200 Hz. Data collected in Nexus required a new upper extremity data collection set up, as shown in Figure 2-2. After initial setup, cameras were calibrated and data was collected through similar procedures as previously outlined.

Participant Preparation

Each participant was asked to wear a dark colored shirt or was provided a tank top to wear. Anthropometric measurements (height and weight), hand dominance and age were recorded. Spherical reflective markers were placed on various landmarks on the body, according to a marker set described by Software for Musculoskeletal Modeling 4.21a2 (SIMM) (SIMM, Santa Rosa, CA) and a previously described biomechanical model.[106, 107] Up to fifteen 3mm half reflective markers were secured to the fingers using eyelash glue. Larger size markers (14mm) were placed on the hand, wrist, body, and the head using double-sided adhesive tape. An example of the marker placement for the body is included in Figure 2-3 and for the hand in Figure 2-4. The model for the marker placement was previously described and tested.[106, 107] Arm length was measured from the acromion to the tip of the middle finger when the participant held the lesser affected arm directly out in front of them. The targets were then placed at 80% of the arm's length. This distance has been referred to as the "critical boundary."[56] Healthy individuals use only the joints of the arm to reach for objects within the workspace; they may lean forward with the trunk to obtain objects beyond the boundary. Individuals with stroke, however, tend to rely on the trunk to assist in retrieving objects both within and beyond the workspace.[21, 26, 56, 108]

Participants were seated on a backless bench with knees flexed to 90 degrees and feet flat on the floor so that the edge of the seat was flush with the dorsal pelvis. The arms rested on a table in front of them and were placed on arm rests so that the elbows were bent to 90 degrees with the shoulder in a neutral position at 0 degrees of flexion. The palms faced down. The table, bench and arm rests were adjustable so that they may be adjusted according to the anthropometrics of each participant. The measurements of the table and bench height were recorded as well as arm rest height. This information was used to ensure that the measurements were the same for both test periods.

Data Collection

Once the setup was completed, the participant was seated and a static trial was captured. The first static trial was collected in order to ensure all critical markers were visible, and this trial would later be labeled and entered into SIMM to create the model for the participant. The participant was then instructed to reach for several targets during the testing session. While several different upper extremity tasks were performed, this manuscript only considered the reach to target and the unilateral reach to grasp can conditions. Specific directions were provided prior to movement, and movements were demonstrated by the instructor. The healthy controls performed each task with their dominant hand first, and the participants with stroke used the lesser –affected hand to perform the task first. Participants practiced each task once, and then performed the task three more times consecutively. The average of these three trials was used for analysis.

Reach to touch was the first task completed by all participants. The target was a tape mark placed midline at 80% of the individual's arm length as previously stated.[56] The participant was asked to reach and touch the target with the hand first at his/her self-selected comfortable pace, and then as fast as possible.

The second and third tasks were the reach to small and larger can tasks. For the small can, an average sized soda pop (56 mm in diameter; 208 mm circumference) can was placed directly in front of the individual's arm and hand at 80 percent of the arm's length. The can was placed on cardboard circles taped to the table to ensure proper placement prior to the beginning of each trial. The participant reached for the can initially with the lesser affected extremity followed by the more affected extremity. The task was then repeated using a larger can (85mm in diameter; 270mm circumference). The cans were both 1.0 pounds (0.45 kilograms). For both conditions, the participant was instructed to reach for the can, grasp it, lift it up off of the table, and brings it back down as fast as possible. The height of the lift did not matter so long as the bottom of the can was off the table, nor did the replacement of the position of can because only the reach and grasp components were of interest for this study. Cans were replaced back to the original start position before each trial. Participants were instructed to grasp the can from the side and not from the top. Once the can was returned to the table, the participant was asked to return to the start position. This task was also completed four times, with the first trial used as a practice.

Kinematic Data Processing

The initial system used to collect and process the data was the Vicon Workstation v.4.6. Data were captured and reconstructed, and each marker was labeled manually using Vicon software. Manual reconstruction was necessary in Vicon Workstation because each camera captured movements as 2-D, and this allowed for the image to be computed as 3-D. Events were also marked, and this was specific to the movements of interest. The events for this protocol consisted of three periods: start, touch and stop. "Start" was marked as the frame prior to movement initiation, and "stop" was marked as the frame where movement ceased to occur. "Touch" varied according to condition. For the reach to target condition, "touch" was considered to be the point were the index finger, or part of the hand, reached the target. For the reach to grasp condition, "touch" was considered to be the frame just before the can was lifted.

Once the data were labeled and events marked, they were filtered using a low pass 4^{th} order Butterworth filter with a cut off frequency of 10 Hz. The filtered data were then modeled using SIMM. Additional kinematic analyses were performed using custom written Matlab program codes (Matlab R2007b, Mathworks Inc, Natick, Mass.) that calculated specific values, read in angle data calculated by SIMM , read the 3D position of every marker, and created plots and excel spreadsheets. The spreadsheets consisted of various metrics obtained and values for each trial. Data for the three trials were averaged and standard deviations were included. This procedure was completed for the nine controls and ten of the participants with stroke.

Data in Nexus were captured similarly, and cameras were calibrated using similar calibration techniques, but with methods specific to Nexus. Data were reconstructed and markers were also manually labeled. The labeled data were exported, filtered and processed. Aperture data (distance between the thumb and index finger expressed in mm) was collected for all participants; however, only reported for twelve participants. Data collected within the Nexus system were clearer and markers were more readily visible due to the better camera resolution. The markers on the fingers were not as clearly visible within Vicon Workstation, and tended to disappear more frequently. This procedure was completed for eight of the participants with stroke.

Data were entered into Excel and SPSS for analysis. For the purpose of this study, only the more affected upper extremity was analyzed for individuals with stroke while the reported dominant hand was analyzed for the healthy controls, which has been reported in previous literature.[10, 75]

Proposed Metrics of Study

Motor performance in healthy individuals as well as individuals living with stroke may be measured in many different ways. It may be examined by several variables, and individuals living with stroke tend to produce actions that contain many discrete submovements demonstrating less smoothness.[19] The metrics of used to examine movement parameters with include:

1. Movement time: onset to offset: amount of time measured from "start" of movement to "touch." Onset is the time it takes the subject to perform their first initial reach for the target, and is defined as the point where velocity surpasses 5% of peak velocity; offset is the point at which velocity fell below 5% of the peak velocity value.

2. Peak velocity: is the point of the reach cycle during which the velocity is the greatest and corresponds to the changeover from acceleration to deceleration and the location in the profile is indicative of strategy.[59, 83] The peak value also depends on the size of the target.[10, 54, 61, 72, 74, 78]

3. Index of curvature: the index of curvature is the ratio of the actual hand path to a straight line. It may also be referred to as the ratio of the actual path to the direct path as measured by the hand marker. The direct path is the 3-D distance of the hand path from onset to offset, and the actual path is the 3-D displacement of the hand marker during the reach cycle.[106] Lower values may demonstrate increased smoothness.

4. Trunk displacement: this is measured by a marker placed at T-10 and determines the displacement of the trunk during the reach cycle. Individuals with stroke tend to lean forward more than healthy control participants when reaching due to deficits within the shoulder and elbow.[16]

5. Aperture and percent movement cycle peak aperture occurs: this is the amount of displacement between the digits, and for the purpose of this study will be measured between the thumb and index finger. Larger size objects require greater aperture and faster movement speeds will affect transport and hand orientation. Peak aperture typically occurs within 55-75% of movement time and individuals with stroke demonstrate altered timing sequences.[64, 73, 74]

Statistical Analysis

Statistical analysis was performed on the values presented for each trial, and the mean and standard deviation was obtained. Joint angle plots were also calculated to compare the movements of the extremities. Specific calculations were performed according to each aim and whether or not the data were normally distributed. Specific methods of analysis are described according to specific aims.

Specific Aim 1

The first aim of this proposal was to establish the baseline stability and normal variance of the tests and measures. To test this, Intra-class Correlation Coefficient (ICC) and the Standard Error of Measure (SEM) was calculated.[38, 109] The range of repeatability was calculated in order to determine the measurement error, which may be referred to as minimal detectable difference (MDD). Paired t-tests were also used to compare means of the dependent variables across the two testing sessions for each of the 3 groups. For those data not meeting the normality assumption, Wilcoxon pairs test was utilized.

Specific Aim 2-3

A 3x2 mixed model ANOVA with repeated measures on the last factor was performed on specific aims 2-3 for those data meeting the normality assumption. Specific aim 2 tested the hypothesis that kinematic variables will be different for the reach to target task depending on speed of the reach produced as well as severity level. Specific aim 3 tested the hypothesis that kinematic variables will be different for the reach to grasp task according to size of the can as well as severity level. Friedman's ANOVA's were used to test for differences based on task requirements (speed of completion or object size) for the data that did not meet the normality assumption. Mann-Whitney U Tests were used to test for differences that may exist between groups. Wilcoxon paired test was used to assess differences within subjects among the two tasks that may exist. Post-hoc analyses were performed when significant group differences were found.

Description of Statistics Used

Physical therapists and other clinicians typically use measurements to assess whether or not a client has changed before and after therapy. It is assumed that changes in performance are representative of a true change, yet realistically this change may be in fact due to measurement error.[38, 39] Several measurements of the same quantity performed on the same individual may also not be the same due to variation within the person, measurement, or both.[110] Establishing reliability of a measurement allows the clinician or researchers to infer that change over time is due to treatment. Reliability may be measured in numerous ways, and it is important when determining which method to use to examine the limitations of each. The intraclass correlation coefficient (ICC) is an index that ranges from 0.00-1.00 and reflects reliability among raters among two or more ratings. It supports the generalizability model which accounts for the influence of specific parameters on measurement error (i.e. rater error). The ICC represents relative reliability, or the relationship between two or more repeated measures on a particular variable.[17, 111] An ICC of .75 and above is indicative of good reliability, and it has been suggested that clinical measures should exceed .90 in order to ensure that the reliability is reasonable; however, this depends on the variable being assessed and degree of precision within the measurement that is acceptable.[17, 111]

Another measure typically reported within the literature is the standard error of measure (SEM). The SEM represents within subject variability and is a measure of response stability for the population of interest.[39, 110, 111] It is representative of the standard deviation of repeated measurements.[39, 110] The SEM is expressed in the same unit as the original measurement, and is calculated by taking the square root of the mean square residual error term from the ANOVA table.[39, 110, 111]

Finally, the SEM may be used to calculate the minimal detectable difference, or minimal detectable change (MDC) which represents the smallest difference that can be detected between two measurements that is not due to error. It is the magnitude of change necessary to exceed measurement error of two repeated measures and can be interpreted as the smallest amount of change that can considered about the threshold of measurement error, and scores surpassing this value may be representative of true change.[38, 39, 110-112] The MDC is also referred to as repeatability.[110]

Table 2-1. Participant demographics / control group

Participant	Age	Gender	Dominant Hand
1	61	F	R
2	43	F	R
3	51	F	R
4	62	M	L
5	62	F	R
6	56	F	R
7	58	F	R
8	65	F	R
9	57	F	R

(M: 57.22 years; SD: 6.74)

Table 2-2. Demographics of participants with mild impairment / stroke

Participant	Age	Gender	Affected Side	Fugl-Meyer	Lesion Location	Months Post CVA
1	76	M	L	41	Right middle cerebral artery	102
2	62	M	L	46	Right M1, middle cerebral artery	48
3	70	F	L	44	Right striatocapsular infarct	131
4	66	F	R	58	Left middle/posterior cerebral artery	102
5	73	M	R	45	Left medullary / brainstem infarct	103
6	76	M	R	53	Left middle cerebral artery	174
7	55	M	L	41	Right medial medullary infarct	43
8	66	M	L	43	Right SCI	105
9	70	M	L	45	Right posterior cerebellar infarct	98

(Mean: 68.22 years; SD: 6.83 years)

Table 2-3 . Demographics of participants with moderate impairment / stroke

Participant	Age	Gender	Affected Side	Fugl-Meyer	Lesion Location	Months Post CVA
1	47	F	L	35	Right basal ganglia	7
2	62	M	L	27	Right middle cerebral artery	118
3	64	F	L	31	Right lacunar infarct	67
4	62	F	L	27	Posterior periventricular white matter	19
5	72	M	R	38	Left lacunar infarct	24
6	77	M	R	38	Left pontine infarct	34
7	72	M	L	30	Right middle cerebral artery	48
8	68	M	R	31	Left middle cerebral artery	16
9	78	M	R	27	Left brainstem lacunar infarct	162

(Mean: 66.89 years; SD: 9.56 years)

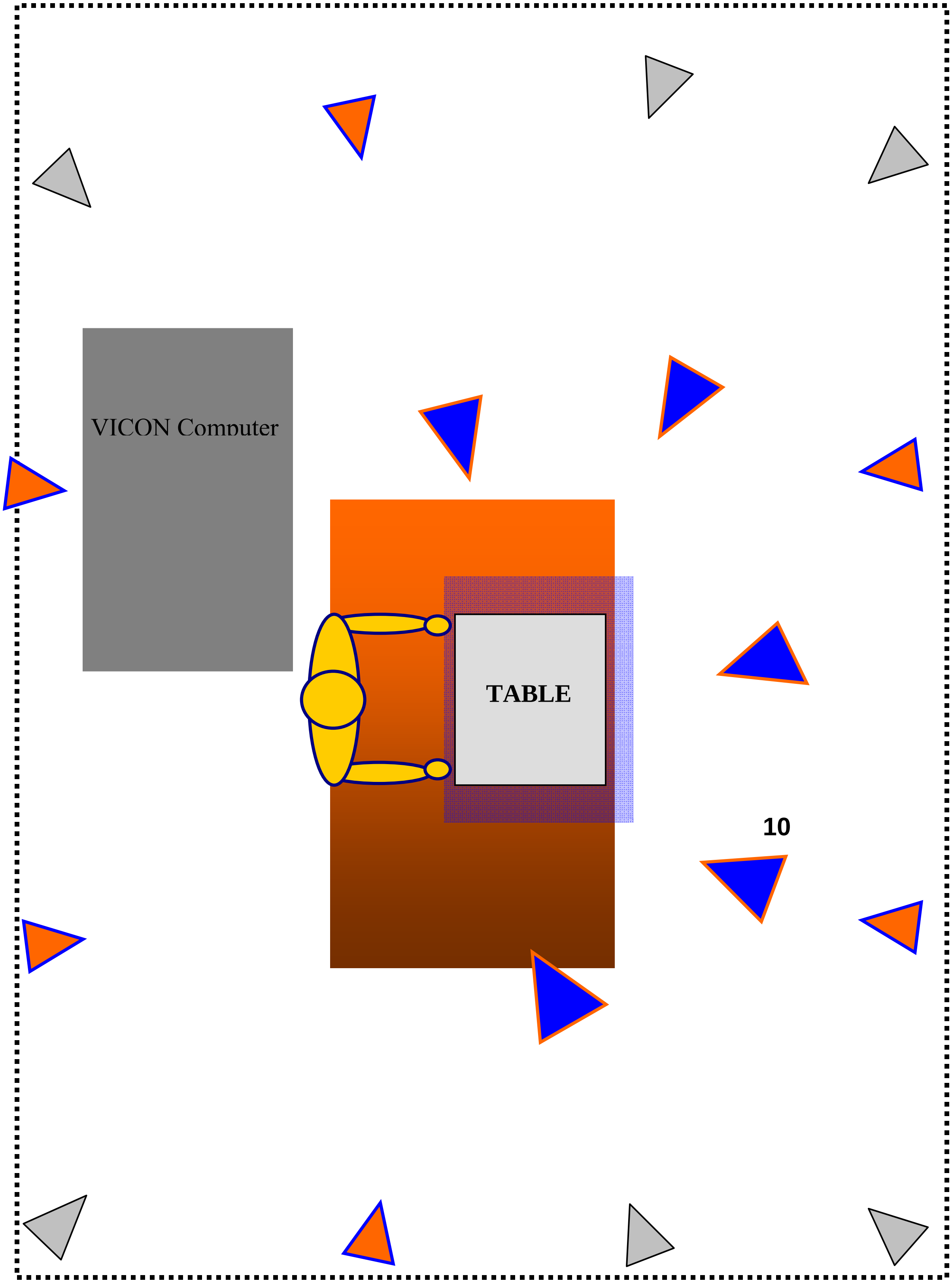

Figure 2-1. Upper extremity Vicon Workstation set-up: ▲ = camera

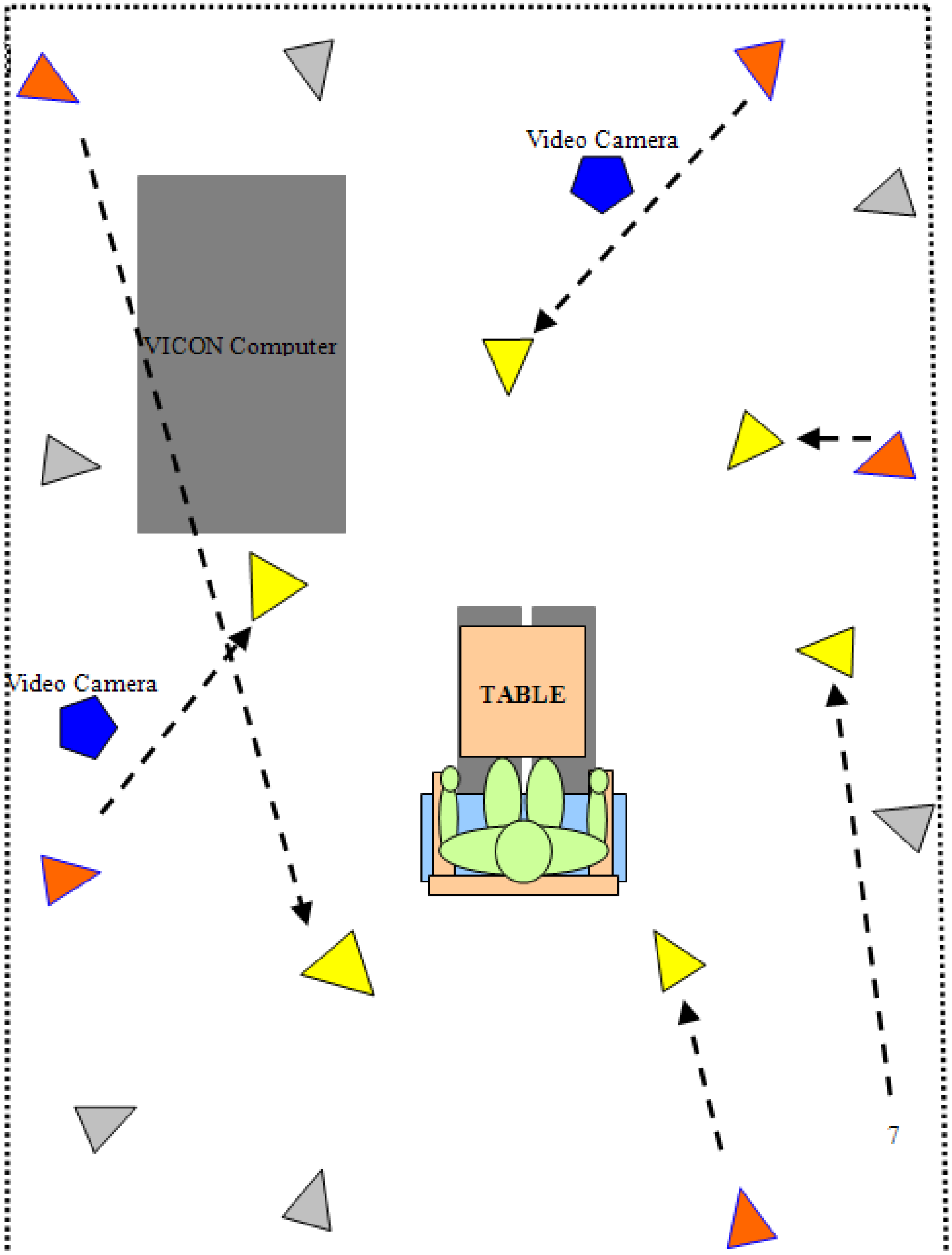

Figure 2-2. Upper extremity Vicon Nexus set-up: ▲ = camera

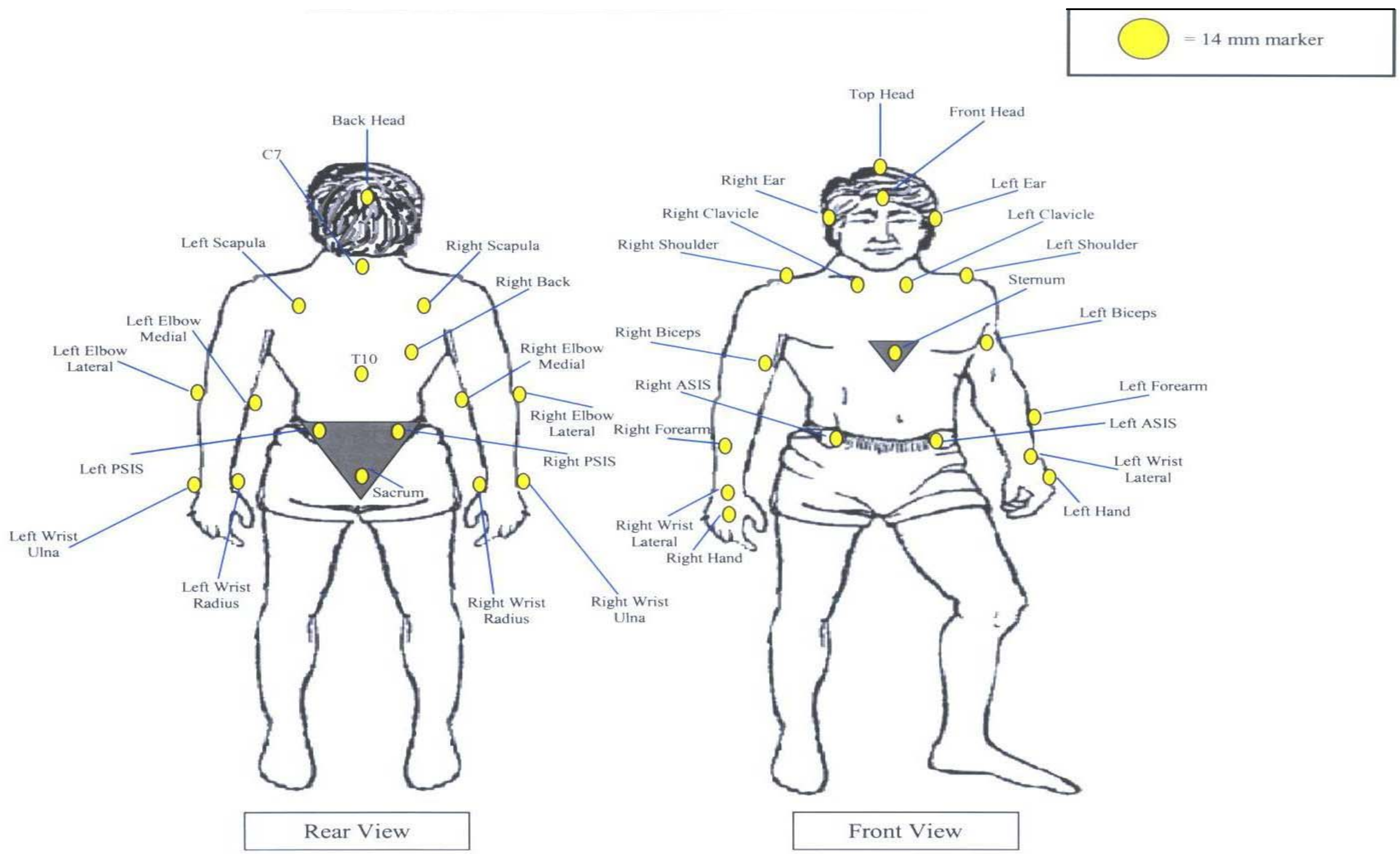

Figure 2-3. Upper body marker placement diagram

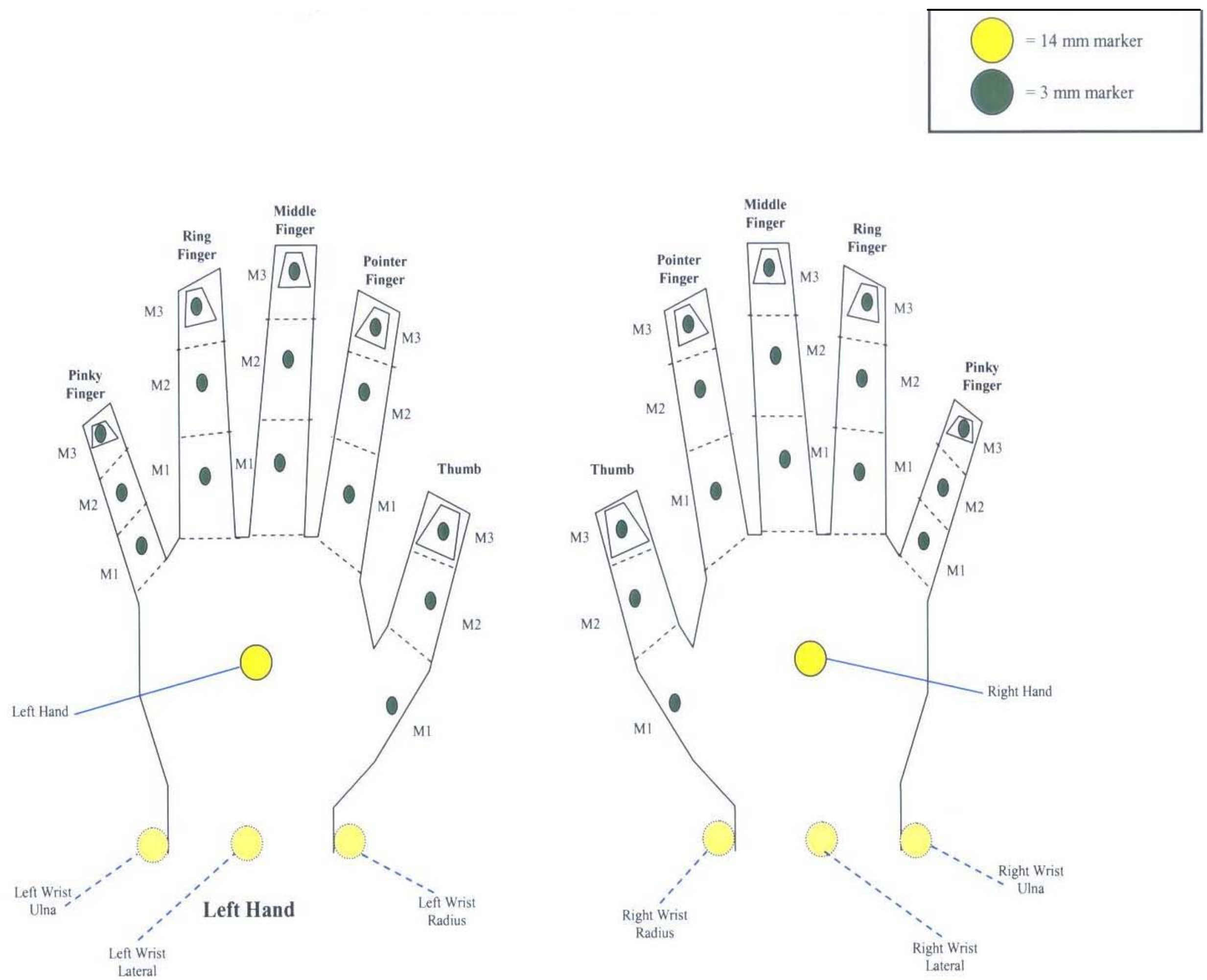

Figure 2-4. Hand marker placement diagram

CHAPTER 3
RESULTS

Descriptive Statistics

The data were entered into SPSS 16.0 (SPSS In., Chicago,IL,) and Microsoft Excel (Microsoft Corporation, Redmond, Washington) and the kinematic outcomes were analyzed. Means and standard deviations were calculated for each of the variables of interest, and are included in Table 3-1 through Table 3-6 and Figures 3-1 through 3-12. The more affected hand of the participants with stroke was compared to the dominant hand of the control group. The use of the dominant hand to compare to paretic hand has been reported within the literature, and may have less variability than the non-dominant hand.[10, 75] The metrics included movement time (MT), peak velocity (PV), index of curvature (IC), trunk displacement (TD), and aperture (AP). Movement time was calculated from onset to offset, which was calculated as the time when movement surpassed or fell below 5% of the peak velocity. This value is reported in seconds (s). Peak velocity is recorded in meters per second (m/s) and trunk displacement and aperture are both reported in millimeters (mm). Index of curvature is unit-less.

Reach to Touch Condition

For the reach to touch task, controls consistently performed faster than both the high and low impairment participants with stroke. Individuals with more moderate impairments tended to perform more slowly than those with mild impairments, even when asked to move as fast as possible. Peak velocity was higher for controls and those with mild impairments for both comfortable and fast speeds as compared to individuals with moderate impairment. Hand paths were straighter for the control group as compared to hand paths of individuals with stroke. However, participants with mild and moderate impairments had similar hand path trajectories for both the comfortable and fast reach to touch. Trunk displacement was much greater for the participants with stroke as compared to controls, and was greatest for those individuals with moderate impairment.

Reach to Grasp Can Condition

In the reach to grasp (small) task, controls consistently were faster with higher peak velocities, and performed the movement with straighter hand paths and significantly less trunk displacement than both groups of participants with stroke. The individuals with mild impairment performed more quickly, had higher peak velocities, and slightly straighter hand paths as compared to those individuals with moderate impairment. Additionally, the former group incorporated less trunk displacement.

In the reach to grasp (large) task, controls produced straighter hand path movements more quickly, had higher peak velocities and incorporated significantly less trunk displacement than both groups of participants with stroke. Individuals with mild impairments performed quicker movements, had higher peak velocities, straighter hand paths, and used less trunk displacement than individuals with moderate impairments.

Aperture was collected for all participants; however, due to poor marker visibility, peak aperture values could only be obtained for 12 participants (four control participants, four with mild impairment, and four with moderate impairment). Controls had lower maximum aperture values than both groups of individuals with stroke. The maximum aperture occurred between 75-80% of the reach cycle, while participants with stroke had maximum aperture values occurring much earlier in the reach cycle. The peak aperture values were smaller for both small and large cans at time 2 as compared to time 1.

Eight participants with moderate impairment were included for trunk displacement. For the participant with moderate impairment, the marker used to calculate trunk displacement (T-10) was not visible during one movement, and trunk displacement could not be calculated. Only three participants with moderate impairment are included in the analysis for grasp large can for maximum aperture and percent movement cycle when maximum aperture occurred. Motion data were not captured for this trial for one participant due to error in data collection and hard drive issues.

Analysis of Specific Aims

For the following specific aims, all data were entered into SPSS and initially checked for normality through the Shapiro-Wilk's test. This test is a robust method assessing normal distributions regardless of sample size.[113, 114] Data meeting the normality assumption ($p<.05$) were then analyzed through parametric analysis, and those data violating the assumption ($p>.05$) were then transformed through either log or square root transformation, and then checked again for normality. If the variables still did not meet the assumption of normality, then the data were analyzed through non- parametric testing methods.[114]

Specific Aim 1

Specific aim 1 was to examine the test-retest reliability of kinematic measures of both individuals with stroke and a healthy control group. This aim was achieved by examining the Intraclass Correlation Coefficient (ICC), the standard error measure (SEM) and repeatability of the measure (MDC).[39, 110, 112]

Hypothesis 1: Baseline and pre-test measures of peak velocity, movement time, peak velocity, index of curvature, and thumb/index finger aperture will produce high reliability across two testing sessions. Intraclass Correlation Coefficients (ICC) were calculated in accordance with the procedures outlined by Bland and Altman.[17, 110] The results of the analysis are presented in tables 3-7 through 3-12. Reliability was calculated using the ICC (2,1) model. A One-way analysis of variance (ANOVA) table was generated and the standard error of measure (SEM) was calculated. The SEM (measurement error) = SD_x X $\sqrt{(1-R_x)}$, but also may be calculated by taking the square root of the mean square residual from the ANOVA table.[110] Repeatability was calculated by multiplying the SEM by √2 x 1.96 or 2.77. For 95% of pairs of observations, the difference between the two measurements for the same participant should be less than this value.[110] ICC values within the range of .5-.6 are considered fair, .6-.7 good, and above .75 are considered to be excellent.[17]

Only the variables meeting the assumption of normality were included in this analysis. The variables were analyzed within each group at Time 1 and Time 2 and for each task condition: speed (comfortable and fast) and task (grasp small and grasp large can). The variables meeting the assumption within the control group were: movement time reach to touch both speeds; peak velocity reach to touch both speeds and reach to grasp both task conditions; trunk displacement in reach to grasp both tasks; peak aperture for both reach to grasp tasks; percent of movement cycle where peak aperture occurs in large can. In the individuals with mild impairment, the variables included: movement time reach to touch both speeds, and reach to grasp small can; peak velocity both speeds and task conditions; index of curvature reach to point both speeds and reach to grasp small can; trunk displacement both speeds and both task conditions; peak aperture grasp small and larger cans; percent movement cycle where peak aperture occurs for smaller can. In individuals with moderate impairment the variables are: reach to touch both speeds and both task conditions; peak velocity both speeds; index of curvature reach to touch comfortable speed and grasping larger can; trunk displacement both speeds and task conditions; peak aperture grasping small and larger cans; percent movement cycle where peak aperture occurs for larger can.

Reach to Touch Condition

Reaching to a target at a comfortable pace produced ICC values that were fair to good for all metrics except for peak velocity in individuals with moderate impairment due to stroke.

Reaching to a target at a fast pace produced ICC values that were fair to excellent for all metrics. SEM values were fairly low for all groups. The MDC values were fairly low except for the trunk displacement metric when reaching at a comfortable or fast pace.

Reach to Grasp Condition

Grasping a smaller can produced excellent ICC values except for trunk displacement in the control group (.52). All variables had low SEM values except for trunk displacement in individuals with mild and moderate impairments. Finally, ICC values for reach to grasp large can were good to excellent with low SEM values for the controls but much higher for trunk displacement in both mild and moderately impaired participants with stroke.

Maximum aperture for reaching to grasp a smaller can produced excellent ICC values for all groups, however, maximum aperture for reaching to grasp a for a larger can produced excellent values for participants with stroke, but not controls. The ICC's for percent of the movement cycle in which peak aperture occurred were fair to excellent with the participants with moderate impairment having slightly higher SEM values.

Hypothesis 2: Comparison of measures across two testing sessions will not produce significant differences for the three groups: control, mild and moderate impairment participants with stroke. Paired t-tests were used to analyze variables meeting the normality assumption, and the non parametric Wilcoxon paired tests were utilized for those variables violating this assumption. The variables meeting the assumption were movement time (comfortable, fast), peak velocity (comfortable, fast), trunk displacement (grasping small and large can), aperture (grasping small and large can), and maximum aperture (grasping small and large can). All variables were equivalent across the two testing times except for the reach to point comfortable pace movement time, $t(9) = 4.84$, $p=.00$, and peak velocity, $t(9) = -2.581$, p=.03, in participants with moderate impairment. These participants moved more quickly and had faster movement times at Time 1 than at Time 2 with higher peak velocities at time 2.

Wilcoxon paired tests were used to test for significant differences across the two testing sessions within each group for the variables movement time (grasping small and large can), peak velocity (grasping small and large can), index of curvature (reach comfortable and fast; grasping small and large can), trunk displacement (grasping small and large can) and percent movement cycle in which peak aperture occurs. No significant differences (p>.05) were found for any of the variables.

Specific Aim 2

This aim was to test the hypothesis that the kinematics of reach to target would be different depending on difficulty (speed) required to complete the task across all three severity levels. Velocity profiles for a representative participant in each group are shown in Figures 3-13 through 3-18.

Data not meeting the normality assumption were transformed by either log or square root transformation and analyzed through a 3x2 repeated measures ANOVA. Index of curvature was the only variable that did not meet this assumption even after transformation; therefore, this variable was analyzed through a non-parametric analysis. The results of the 3 (group) x 2 (speed) mixed model ANOVA are presented in Tables 3-13 through 3-15, and Figures 3-19 and 3-22.

Hypothesis 1: Movement time will be significantly shorter for reaching at a fast pace as compared to comfortable pace. There was a significant main effect for speed of movement produced and group as well as an interaction effect for the dependent variable movement time. Movement time for the reach to touch at a comfortable pace was significantly slower (M=.86s) than reaching at a fast pace (M=.65s). Movement time was also significant for group based on severity level. Examination of the cell means for the interaction effect indicated that there was a significant difference in movement time for movements produced at comfortable verses fast pace for each group. The control group produced much quicker movements from a comfortable pace (M=.67s) to a faster pace (M=.42s), and the moderately impaired group performed much quicker movements from a comfortable pace (M=1.08) to a fast pace (M=.84). Individuals with mild impairment moved more quickly when instructed to perform the movement as “fast as possible,” but the overall difference between the comfortable pace (M=.85) to fast pace (M=.69) was not as large as it was for the control and moderately impaired group. A Bonferroni post hoc comparison was computed in order to account for multiple comparisons, and a significant difference was found for the control group compared to both the mild (p=.01) and moderately (p=.00) impaired participants with stroke; however, the two groups of participants with stroke were not significantly different from each other (p=.09).

Hypothesis 2: Peak velocity will be significantly higher for reaching at a faster pace as compared to a comfortable pace. A significant main effect of speed was obtained, and peak velocity values were significantly higher for faster movements (M=.95m/s) as compared to comfortable movements (M=.73m/s). A significant interaction effect of Speed*Group was also obtained, and although all groups produced higher peak velocities for faster movements compared to comfortable movements, the control group produced much higher peak velocity values (M=1.24m/s) than the mild (M=.91m/s) and moderately impaired (M=.71m/s) participants with stroke. Post hoc analysis for multiple comparisons showed a significant difference in peak velocity values among all groups. The control group was significantly different from the mild (p=.00) and moderately (p=.00) impaired participants, and the two groups of participants with stroke were significantly different from each other (p=.03).

Hypothesis 3: Trunk displacement will be larger at a fast pace as compared to comfortable pace.. The 3x2 mixed model ANOVA revealed that the main effect of speed was not significant. There was no overall difference in the amount of trunk displacement utilized to reach at a comfortable pace (M=68.83mm) compared to a fast pace (M=67.75mm). However, there was a significant main effect of group. Post hoc analysis showed that only the controls were significantly different than the participants with mild (p=.02) and moderate impairment (p=.00), but the two groups of participants with stroke were not significantly different from each other (p=.14). A significant Speed*Group interaction was also found. Interestingly, average trunk displacement for controls (M=34.47mm) and individuals with mild impairment (M=71.97mm) were slightly higher when reaching at a faster pace as compared to comfortable pace (controls, M=30.31mm; mild, M=71.59mm), while individuals with more moderate impairment used less trunk displacement for reaching at a faster pace (M=96.81mm) as compared to comfortable pace (M=104.59mm).

Hypothesis 4: Hand paths will be significantly straighter for controls and individuals with mild impairment than moderate impairment. A Friedman ANOVA was used to test for group differences for the dependent variable index of curvature for reaching at a fast verses comfortable pace. No significant difference, (x^2=3.00, p=.08) was found for this variable. A non-parametric Mann-Whitney U test was performed to test for significant differences between groups for index of curvature at the comfortable, and then at the fast pace. The control group was significantly different than the mild impairment group for the reach to touch fast pace (U=5.00, p.00), and was not significantly different from the mild group for reach to touch at a comfortable pace (U=21, p=.085). The control group also had significantly straighter hand paths as compared to the moderately impaired group at both reach to touch comfortable (U=18, p=.05) and fast pace (U=8, p=.00). The two groups of participants with stroke were not significantly different from each other at either the comfortable (U=38, p=.83) of fast (U=40, p=.97) pace.

Pair-wise Wilcoxon tests were used to test for within group differences, and a significant difference was found for index of curvature at comfortable verses fast speed for controls, (z= -2.31, p= .021). The hand path was straighter at the faster speed. However, no significant difference between speeds of tasks was revealed for those with mild or moderate impairment.

Specific Aim 3

Specific aim 3 was to test the hypothesis that kinematics of reach to grasp would be different depending on size of task and severity level. Velocity profiles for a representative participant in each group are shown in Figures 3-23 through 3-28. The results of the analysis are presented in Tables 3-16 through 3-19, and Figures 3-29 through 3-34.

Hypothesis 1: Movement time will be significantly slower for reach to grasp large can as compared to small especially for the moderately impaired group. Procedures for assessing normality and analysis methods were followed as previously described in specific aim 2. For movement time, there was a significant main effect for task and group, but no significant interaction effect. Movement time was significantly faster when reaching to grasp a small can (M=1.00s) than when reaching to grasp the larger can (M=1.10s). Post hoc comparisons were computed in order to account for multiple comparisons. The Games-Howell post hoc comparison method was utilized because the assumption of equal error variances was not met (p>.05). The control group was significantly different from the two groups of participants with stroke (mild, p=.00; moderate, p=.00), but participants with stroke were not significantly different from each other (p=.14). Movement time for reaching to grasp a small can (M=.48s) as compared to a larger can (M=.50s) was slightly slower for the control group, but significantly faster as compared to the amount of time the participants of stroke used to reach to grasp the cans. No significant difference was found between mild and moderately impaired participants with stroke; mildly impaired participants reached more slowly for reaching to grasp the large can (M=1.19s) as compared to a smaller can (M=1.05s), and moderately impaired participants reached much more slowly for reaching to grasp a large can (M=1.61s) as compared to the smaller can (M=1.46s); however, the difference in movement time was about the same for these two groups.

Hypothesis 2: Peak velocity values will be lower for reaching to grasp larger can especially for the moderately impaired group. For peak velocity, there was a significant main effect of group, but not for task. No significant interaction effect was found. Post hoc comparisons produced a significant difference for controls compared to both groups of participants with stroke (mild, p=.00; moderate, p=.00), and for the two groups of participants with stroke compared to each other (p=.04). Controls (M=.95m/s) had significantly larger peak velocity values as compared to both individuals with mild (M=.67m/s) and moderate impairment (M=.50m/s).

Hypothesis 3: Maximum aperture will be greater for the larger can and occur later in the movement cycle. The 3x2 mixed model ANOVA revealed a significant main effect of task for peak aperture, as well as an interaction effect. No significant main effect for group was found; therefore, post hoc comparisons were not computed. Aperture was significantly different for the large can (M=138.93mm) as compared to the small can (M=128.212mm). Each group produced larger aperture values to pick up the larger can; however, the difference in maximum aperture value was much greater for the control group for the larger can (M=138.93mm) as compared to the small can (M=115.83mm). Participants with mild impairment had a higher maximum value for the small can (M=142.93mm) as compared to controls (M=115.83mm) and so did the moderately impaired group (M=125.90mm) as compared to controls (M=115.83mm). However, while controls increased aperture to a greater extent to pick up the large can, there was only a slight increase in maximum aperture for both groups of participants with stroke. Maximum aperture values for the large can in the control group (M=138.93mm) were very similar to the moderately impaired participants for the large can (M=133.78mm).

For percent of movement cycle in which peak aperture occurred, only a significant main effect of group only was found. The assumption for equality of error variances was not met; therefore, the Games-Howell test was used for post hoc comparisons. There was a significant difference for the control group as compared to both the mild (p=.05) and moderately (p=.05) impaired group, but not for the two groups of participants with stroke compared to each other (p=1.00). The overall percent of movement cycle where peak aperture occurred was much higher for controls (M=78.45%) as compared to individuals with mild (56.55%) and moderate (M=57.10%) impairment.

Hypothesis 4: Trunk displacement will be greater for the reaching to grasp larger can condition than a smaller can, especially for the moderately impaired group. A Friedman ANOVA was test for group differences for trunk displacement for grasping a large can verses a small can. A significant difference was found for amount of trunk displacement (x^2=7.54, p=.01). Mann-Whitney U tests were performed to test for differences between groups for reaching to grasp a small can, and then reaching to grasp a large can. A significant difference was found for trunk displacement for the control group as compared to the individuals with mild stroke for grasping a small can (U=12, p=.01) and larger can (U=10, p=.01). There was also a significant difference for the control group compared to the more moderately impaired participants with stroke for the smaller (U=0, p=.00) and larger can (U=0, p=.00). However, the two groups of participants with stroke were not significantly different for reaching to grasp a small can (U=19, p=.06) but were significantly different for reaching to grasp a large can (U=16, p=.05). The control group utilized much less trunk displacement for both the small can (M=41.14mm) and large can (M=44.99mm) than both the mild (small M=114.09mm; large M=119.61mm) and moderately impaired (small M=163.30mm; large M=173.43mm) participants with stroke. Pairwise Wilcoxon test did not show a significant difference within each group for trunk displacement for grasping a small verses larger can.

Hypothesis 5: Hand paths will be less straight for grasping a larger can especially for the moderately impaired group. Finally, a non parametric Friedman Anova produced a significant group difference for index of curvature (x^2=7.54, p=.01) for grasping a small verses large can. Mann-Whitney U tests were used to test for differences between groups for index of curvature reaching to grasp a small can, and then reaching to grasp a large can. A significant difference was found for the control group compared to both levels of impairment in individuals with stroke; the control group was able to produce a straighter hand path as compared to both groups of participants. The control group was significantly different from the participants with mild impairment for grasping a smaller can (U=5, p=.00) and a larger can (U=7, p=.00). The control group also was significantly different for index of curvature from the more moderately impaired group for grasping both a smaller can (U=0, p=.00) and larger can (U=3, p=.00). The two groups of stroke participants were not significantly different from each other for either grasping a small (U=26, p=.20) or large (U=26, p=.19) can. Wilcoxon pairwise tests did not produce a significant difference within the participants with mild or moderate impairment; however, a significant difference was found for the control group (z= -2.31, p=.02).

Table 3-1. Mean and standard deviations for reach to touch comfortable speed

Variable		Control (mean,sd)	Mild (mean,sd)	Moderate (mean, sd)
MT	T1	.75 (.14)	.99 (.32)	1.35 (.35)
	T2	.67 (.12)	.85 (.27)	1.08 (.23)
PV	T1	.89 (.13)	.71 (.17)	.47 (.08)
	T2	.91 (.11)	.73 (.17)	.55 (.09)
IC	T1	1.08 (.08)	1.13 (.07)	1.14 (.09)
	T2	1.07 (.07)	1.13 (.07)	1.16 (.12)
TD	T1	30.12 (8.49)	74.52 (31.76)	85.65 (23.34)
	T2	30.31 (16.20)	71.59 (32.95)	104.59 (30.95)*

* Only 8 participants included

Table 3-2. Mean and standard deviations for reach to touch fast speed

Variable		Control (mean,sd)	Mild (mean,sd)	Moderate (mean, sd)
MT	T1	.46 (.06)	.75 (.20)	.85 (.18)
	T2	.43 (.05)	.69 (.22)	.84 (.18)
PV	T1	1.21 (.14)	.91 (.22)	.69 (.16)*
	T2	1.24 (.17)	.92 (.22)	.72 (.11)
IC	T1	1.03 (.02)	1.13 (.09)	1.21 (.29)
	T2	1.03 (.02)	1.14 (.09)	1.14 (.11)
TD	T1	35.75 (9.45)	81.31 (32.67)	90.82 (25.72)*
	T2	34.47 (17.27)	71.97 (34.69)	96.81 (34.48)

Only 8 participants included

Table 3-3. Mean and standard deviations for reach to grasp small

Variable		Control (mean,sd)	Mild (mean,sd)	Moderate (mean, sd)
MT	T1	.51 (.10)	1.17 (.56)	1.63 (.56)
	T2	.48 (.08)	1.05 (.46)	1.46 (.51)
PV	T1	.95 (.14)	.66 (.20)	.50 (.12)
	T2	.95 (.14)	.68 (.16)	.52 (.10)
IC	T1	1.03 (.02)	1.13 (.08)	1.23 (.16)
	T2	1.03 (.02)	1.13 (.07)	1.18 (.09)
TD	T1	44.62 (16.90)	113.69 (46.25)	164.07 (37.88)
	T2	41.14 (14.04)	114.09 (61.83)	163.30 (39.70)

Table 3-4. Mean and standard deviations for reach to grasp large

Variable		Control (mean,sd)	Mild (mean,sd)	Moderate (mean, sd)
MT	T1	.50 (.08)	1.13 (.54)	1.69 (.77)*
	T2	.50 (.08)	1.19 (.68)	1.61 (.45)
PV	T1	1.01 (.22)	.69 (.13)	.51 (.12)*
	T2	.95 (.10)	.66 (.17)	.49 (.14)
IC	T1	1.04 (.02)	1.14 (.12)	1.24 (.16)*
	T2	1.04 (.02)	1.14 (.09)	1.21 (.11)
TD	T1	51.42 (17.68)	130.96 (50.12)	167.89 (48.79)*
	T2	44.99 (17.76)	119.61 (60.57)	173.43 (42.75)*

* Only 8 participants included

Table 3-5. Mean and standard deviations for maximum aperture (mm)

Group	Grasp Small	Grasp Large
Control (mean,sd): 4 Participants		
T1	119.83 (9.15)	128.25 (8.87)
T2	115.83 (11.19)	135.15 (7.18)
Mild (mean,sd): 4 Participants		
T1	143.05 (15.19)	146.93 (15.22)
T2	142.93 (19.38)	147.88 (13.97)
Moderate (mean, sd): 4 Participants		
T1	126.16 (24.21)	141.17 (14.07)*
T2	125.90 (23.34)	133.78 (20.66)

* Only 3 participants included

Table 3-6. Mean and standard deviations for percent movement cycle to maximum aperture

Group	Grasp Small	Grasp Large
Control (mean,sd): 4 Participants		
T1	68.25 (3.57)	72.60 (10.90)
T2	75.83 (8.08)	81.07 (7.89)
Mild (mean,sd): 4 Participants		
T1	54.19 (12.67)	62.88 (7.66)
T2	57.26 (13.36)	55.84 (11.32)
Moderate (mean, sd): 4 Participants		
T1	51.24 (16.88)	45.47 (11.06)*
T2	64.26 (10.18)	49.92 (15.79)

*Only 3 participants included

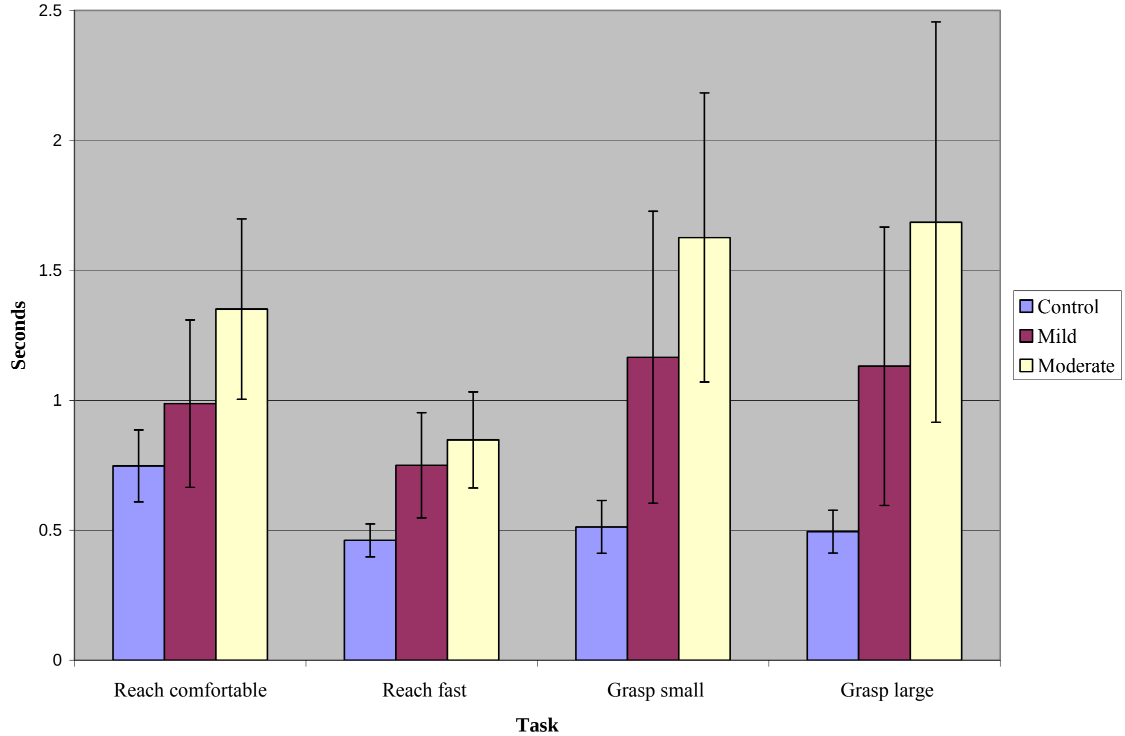

Figure 3-1. Time 1 average movement time for each task

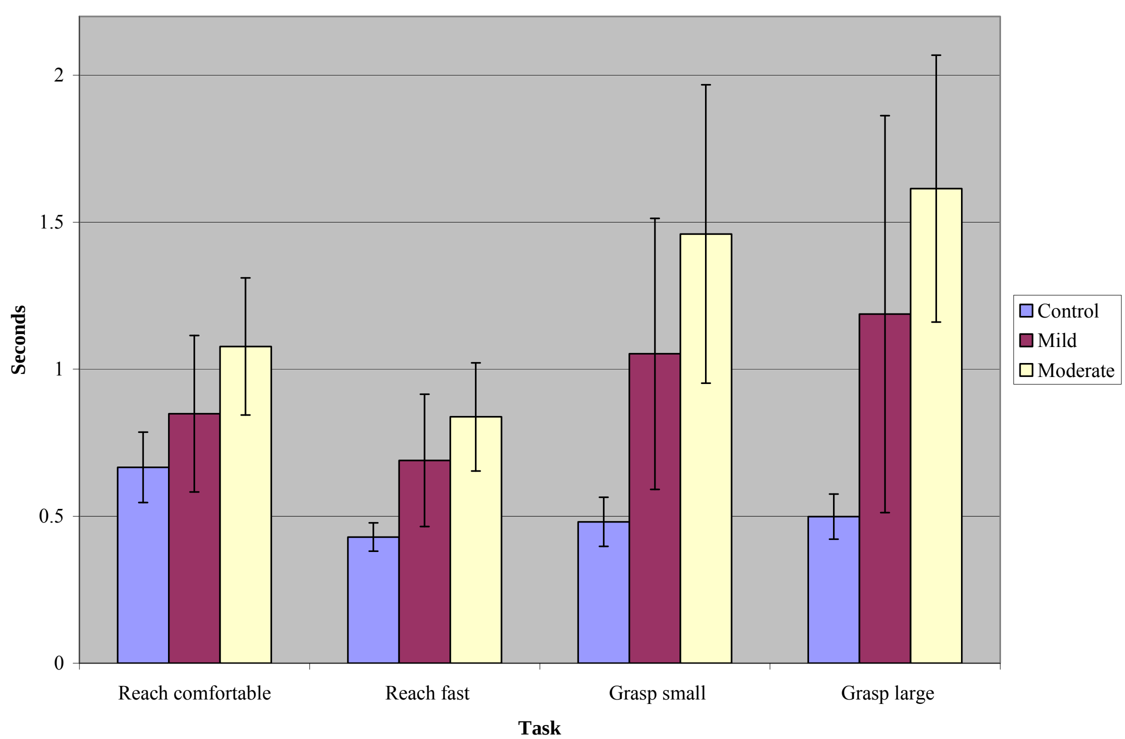

Figure 3-2. Time 2 average movement time for each task

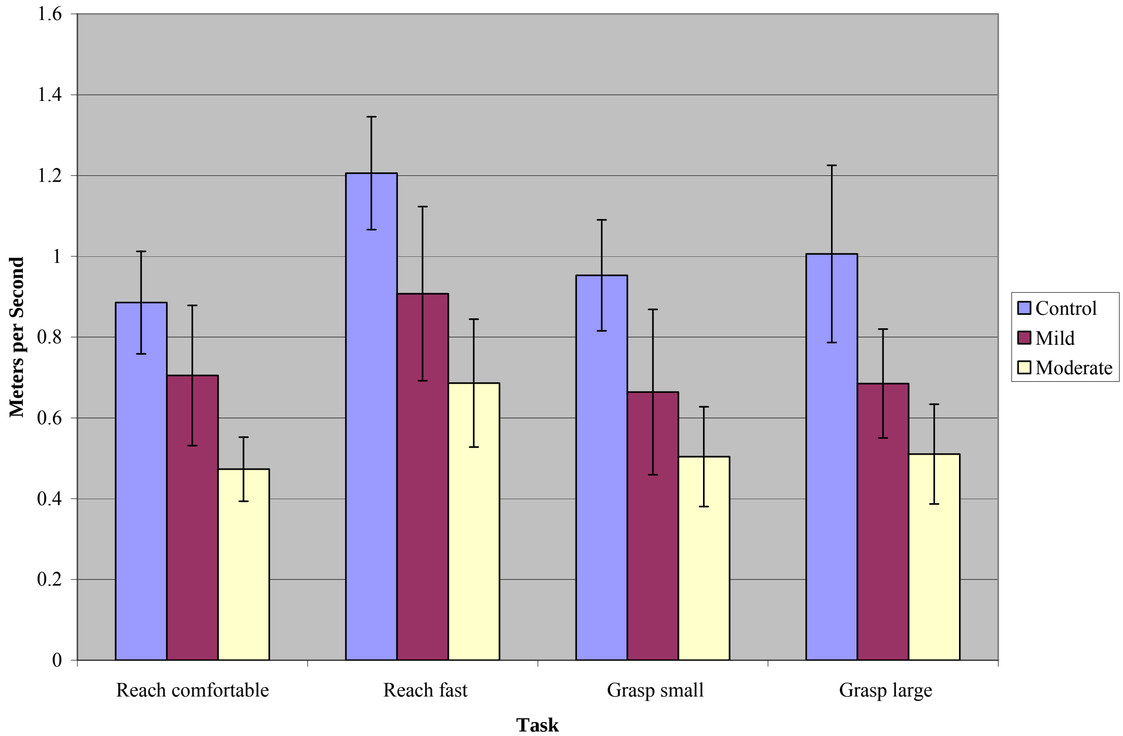

Figure 3-3. Time 1 average peak velocity for each task

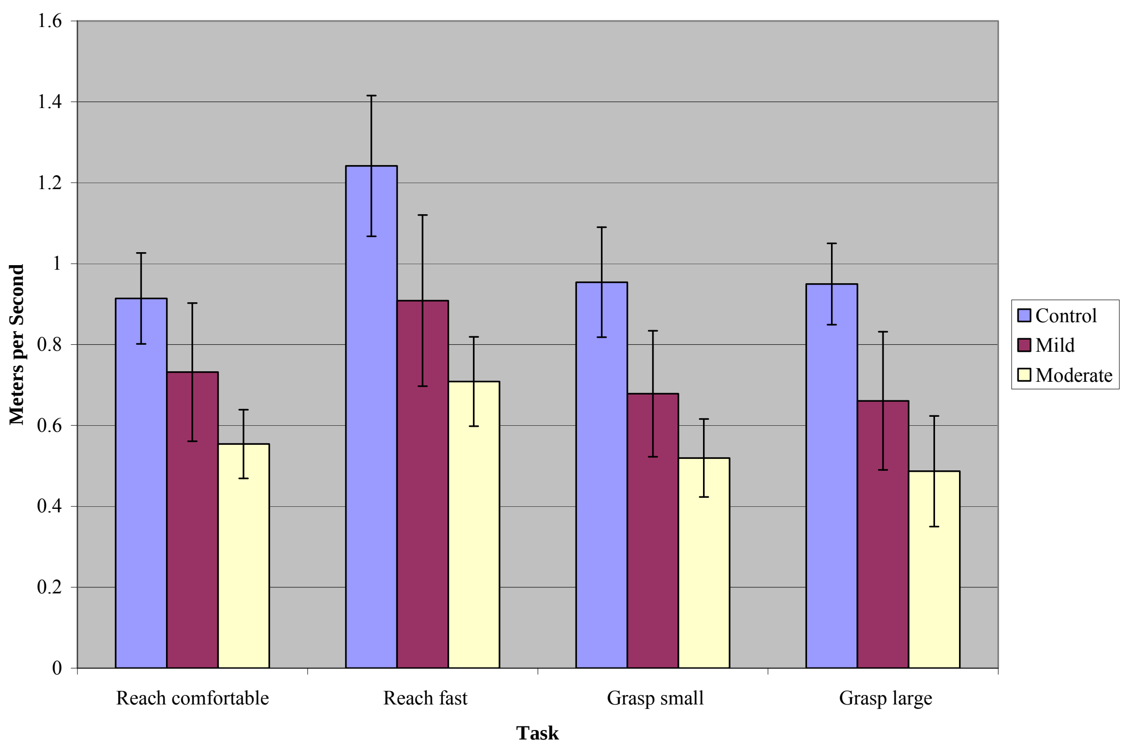

Figure 3-4. Time 2 average peak velocity for each task

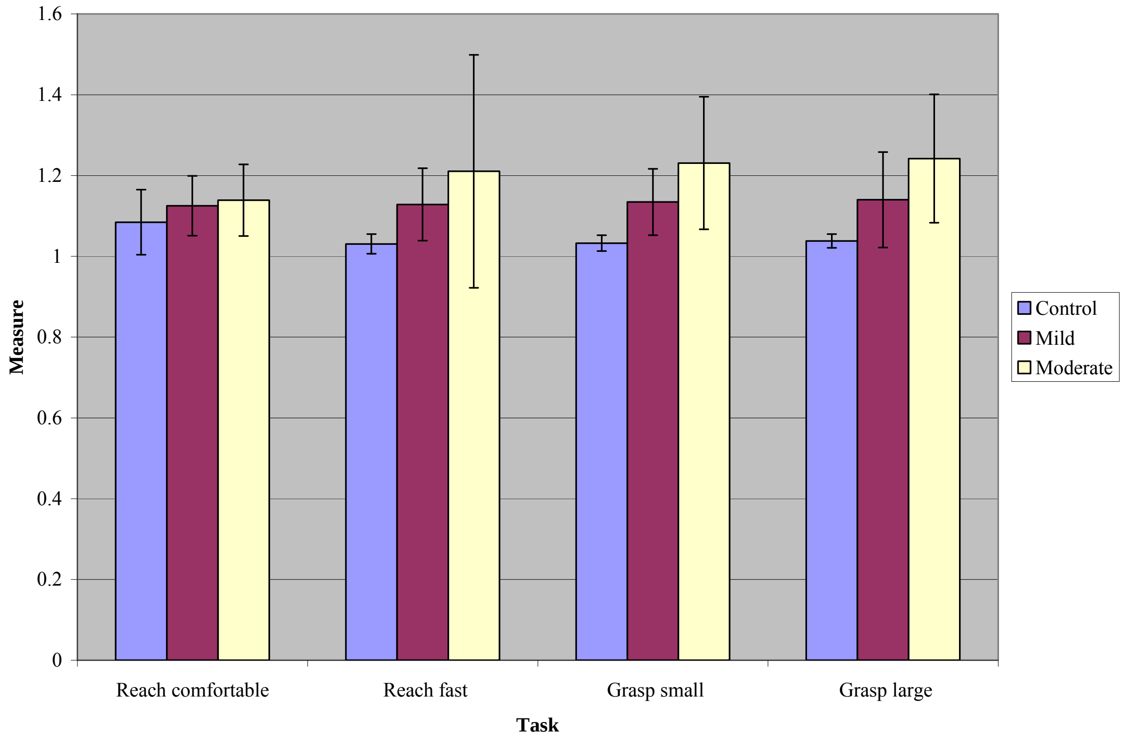

Figure 3-5. Time 1 average index of curvature for each task

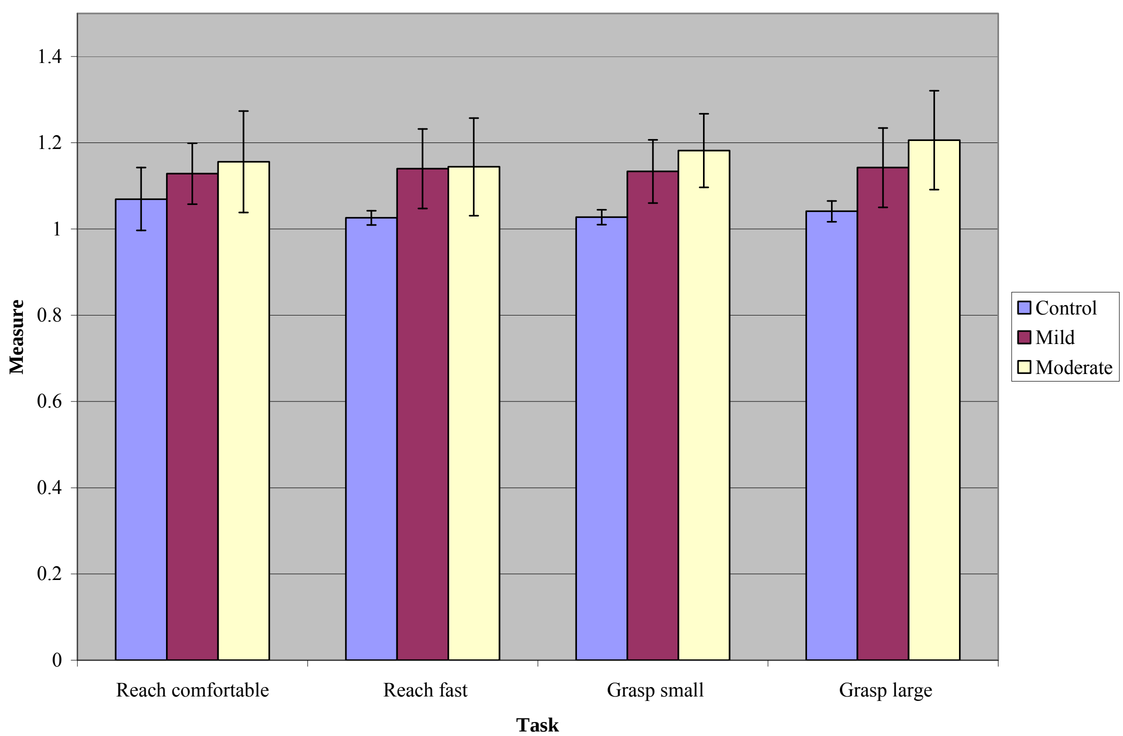

Figure 3-6. Time 2 average index of curvature for each task

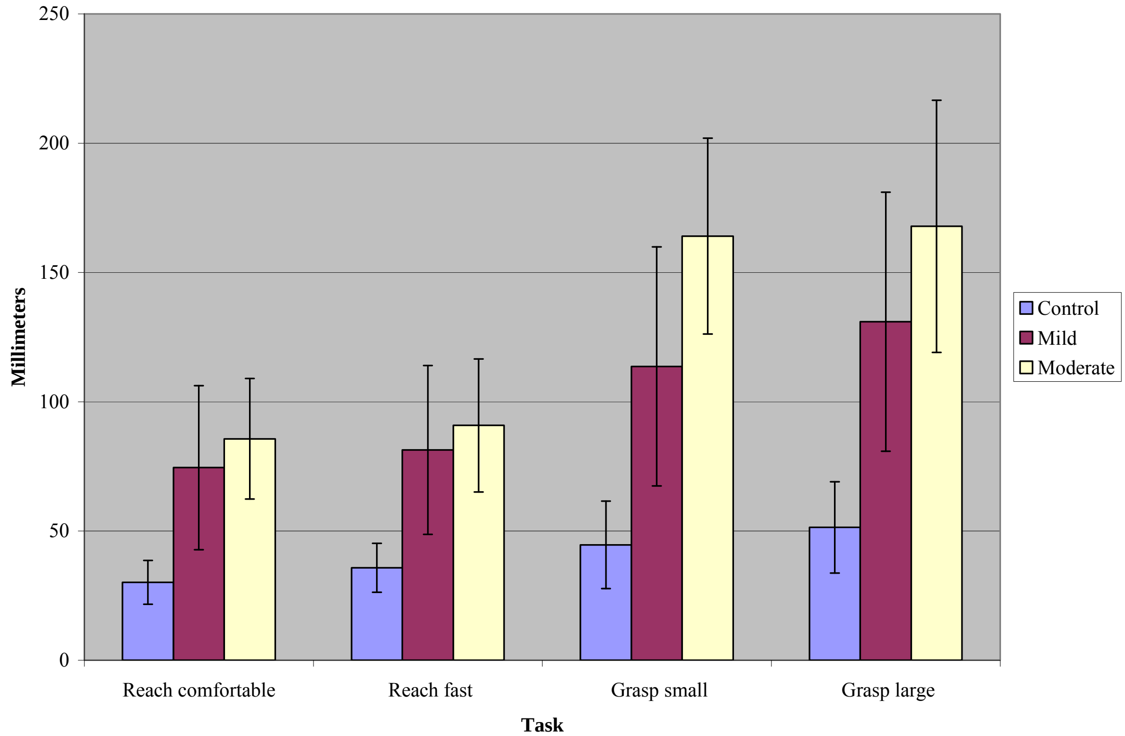

Figure 3-7. Time 1 average trunk displacement for each task

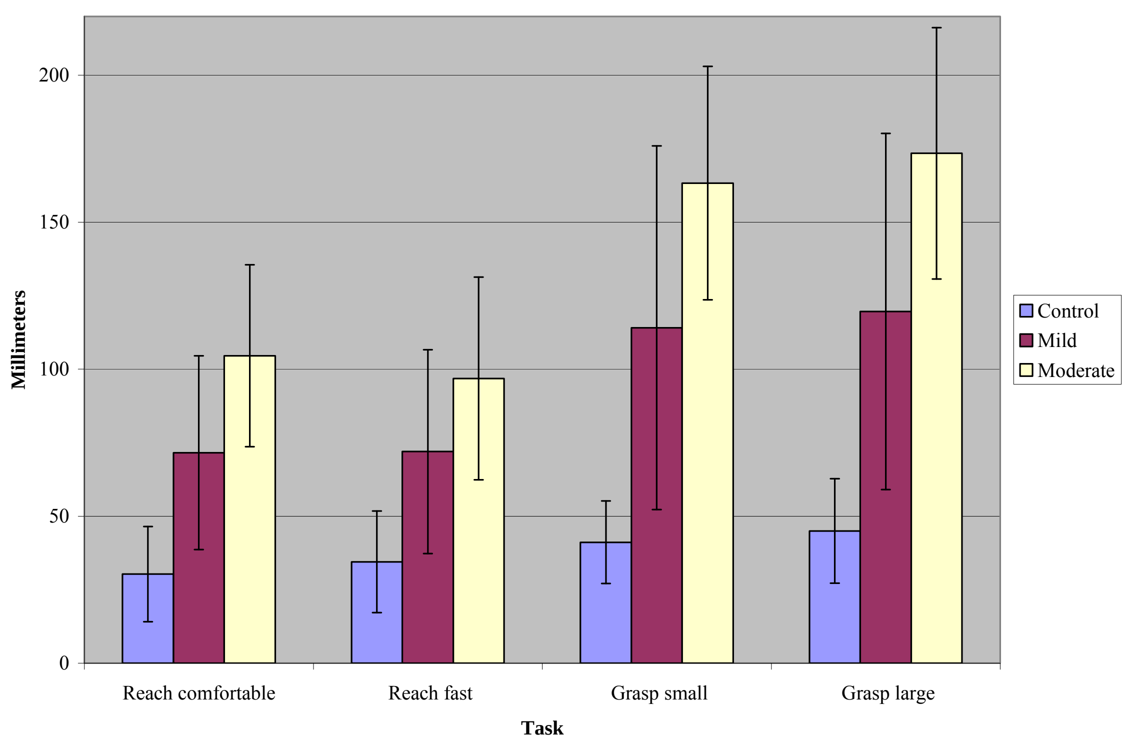

Figure 3-8. Time 2 average trunk displacement for each task

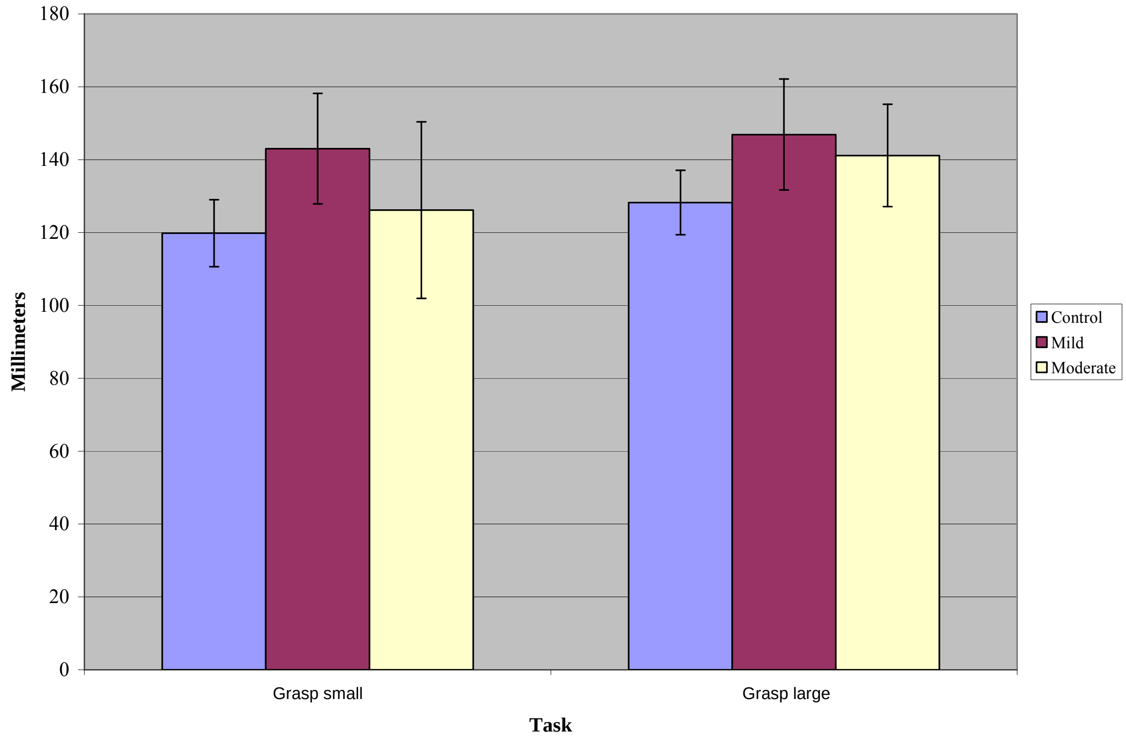

Figure 3-9. Time 1 average maximum aperture for each task

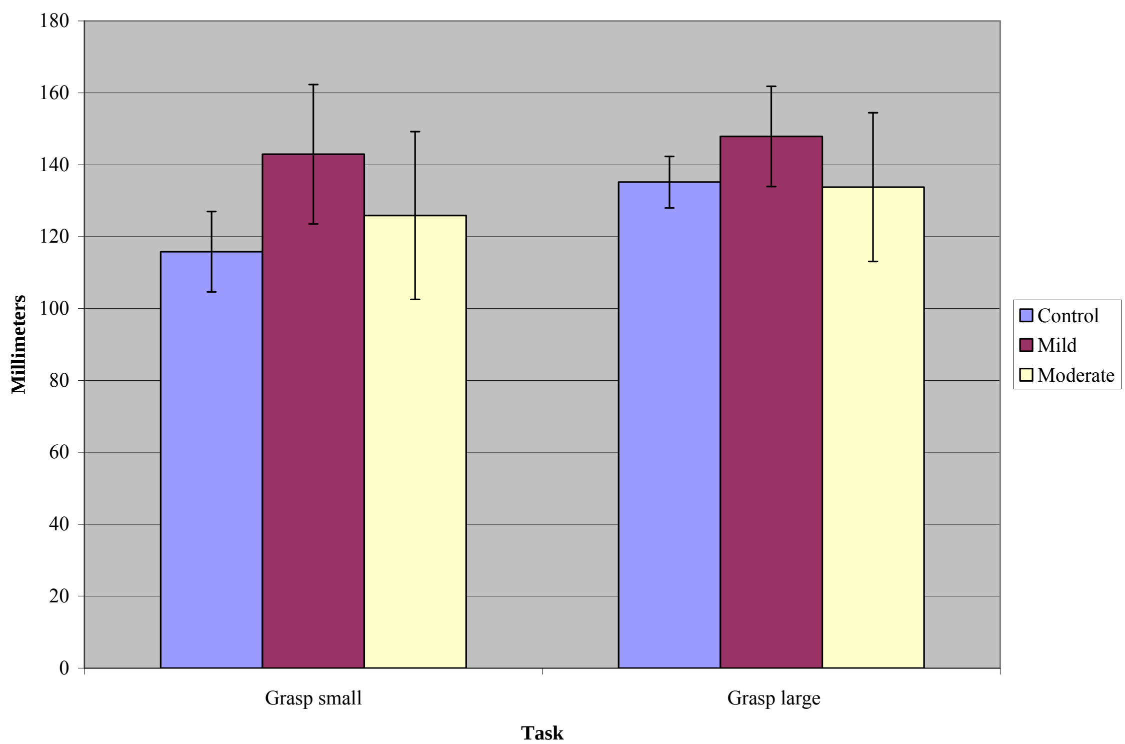

Figure 3-10. Time 2 average maximum aperture for each task

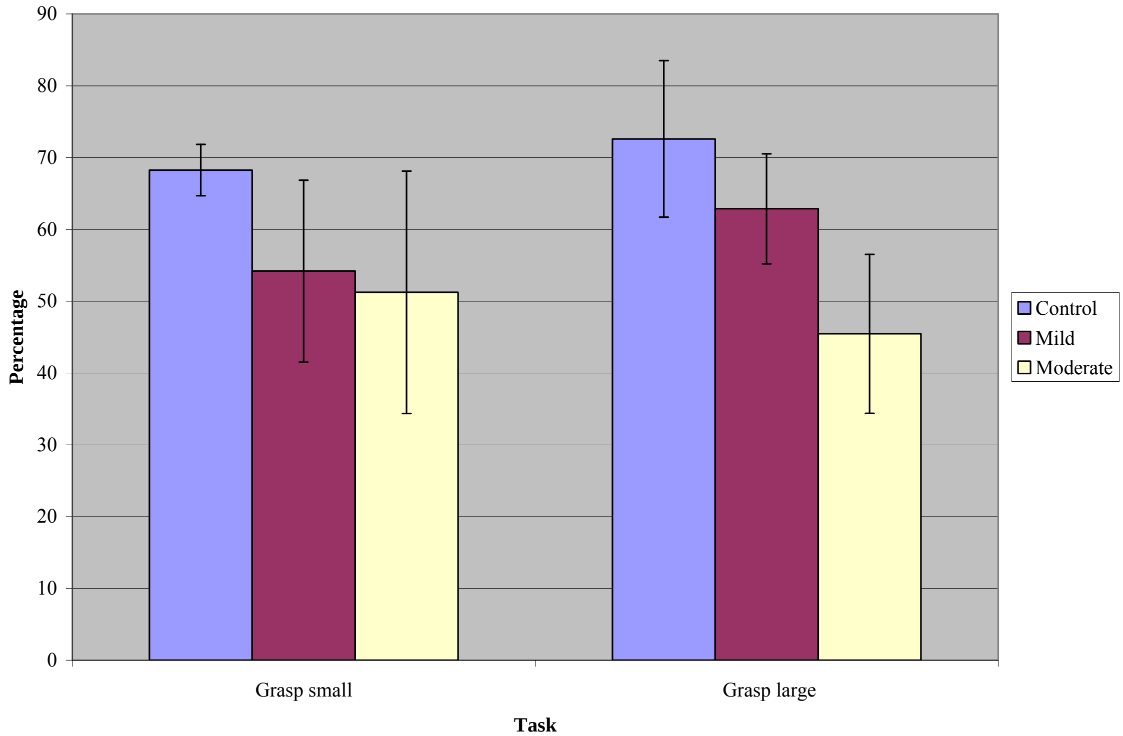

Figure 3-11. Time 1 average percent movement cycle of peak aperture for each task

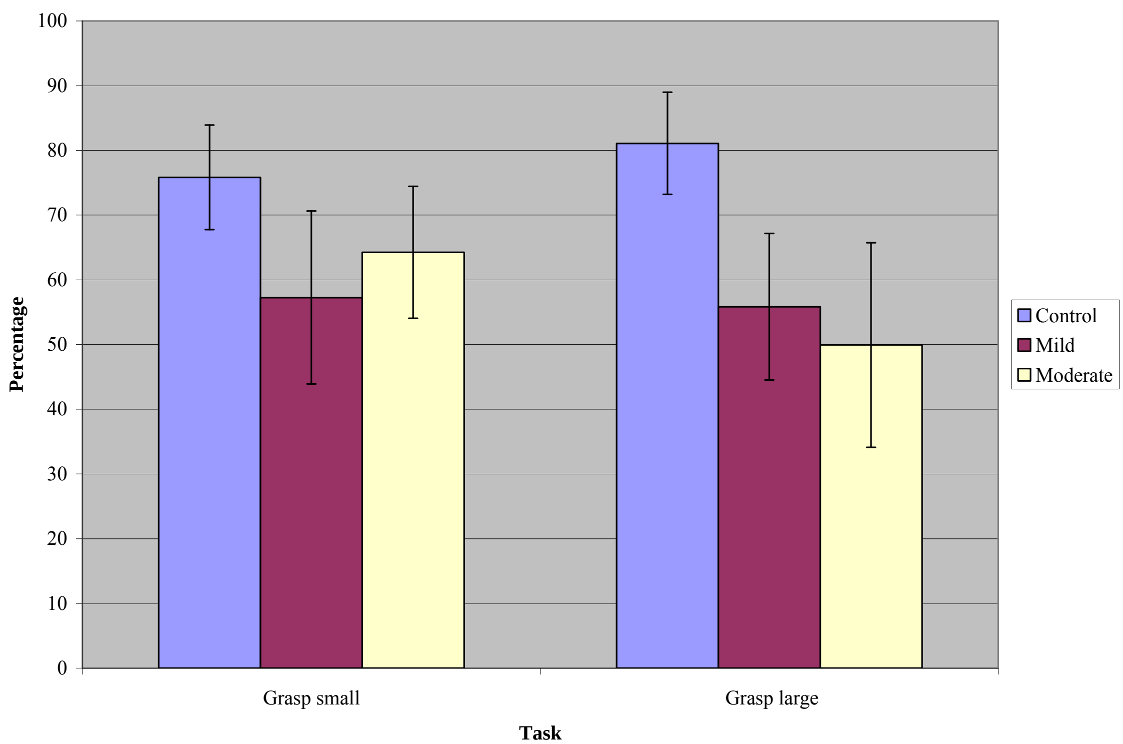

Figure 3-12. Time 2 average percent movement cycle of peak aperture for each task

Table 3-7. Intraclass correlation coefficient (ICC), standard error of measure (SEM), and minimal detectable change (MDC) reach to touch comfortable speed

Metric	ICC	SEM	MDC
MT (s)			
Control	.55	.09	.25
Mild	.79	.16	.44
Moderate	.67	.13	.36
PV (m/s)			
Control	.81	.07	.19
Mild	.91	.07	.19
Moderate	.21	.06	.17
IOC			
Mild	.85	.04	.11
TD (mm)			
Mild	.91	14.02	38.84
Moderate	.77	13.72	38.00

Table 3-8. Intraclass correlation coefficient (ICC), standard error of measure (SEM), and minimal detectable change (MDC) reach to touch fast speed

Metric	ICC	SEM	MDC
MT (s)			
Control	.49	.04	.11
Mild	.87	.10	.28
Moderate	.88	.09	.25
PV (m/s)			
Control	.55	.13	.36
Mild	.94	.08	.22
Moderate	.75	.09	.25
IOC			
Mild	.93	.03	.08
TD (mm)			
Mild	.82	18.69	51.77
Moderate	.91	12.25	33.93

Table 3-9. Intraclass correlation coefficient (ICC), standard error of measure (SEM), and minimal detectable change (MDC) grasp small can

Metric	ICC	SEM	MDC
MT (s)			
Mild	.94	.16	.44
Moderate	.92	.18	.50
PV (m/s)			
Control	.85	.07	.19
Mild	.93	.07	.19
IOC			
Mild	.98	.00	.00
TD (mm)			
Control	.52	12.81	35.48
Mild	.92	22.15	61.36
Moderate	.82	22.38	61.99

Table 3-10. Intraclass correlation coefficient (ICC), standard error of measure (SEM), and minimal detectable change (MDC) grasp large can

Metric	ICC	SEM	MDC
MT (s)			
Control	.86	.04	.11
Moderate	.91	.27	.75
PV (m/s)			
Control	.63	.13	.36
Mild	.85	.08	.22
IOC			
Moderate	.90	.05	.14
TD (mm)			
Control	.79	10.10	27.98
Mild	.91	22.40	62.05
Moderate	.85	24.37	67.50

Table 3-11. Intraclass correlation coefficient (ICC), standard error of measure (SEM), and minimal detectable change (MDC) grasp can maximum aperture

Metric	ICC	SEM	MDC
Grasp Small (mm)			
Control	.95	2.08	5.76
Mild	.98	4.29	11.88
Moderate	.99	1.02	2.83
Grasp Large (mm)			
Control	*.29*	6.85	18.97
Mild	.99	1.97	5.46
Moderate	.93	5.87	16.26

Table 3-12. Intraclass correlation coefficient (ICC), standard error of measure (SEM), and minimal detectable change (MDC) grasp can percent movement cycle

Metric	ICC	SEM	MDC
Grasp Small (%)			
Mild	.95	3.84	10.64
Grasp Large (%)			
Control	.67	4.78	13.24
Moderate	.90	6.15	17.04

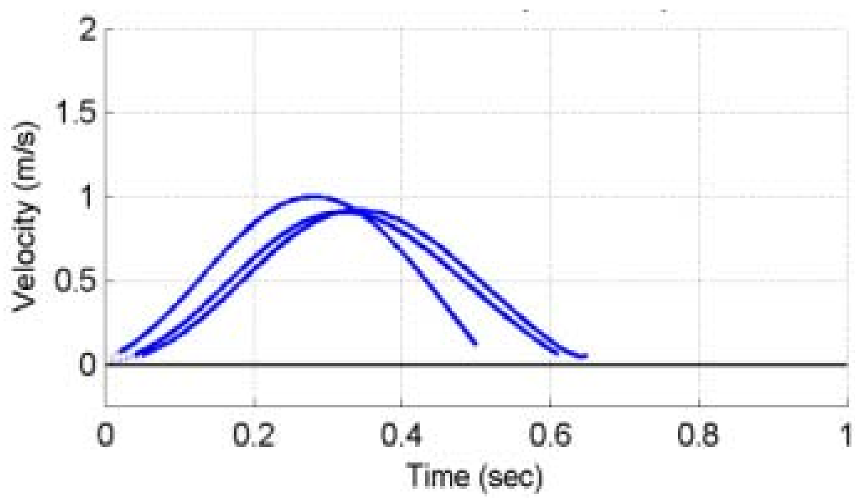

Figure 3-13. Velocity profile reach to touch comfortable pace for one representative control participant

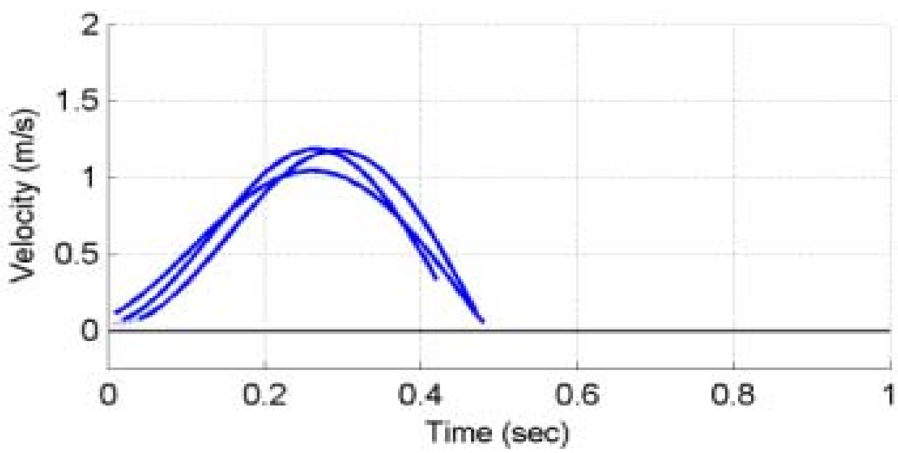

Figure 3-14. Velocity profile reach to touch fast pace for one representative control

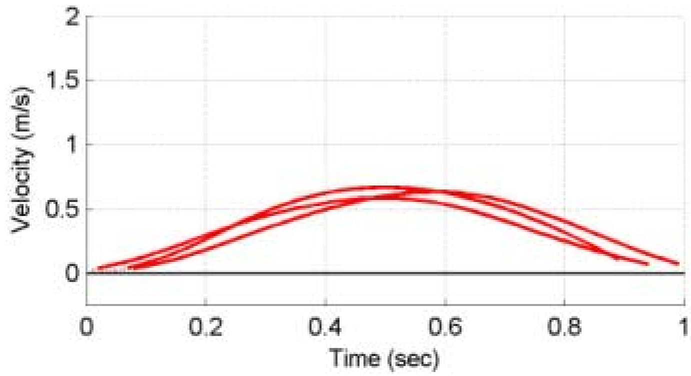

Figure 3-15. Velocity profile for reach to touch comfortable pace for one representative participant with mild impairment

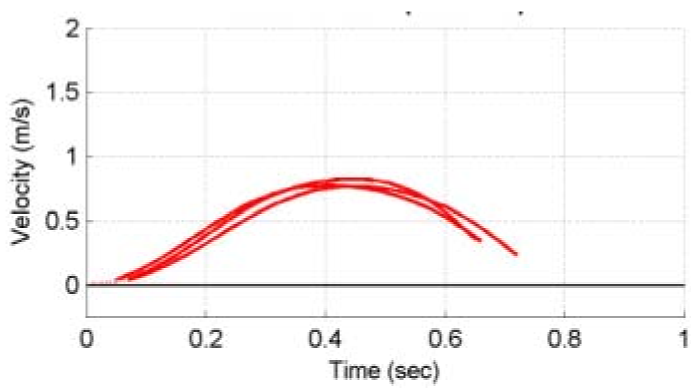

Figure 3-16. Velocity profile for reach to touch fast pace for one representative participant with mild impairment

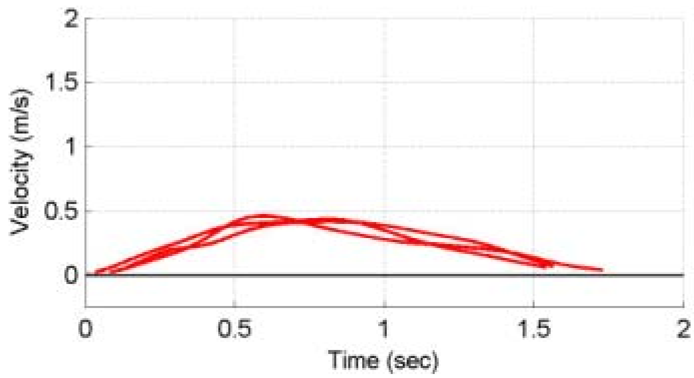

Figure 3-17. Velocity profile for reach to touch comfortable pace for one representative participant with moderate impairment

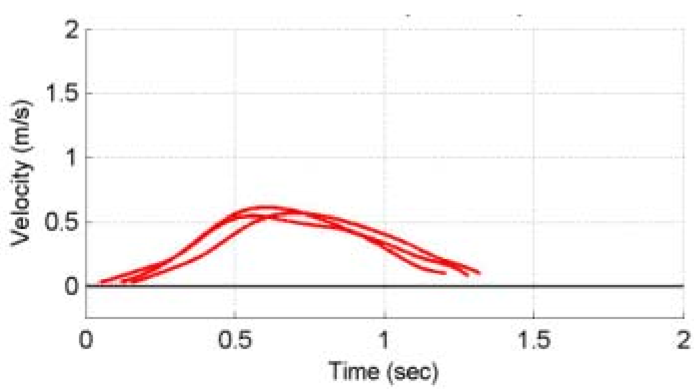

Figure 3-18. Velocity profile for reach to touch fast pace for one representative participant with moderate impairment

Table 3-13. ANOVA table reach to touch comfortable verses fast

	Mean Square	F	df	p-value
Movement Time				
Speed	1.19	192.68	1,24	.00
Group	1.45	15.16	2,24	.00
Speed*Group	.06	10.42	2,24	.00

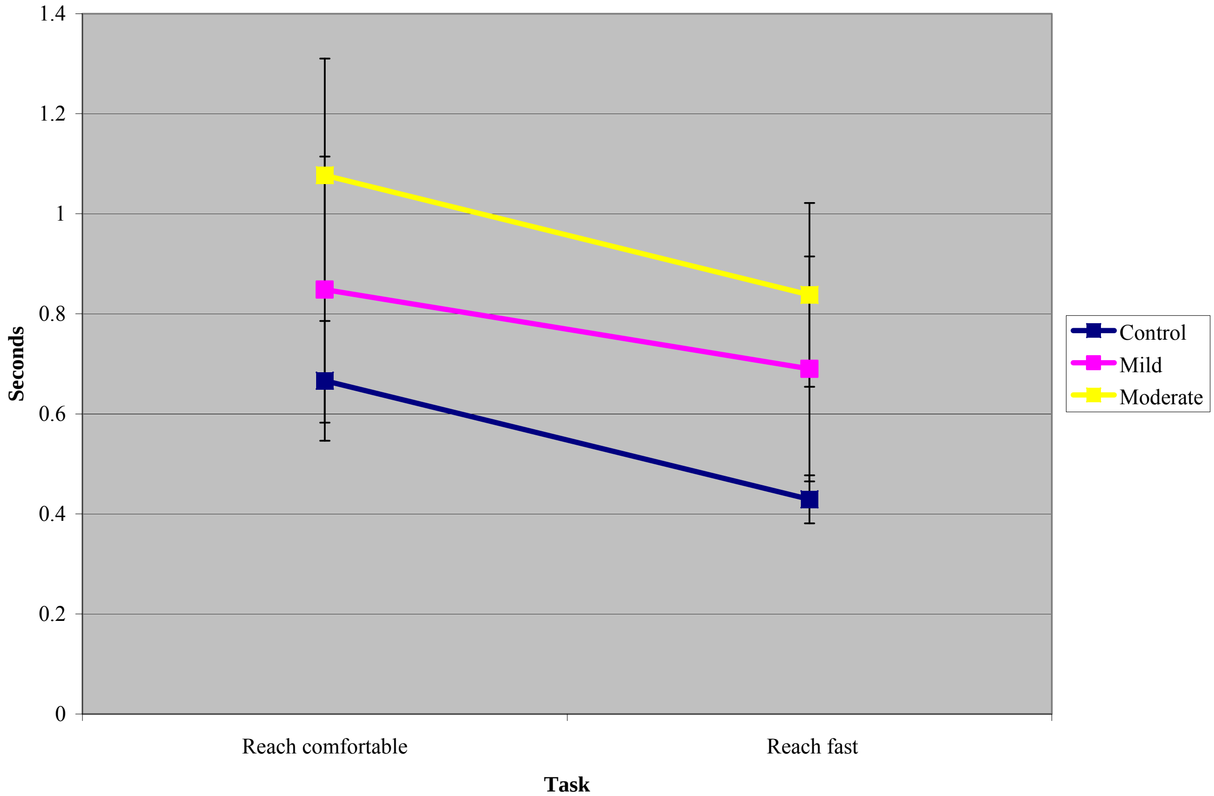

Figure 3-19. Movement time for reach to touch comfortable versus fast

Table 3-14. ANOVA table reach to touch comfortable verses fast

	Mean Square	F	df	p-value
Peak Velocity				
Speed	.65	228.75	1,24	.00
Group	.90	21.26	2,24	.00
Speed*Group	.04	14.02	2,24	.00

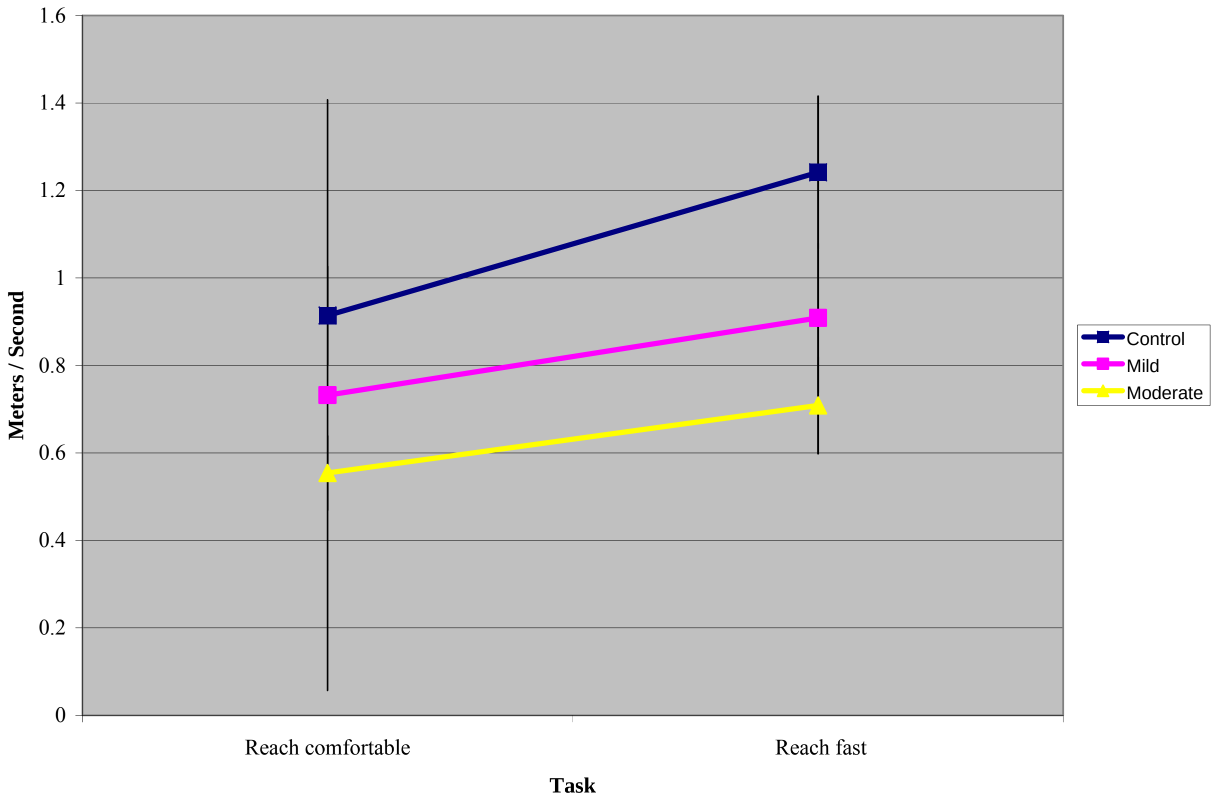

Figure 3-20. Peak velocity for reach to touch comfortable verses fast

Table 3-15. ANOVA table reach to touch comfortable verses fast

	Mean Square	F	df	p-value
Trunk Displacement				
Speed	15.12	0.40	1,24	.54
Group	20072.91	12.49	2,24	.00
Speed*Group	155.72	4.08	2,24	.03

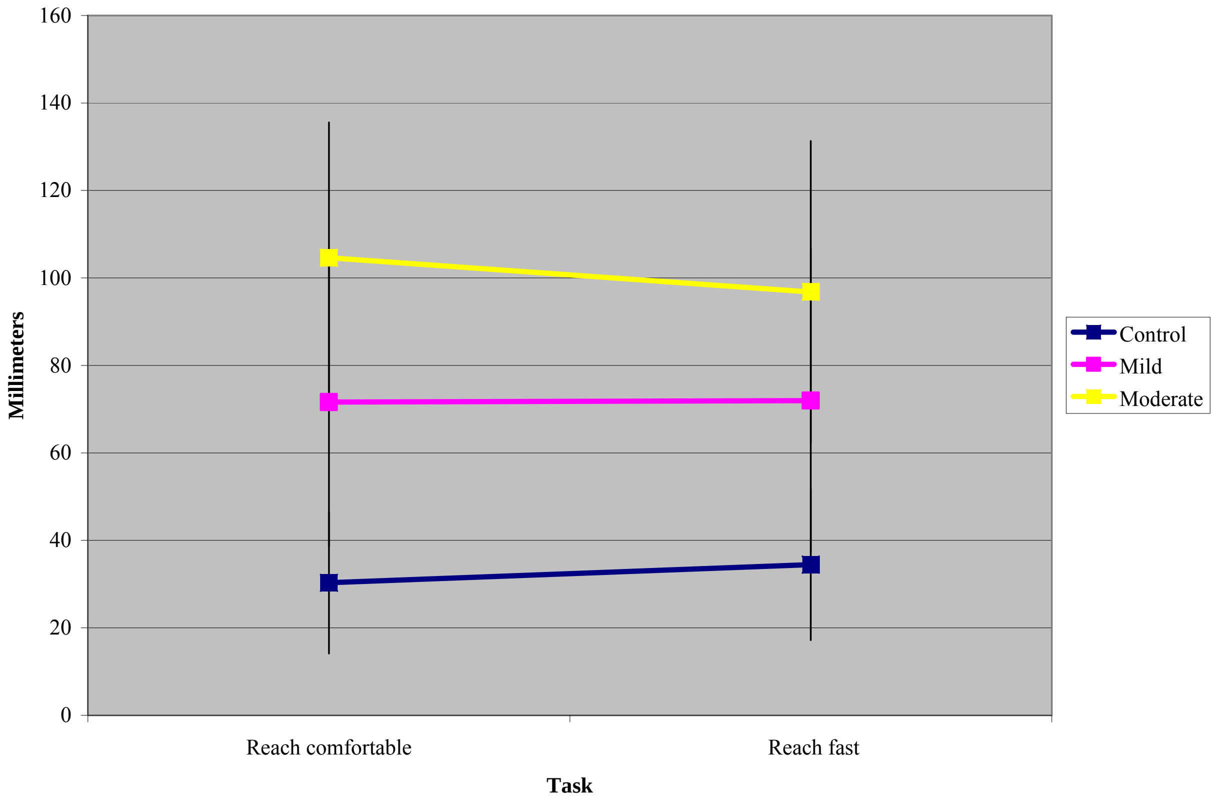

Figure 3-21. Trunk displacement for reach to touch comfortable versus fast

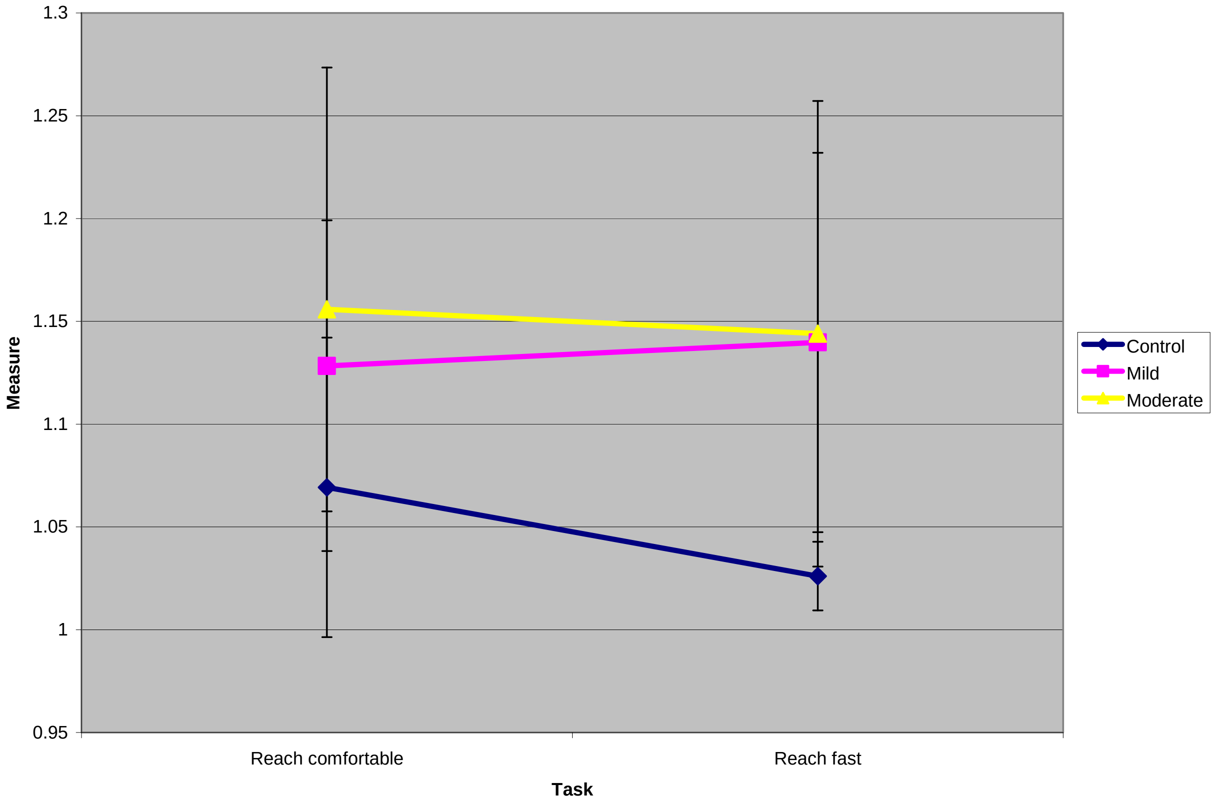

Figure 3-22. Index of curvature for reach to touch comfortable versus fast

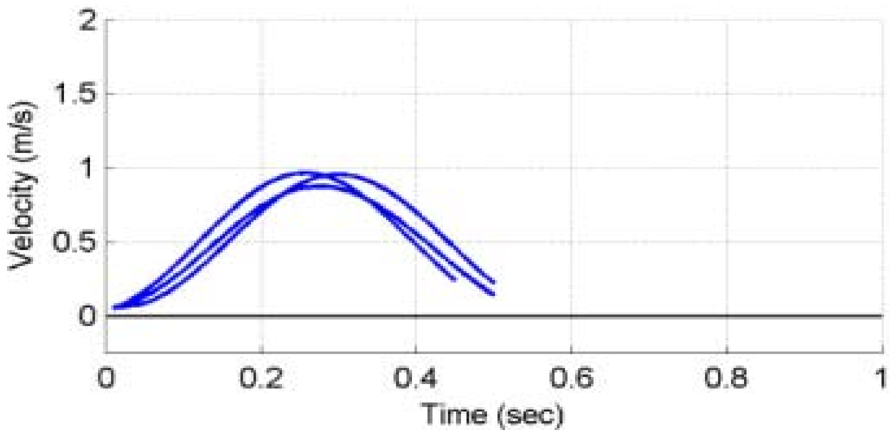

Figure 3-23. Velocity profile for participant reach to grasp small can for one representative control participant

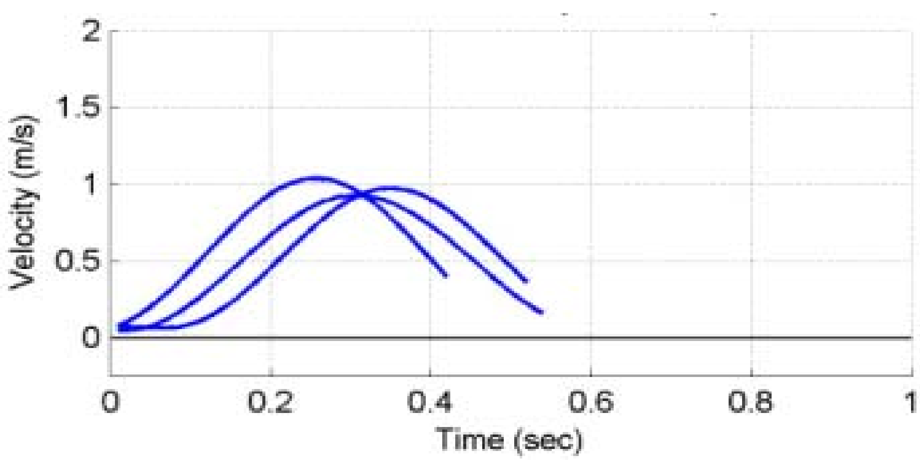

Figure 3-24. Velocity profile for reach to grasp large can for one representative control participant

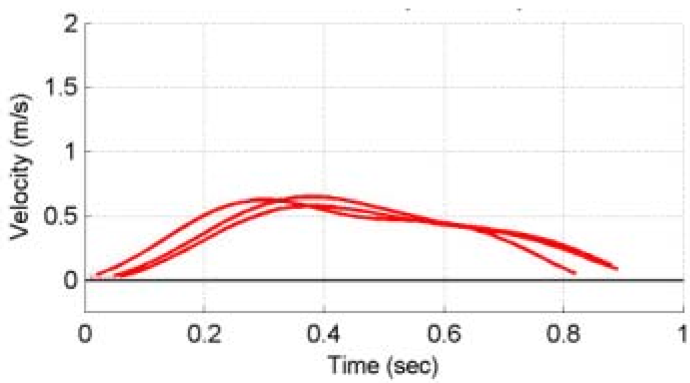

Figure 3-25. Velocity profile for reach to grasp small can for one representative participant with mild impairment

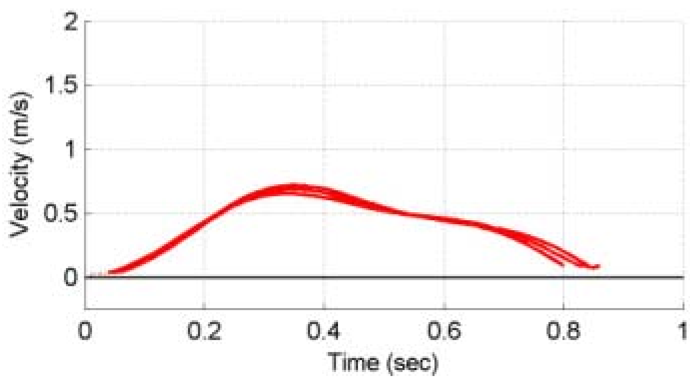

Figure 3-26. Velocity profile for reach to grasp large can for one representative participant with mild impairment

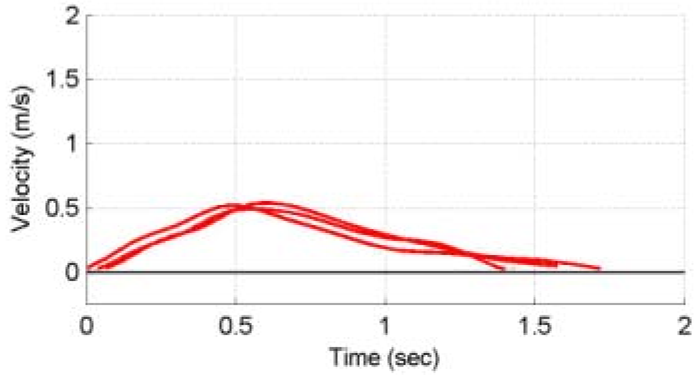

Figure 3-27. Velocity profile for reach to grasp small can for one representative participant with moderate impairment

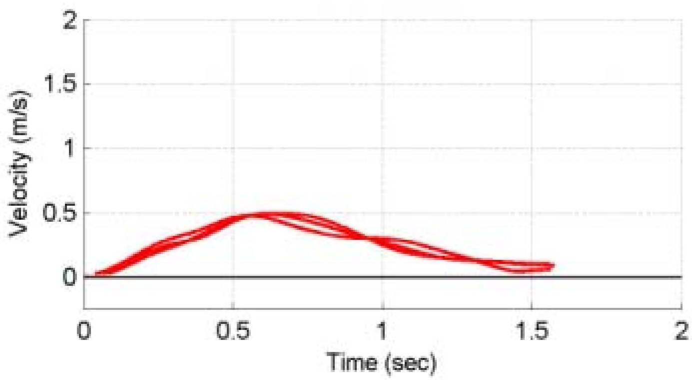

Figure 3-28. Velocity profile for reach to grasp large can for one representative participant with moderate impairment

Table 3-16. ANOVA table grasp small verses large

	Mean Square	F	df	p-value
Movement Time				
Task	.09	11.31	1,24	.00
Group	5.74	26.23	2,24	.00
Task*Group	.01	0.87	2,24	.43

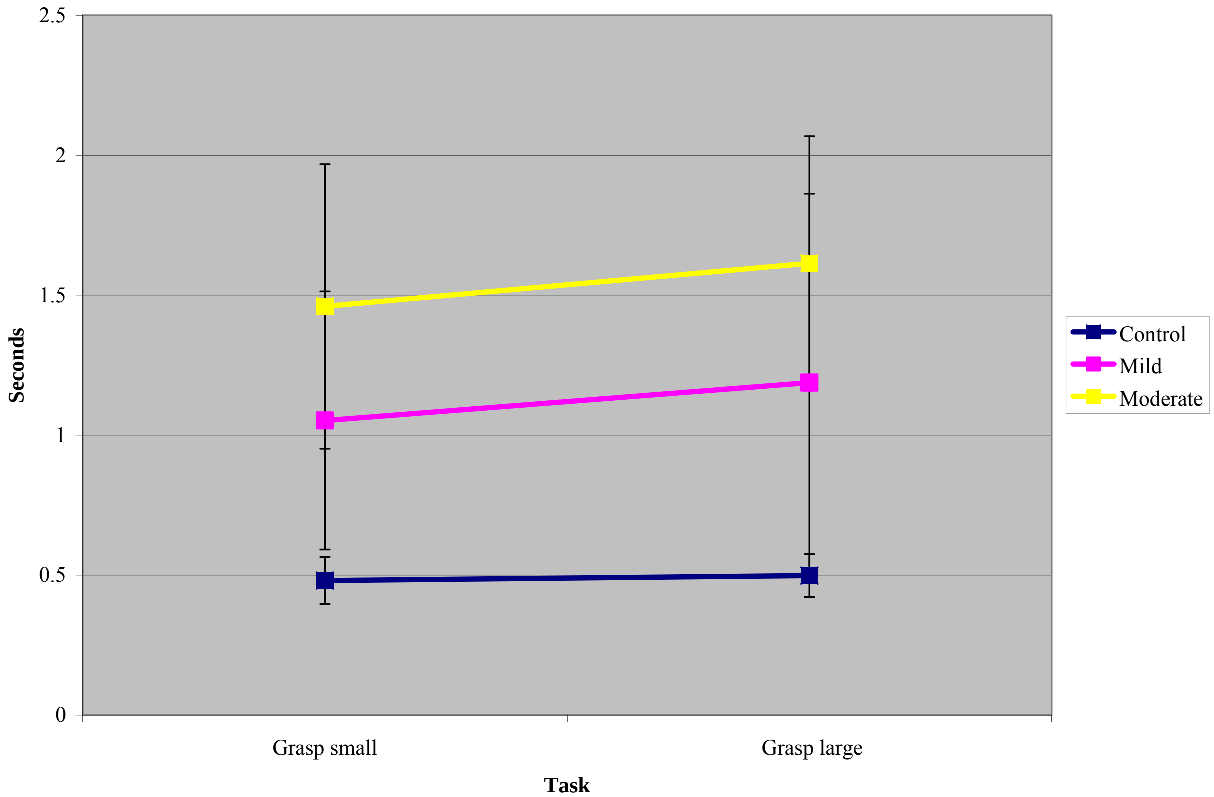

Figure 3-29. Movement time for reaching to grasp small versus large can

Table 3-17. ANOVA table grasp small verses large

	Mean Square	F	df	p-value
Peak Velocity				
Task	.00	1.40	1,24	.25
Group	.92	27.65	2,24	.00
Task*Group	.00	0.28	2,24	.78

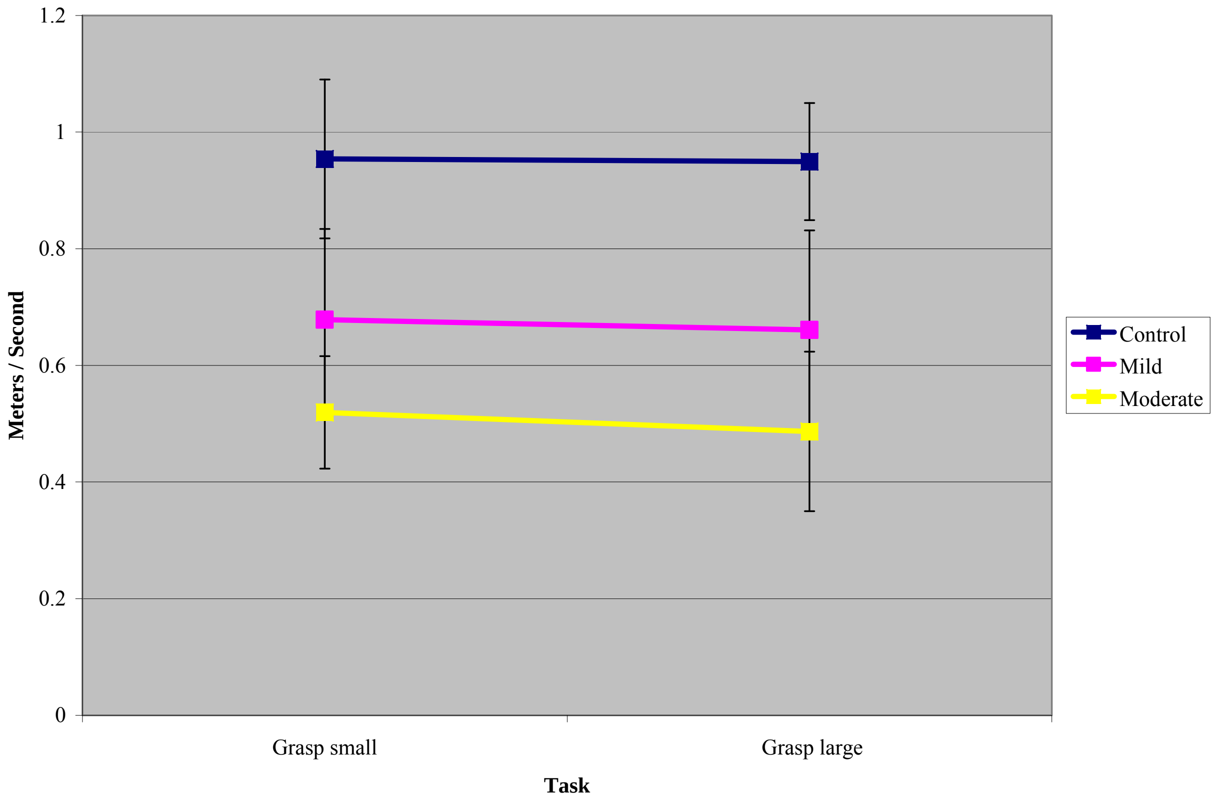

Figure 3-30. Peak velocity reaching to grasp small versus large can

Table 3-18. ANOVA table grasp small verses large

	Mean Square	F	df	p-value
Aperture				
Task	688.98	33.15	1,9	.00
Group	876.79	0.59	2,9	.26
Task*Group	115.45	5.56	2,9	.03

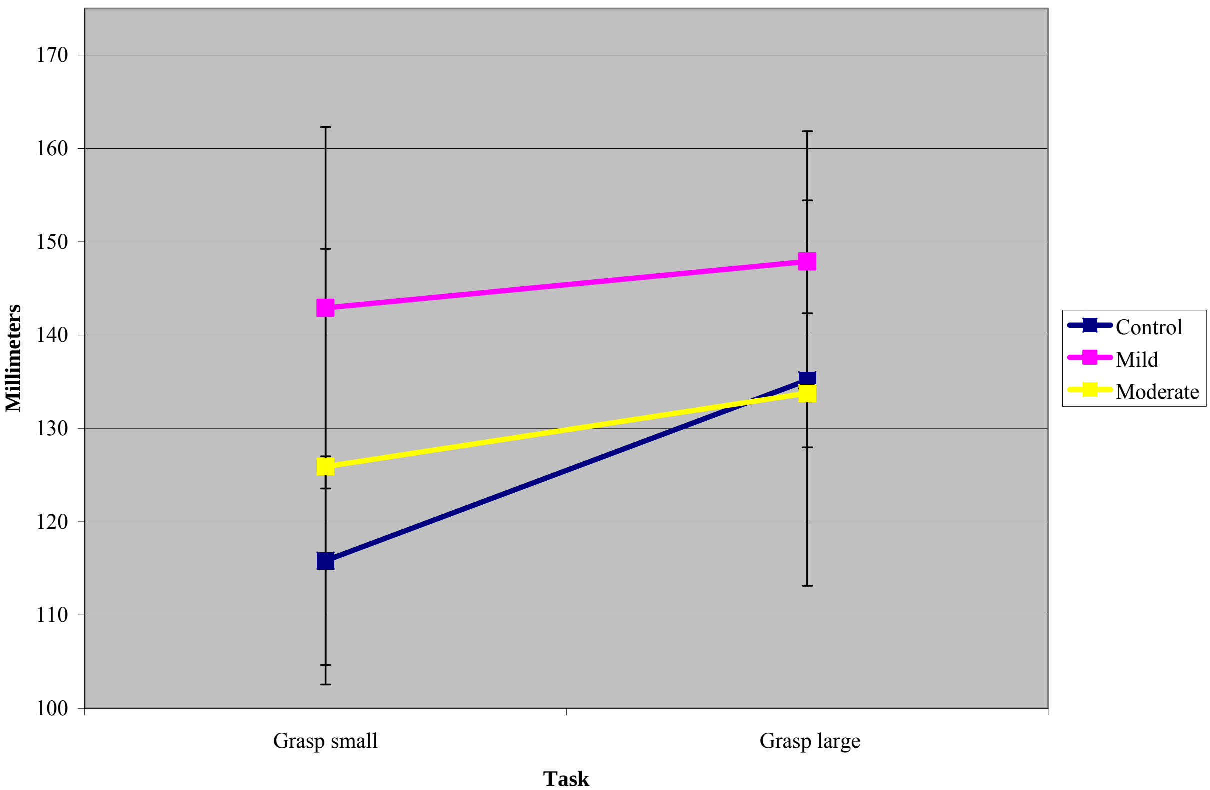

Figure 3-31. Peak aperture reach to grasp small verses large can

Table 3-19. ANOVA table grasp small verses large

	Mean Square	F	df	p-value
% of Movement Cycle				
Task	73.71	1.22	1,9	.30
Group	1247.69	6.18	2,9	.02
Task*Group	198.01	3.28	2,9	.089

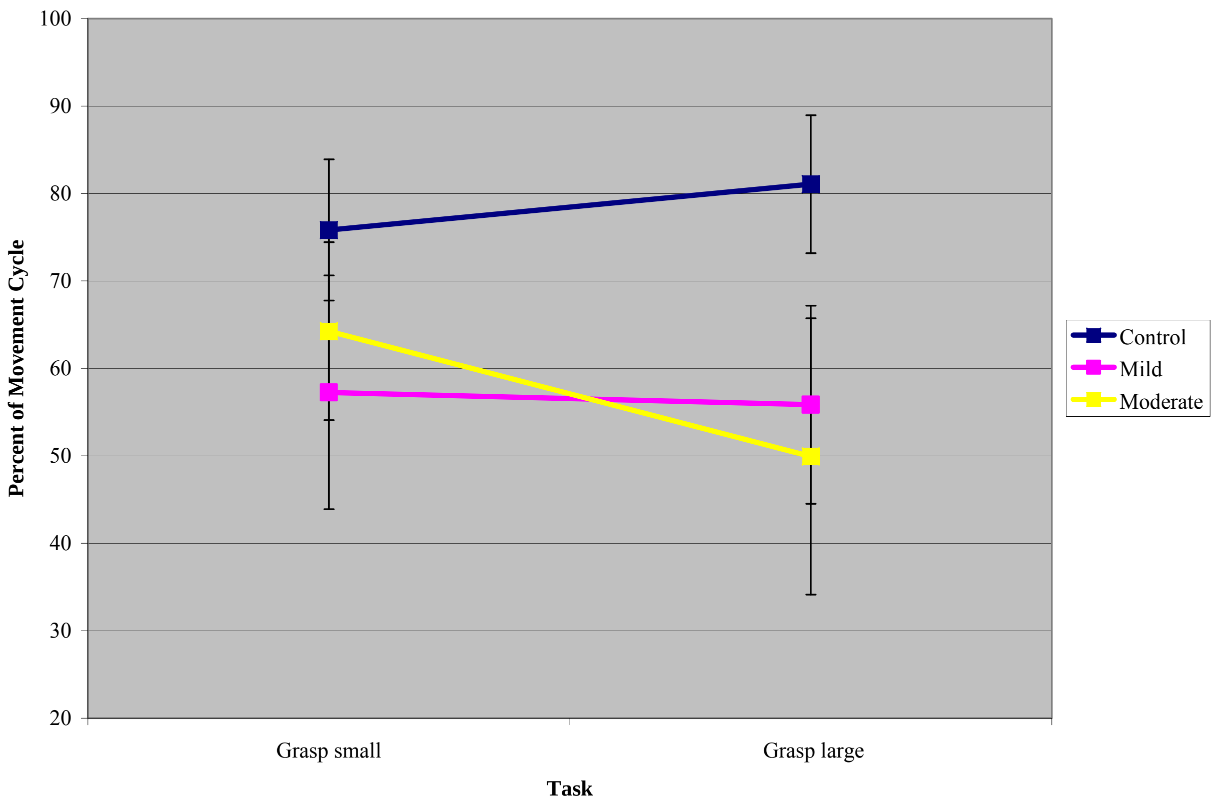

Figure 3-32. Percent movement cycle peak aperture reach to grasp small verses large can

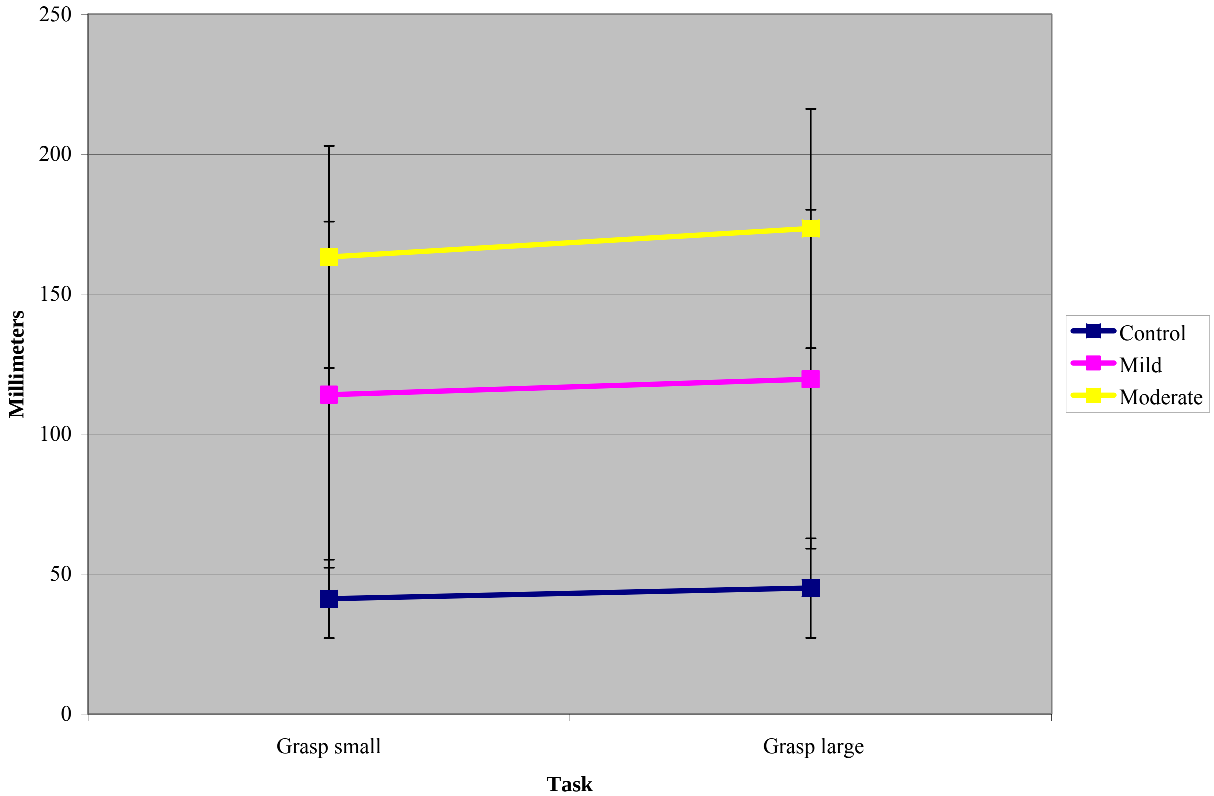

Figure 3-33. Trunk displacement reach to grasp small verses large can

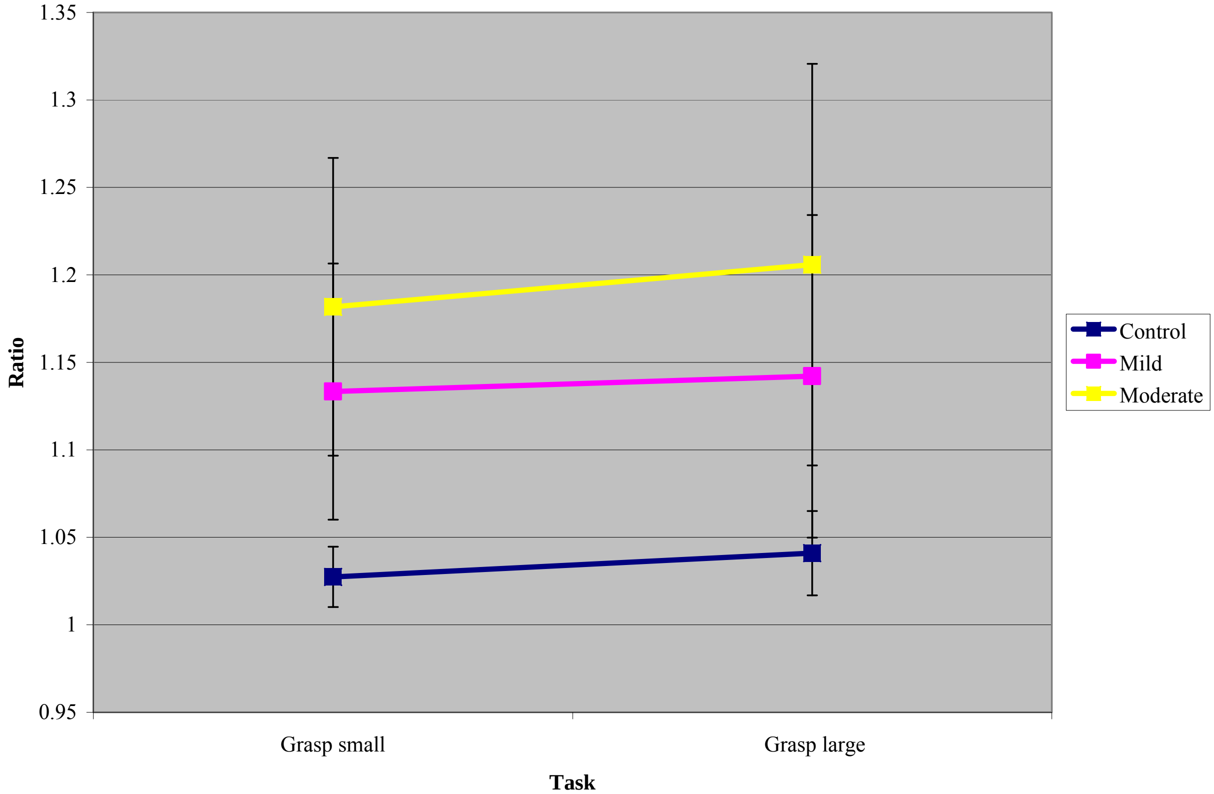

Figure 3-34. Index of curvature reach to grasp small verses large can

CHAPTER 4
DISCUSSION

Kinematic analysis is one type of methodology that may be used to objectively quantify movement biomechanics in individuals living with stroke, as well as to evaluate the effects of therapeutic interventions on motor performance.[11, 15, 16, 18] Kinematic analysis has been widely used to examine gait, and more recently has been extended to evaluate movement in the upper extremity. However, reliability of these measures has not been routinely reported or well established.[15, 17, 115] It is crucial to establish reliability of these measures before using kinematic variables as outcome measures to assess change in performance due to treatment. Clinicians and research may incorrectly assume that change in an individual's motor performance was due to a "true" change in ability, when in fact change may be due to measurement error.[39] This study was conducted in order to establish reliability using an upper extremity model of six kinematic measures of upper extremity performance in healthy controls and individuals with mild and moderate impairment due to stroke: movement time, peak velocity, index of curvature, trunk displacement, peak aperture, and time to peak aperture. Reliability of kinematic upper extremity variables has not been routinely reported within the literature, and only a few studies exist to date that provide such measures.[15, 17] Additionally, this study examined a model specific to the upper extremity developed and modified by engineers performing research studies within the lab.[107]

Reliability

Reliability, as presented by the ICC, was established for those variables meeting the assumption of normality. Reliability was excellent for the individuals with mild impairment and generally good to excellent for individuals with moderate impairment. Lower ICC values were computed for movement time and peak velocity in reach to touch at a comfortable pace for individuals with moderate impairments. These individuals performed the movement with higher peak velocities, less straight hand paths, and utilized more trunk displacement at Time 2 as compared to Time 1. This may have been the result of a practice effect, and these individuals may have learned to move "more comfortably" by using the extra degree of freedom of the trunk to accomplish this goal. The "organism" constraints for individuals with moderate impairments may be greater than those with mild impairments, and coordination solutions and ability to solve the problem (or task) may be more variable within these individuals. Additionally, there may be a higher degree of involvement in exploratory behavior for possible solutions to the task constraint, and strategies may develop gradually.

Individuals with less impairment may have a greater ability to perform the reaching movement according to the constraint imposed on the movement, to "move at a comfortable pace," in a more consistent manner.[12, 13, 21, 55] The nature of variability in movement may be driven by the interaction of the constraints imposed on an action,[46] and these individuals may be more able to adapt to the task constraints due to higher level of functional ability as compared to individuals with moderate impairment after stroke. However, it is important to note that variability in movement may be beneficial, and prevents a system from becoming too stable and not able to adapt to more complex constraints that may occur within various environments.[46] The control group was more variable but produced high ICC values for peak velocity, maximum aperture for grasping a small can and percent of movement cycle where peak aperture occurred. Previous research conducted by Caimmi and colleagues demonstrated high test re-test reliability for controls performing kinematic analysis, but these researchers included 10 repetitions of movement, which maybe a better paradigm reducing practice carry over effects.[15] Individuals with stroke may have less flexible motor systems and are less able to move about all degrees of freedom within the joints demonstrating less variability, whereas controls may be more flexible leading to more variability in movement production.

Minimal detectable change values were found to be relatively small, except for the trunk displacement variable. These values tended to be generally much higher than expected. This may be due to the method used to determine the MDD. As presented by Stratford, the MDD was determined by multiplying the SEM by $\sqrt{2} \times 1.96$ or 2.77. This is a very conservative approach to determining the MDD, which have resulted in higher values.[112]

Description of Movements

The healthy control group performed all movements in all conditions more quickly with higher peak velocities, straighter hand paths, and less trunk displacement than both groups of individuals with stroke. The control group was also better able to scale maximum aperture according to the size of the can, and peak aperture occurred later in the movement cycle, which was consistent with previous findings.[75] In contrast, individuals with stroke tended to perform more slowly and consistently incorporating the trunk to achieve the goal of the task. As shown in previous findings, individuals with stroke tend to use the trunk to reach for targets well within arm's length, and significance of trunk usage was associated with severity of impairment.[21, 27-29, 56, 65, 108] Individuals with more moderate impairments in this study had significantly more trunk displacement than participants with mild impairment.

Finally, it is also interesting to observe that, in this study, even individuals with more moderate impairment were able to achieve higher maximum aperture values, although for both groups of participants with stroke, maximum values tended to occur much earlier in the reach cycle as compared to controls. Previous literature suggests that individuals with hemiplegia tend to increase aperture size with larger targets to a larger extent than healthy adults and larger aperture tends to occur with fast movements, which was demonstrated in this study.[116] A change in size of the object being grasped may produce a change in time to peak aperture which may be due to the influence of feedforward and feedback control. The first phase of the reach cycle is a fast ballistic movement, and the second phase is based on more feedback to orient the hand in the proper position to grasp the object.[21] Individuals with both mild and moderate impairments in this study produced similar movement patterns for the grasping the object independent of the size of the can. However, it is commonly observed and reported that individuals with stroke tend to have difficulty opening the hand potentially due to weak finger extensors.[32] This was not the case for the participants with stroke in this study, and the participants with stroke were able to grasp the cans, regardless of the size.

There is controversy as to whether maximum aperture also occurs later or earlier in the movement than for individuals with stroke as compared to healthy adults. The timing of maximum aperture in the movement cycle may represent strategy. The participants with stroke achieved maximum aperture much earlier in the movement cycle, although the amount of maximum aperture did not really vary according to size of the target [75, 91]. Maximum aperture occurring earlier in the movement cycle may be compensation due to increased spatial variability within these individuals above what would typically occur in control participants, and these individuals may rely more on feedback to meet the increased demands of the task. [32, 116]

Task Descriptions

A significant main effect of speed was only found for movement time and peak velocity variables in the reach to touch comfortable verses fast paced condition. This suggests that these movement parameters depend on the speed of movement production, and as individuals perform faster movements, kinematic variables alter according to the task constraints. The control participants performed movements that were consistently significantly different than that of the participants with stroke, regardless of severity level. Individuals with mild impairment were significantly different than individuals with moderate impairment for only the peak velocity variable. The two groups were not significantly different for amount of trunk displacement used to accomplish the reach to touch task nor the index of curvature. Hand paths that were less straight depended on the use of the trunk to complete the task, and this may be representative of the nervous system substituting the loss of full range of motion of the elbow and shoulder by incorporating a compensatory strategy.

Reaching to grasp a can of different size produced differences among groups, but not based on severity after stroke. The individuals with mild and moderate impairments did not significantly differ from each other. In accordance with Newell's model, varying the task constraints should produce variability in movement. However, this would suggest that by changing the demands of the task by altering size, individuals with stroke tend to display similar movement which was produced at a "fast as possible" speed.[51, 53] These individuals tend to incorporate much more trunk displacement than healthy controls in order to achieve a goal. This was not dependent on the severity of impairment at the "organism" component for the participants with stroke. Additionally, participants were instructed to reach and grasp the cans "as fast as possible" and while control participant's movement time was very similar to reaching to a target as fast as possible, individuals with stroke performed the reach to grasp task and much slower speeds than even their preferred, comfortable pace. This may be representative of difficulty adapting to task demands, and incorporating compensatory strategies (slowed movement time) in order to adjust movement parameters to achieve the task goal.

Newell's theory of constraints suggests examining performance based on characteristics of individuals at the level of organism, task and environment in order to understand the patterns of coordination and control that are produced. [51-53] Movements were observed in healthy individuals when task constraints changed, and compared to those individuals with a damaged neurologic system under those same task constraints. Altering the demands of the motor task by changing speed of movement production required to complete the task produced greater significant differences that did altering the size of the object. Those individuals with less impairment were able to accomplish the task more quickly with less trunk displacement which is not a surprising result. However, it is clinically important to recognize that, regardless of severity, individuals were able to perform the movements under each variation of task constraints.

Implications

A prerequisite for success in rehabilitation is the understanding of the mechanisms underlying motor deficits present in individuals with stroke. It is important to study how the damaged nervous system recovers or compensates in performing such tasks as reaching, as well as the relationship of impairments to ability to perform purposeful movements in the upper extremity.[21] The organism, task and environment interaction describes the development and emergence of coordination and control,[51] and examination of these components may help to better understand motor performance in individuals with stroke. Changing task demands may demonstrate changes in movement production that may be unique to the severity of impairment and this may assist in developing rehabilitation techniques tailored to improve the specific deficits present in the population of interest.

Limitations

This study was confounded by limitations that are important to address. The motion analysis system was changed during the middle of the study. Labeling data within Vicon workstation is very subjective, and this may have contributed to some of the error produced. As reported in previous literature, marker placement is one of the most difficult challenges in capturing kinematics of upper extremity movements, and it hard to avoid excessive errors. Markers tend to disappear and reappear during movements and critical markers may not be visible at all times. [36] Judgments need to be made as to which markers may be the critical marker of interest, when two or more markers appear in the same time point. Ghost markers, or markers that appear due to a reflection or some other reason, but are not "true markers," were also an issue. Data labeling also required a great deal of decision making for snipping and creating trajectories. A trajectory may also not be visible for longer time periods when the markers disappear.

Data collected within the new Nexus system is much clearer, and only ten participants with stroke were collected within this system. This system does not allow a marker to be labeled twice within the same time period, and this helped to eliminate some of the error due to subjective decision making. Additionally, aperture data collected with Vicon workstation was very poor and therefore not included for five of the participants of the control participants, seven of the participants with mild impairment, and three participants with moderate impairment.

Marker placement was on clothing for several of the landmarks, including the trunk and back. This may have affected the outcomes for some in that movement changes due to the marker shifting may have occurred. Also, the goal of the analysis was to average three movements for each condition. However, for some individuals only one or two trials were captured. Another limitation is sample size, although sufficient power was produced for several of the variables of interest. Normality violations tend occur less in larger sample sizes, and more robust measures (like ANOVA) can be used with larger sample sizes even when small deviations from the normality assumptions are not met. The ICC values were only calculated for those variables meeting the normality assumptions as well. Finally, the individuals were divided into severity of impairment by a median split of the fugl-meyer, which may not have provided a true representation of “mild” and “moderate” impairments due to stroke. Although the Fugl Meyer is an impairment index specific to measure recovery of function in individuals post stroke, greater variability of scores may be produced for individuals with mild and moderate impairments.[117] The scores are based on a summation indicating motor function, which may be inappropriate and may mask small discrepancies in ability of the individual.[118] Future research should examine individual data in order to determine whether or not the score is appropriate or representative of actual severity of impairment within the individual.

CHAPTER 5
CONCLUSIONS

Kinematic analysis of the upper extremity after stroke is useful and powerful tool that examines quality of movement. The results of this dissertation suggest that data collections, for variables such as movement time, peak velocity, trunk displacement, and aperture are generally reliable in participants with stroke. This is crucial so that studies examining movement kinematics pre and post intervention may infer that change is due to treatment rather than error. Further inspection of the reliability of additional kinematic parameters is necessary prior to incorporating these measures as evaluative tools to assess changes due to treatment.

Interventions focusing on tasks varying on level difficulty may be beneficial for individuals with stroke. Those individuals with more moderate impairment may benefit from interventions focusing on restraining the trunk, since this group seemed to rely on the trunk to complete more difficult tasks. However, the question still remains as to whether or not movement patterns that maybe different from a healthy, non impaired population, should be corrected. It is natural to assume that a deviation from normal behavior or variability in movement may be negative, but the patterns exhibited by populations with altered nervous systems due to neurologic insult may be optimal for that individual.[119] The central nervous system may still be able to produce the movements, but a new system may have been created due to plasticity and reinforcement of alternate strategies of goal completion.[119] Examining movement through the interaction of constraints may help researchers decide what patterns of movement may be beneficial and those that may be detrimental to the individual and interventions may be designed according to the level of severity of impairment. Improving upper extremity function is a high priority for individuals living with stroke, and failure to have substantial gains in upper extremity functional ability may lead to depression and decreased quality of life.[26]

Future studies should include larger sample sizes with further inspection of such parameters as range of motion in order to determine correlations and contributions of joint segments, as well as determining which joints may be more impaired. Additionally, while this study examined reach to grasp during a fast pace, it would be interesting to examine this task performed at also a comfortable pace, and compare the outcomes across different speeds of movement production. It is not known if the movements are truly performed as quickly as possible in participants with stroke because the movement times are much lower than even the comfortable pace for the reach to target condition.

Future studies should also examine tasks of increased difficulty, such as pinching, as well as bilateral tasks. Examining impairment level on other measures than just the Fugl-Meyer may also provide more concrete insight into the deficits these groups may have. However, the median split did seem to produce movement different outcomes based on level of severity. Future studies should include fewer markers which may remove errors due to marker disappearance as well as the presence of ghost markers. It would also produce clearer visibility of critical markers and less subjective judgments when labeling. Future studies should also include of other variables, such as smoothness metrics, which may be more robust. Testing over more than 2 baseline periods and increasing the number of trials for each task may assist in increasing reliability by removing the potential practice effect and reducing the within subject variability.

LIST OF REFERENCES

1. Association AH. *Heart disease and stroke statistics-2008 update.* Dallas, TX: American Heart Association; 2008.

2. Chen R, Cohen LG, Hallett M. Nervous system reorganization following injury. *Neuroscience*. 2002;111:761-773

3. Alberts JL, Butler AJ, Wolf SL. The effects of constraint-induced therapy on precision grip: A preliminary study. *Neurorehabil Neural Repair*. 2004;18:250-258

4. Whitall J, McCombe Waller S, Silver KH, Macko RF. Repetitive bilateral arm training with rhythmic auditory cueing improves motor function in chronic hemiparetic stroke. *Stroke*. 2000;31:2390-2395

5. Morris DM, Taub E. Constraint-induced therapy approach to restoring function after neurological injury. *Top Stroke Rehabil*. 2001;8:16-30

6. Kunkel A, Kopp B, Muller G, Villringer K, Villringer A, Taub E, Flor H. Constraint-induced movement therapy for motor recovery in chronic stroke patients. *Arch Phys Med Rehabil*. 1999;80:624-628

7. Miltner WH, Bauder H, Sommer M, Dettmers C, Taub E. Effects of constraint-induced movement therapy on patients with chronic motor deficits after stroke: A replication. *Stroke*. 1999;30:586-592

8. Taub E, Uswatte G. Constraint-induced movement therapy: Bridging from the primate laboratory to the stroke rehabilitation laboratory. *J Rehabil Med*. 2003:34-40

9. Taub E, Uswatte G, Morris DM. Improved motor recovery after stroke and massive cortical reorganization following constraint-induced movement therapy. *Phys Med Rehabil Clin N Am*. 2003;14:S77-91, ix

10. Michaelsen SM, Jacobs S, Roby-Brami A, Levin MF. Compensation for distal impairments of grasping in adults with hemiparesis. *Exp Brain Res*. 2004;157:162-173

11. Krakauer JW. Motor learning: Its relevance to stroke recovery and neurorehabilitation. *Curr Opin Neurol*. 2006;19:84-90

12. Roby-Brami A, Feydy A, Combeaud M, Biryukova EV, Bussel B, Levin MF. Motor compensation and recovery for reaching in stroke patients. *Acta Neurol Scand*. 2003;107:369-381

13. Platz T, Denzler P, Kaden B, Mauritz KH. Motor learning after recovery from hemiparesis. *Neuropsychologia*. 1994;32:1209-1223

14. Bowman MH, Taub E, Uswatte G, Delgado A, Bryson C, Morris DM, McKay S, Mark VW. A treatment for a chronic stroke patient with a plegic hand combining ci therapy with conventional rehabilitation procedures: Case report. *NeuroRehabilitation*. 2006;21:167-176

15. Caimmi M, Carda S, Giovanzana C, Maini ES, Sabatini AM, Smania N, Molteni F. Using kinematic analysis to evaluate constraint-induced movement therapy in chronic stroke patients. *Neurorehabil Neural Repair*. 2007

16. Steenbergen BvT, E.; Hulstijn, W.; Meulenbroek, R.G.J. The coordination of reaching and grasping in spastic hemiparesis. *Hum Mov Sci*. 2000;19:75-105

17. Wagner JM, Rhodes JA, Patten C. Reproducibility and minimal detectable change of three-dimensional kinematic analysis of reaching tasks in people with hemiparesis after stroke. *Phys Ther*. 2008;88:652-663

18. Ramos E, Latash MP, Hurvitz EA, Brown SH. Quantification of upper extremity function using kinematic analysis. *Arch Phys Med Rehabil*. 1997;78:491-496

19. Rohrer B, Fasoli S, Krebs HI, Hughes R, Volpe B, Frontera WR, Stein J, Hogan N. Movement smoothness changes during stroke recovery. *J Neurosci*. 2002;22:8297-8304

20. Beer RF, Dewald JP, Rymer WZ. Deficits in the coordination of multijoint arm movements in patients with hemiparesis: Evidence for disturbed control of limb dynamics. *Exp Brain Res*. 2000;131:305-319

21. Cirstea MC, Levin MF. Compensatory strategies for reaching in stroke. *Brain*. 2000;123 (Pt 5):940-953

22. Cirstea MC, Mitnitski AB, Feldman AG, Levin MF. Interjoint coordination dynamics during reaching in stroke. *Exp Brain Res*. 2003;151:289-300

23. Cirstea MC, Ptito A, Levin MF. Arm reaching improvements with short-term practice depend on the severity of the motor deficit in stroke. *Exp Brain Res*. 2003;152:476-488

24. Gentilucci M, Castiello U, Corradini ML, Scarpa M, Umilta C, Rizzolatti G. Influence of different types of grasping on the transport component of prehension movements. *Neuropsychologia*. 1991;29:361-378

25. Levin MF. Interjoint coordination during pointing movements is disrupted in spastic hemiparesis. *Brain*. 1996;119 (Pt 1):281-293

26. McCrea PH, Eng JJ, Hodgson AJ. Biomechanics of reaching: Clinical implications for individuals with acquired brain injury. *Disabil Rehabil*. 2002;24:534-541

27. Michaelsen SM, Dannenbaum R, Levin MF. Task-specific training with trunk restraint on arm recovery in stroke: Randomized control trial. *Stroke*. 2006;37:186-192

28. Michaelsen SM, Levin MF. Short-term effects of practice with trunk restraint on reaching movements in patients with chronic stroke: A controlled trial. *Stroke*. 2004;35:1914-1919

29. Michaelsen SM, Luta A, Roby-Brami A, Levin MF. Effect of trunk restraint on the recovery of reaching movements in hemiparetic patients. *Stroke*. 2001;32:1875-1883

30. Roby-Brami A, Jacobs S, Bennis N, Levin MF. Hand orientation for grasping and arm joint rotation patterns in healthy subjects and hemiparetic stroke patients. *Brain Res*. 2003;969:217-229

31. Thielman GT, Dean CM, Gentile AM. Rehabilitation of reaching after stroke: Task-related training versus progressive resistive exercise. *Arch Phys Med Rehabil*. 2004;85:1613-1618

32. van Vliet PM, Sheridan MR. Coordination between reaching and grasping in patients with hemiparesis and healthy subjects. *Arch Phys Med Rehabil*. 2007;88:1325-1331

33. Wagner JM, Dromerick AW, Sahrmann SA, Lang CE. Upper extremity muscle activation during recovery of reaching in subjects with post-stroke hemiparesis. *Clin Neurophysiol*. 2007;118:164-176

34. Wu CY, Chou SH, Chen CL, Kuo MY, Lu TW, Fu YC. Kinematic analysis of a functional and sequential bimanual task in patients with left hemiparesis: Intra-limb and interlimb coordination. *Disabil Rehabil*. 2008:1-9

35. Wu CY, Chou SH, Kuo MY, Chen CL, Lu TW, Fu YC. Effects of object size on intralimb and interlimb coordination during a bimanual prehension task in patients with left cerebral vascular accidents. *Motor Control*. 2008;12:296-310

36. Yang N, Zhang M, Huang C, Jin D. Synergic analysis of upper limb target-reaching movements. *J Biomech*. 2002;35:739-746

37. Wagner JM, Lang CE, Sahrmann SA, Edwards DF, Dromerick AW. Sensorimotor impairments and reaching performance in subjects with poststroke hemiparesis during the first few months of recovery. *Phys Ther*. 2007;87:751-765

38. Steffen T, Seney M. Test-retest reliability and minimal detectable change on balance and ambulation tests, the 36-item short-form health survey, and the unified parkinson disease rating scale in people with parkinsonism. *Phys Ther*. 2008;88:733-746

39. Stratford PW, Binkley J, Solomon P, Finch E, Gill C, Moreland J. Defining the minimum level of detectable change for the roland-morris questionnaire. *Phys Ther*. 1996;76:359-365; discussion 366-358

40. Hong SL, Newell KM. Entropy conservation in the control of human action. *Nonlinear Dynamics Psychol Life Sci*. 2008;12:163-190

41. Clark JE. On becoming skillful: Patterns and constraints. *Res Q Exerc Sport*. 1995;66:173-183

42. Rose DJ. *A multilevel approach to the study of motor control and learning*. Needham Heights, MA: Allyn & Bacon; 1997.

43. Newell KM. *Motor development during childhood and adolescence*. Minneapolis, MN: Burgess; 1984.

44. Bernstein NA. *The coordination and regulation of movements*. London: Pergamon Press; 1967.

45. Bongaardt R, Meijer OG. Bernstein's theory of movement behavior: Historical development and contemporary relevance. *J Mot Behav*. 2000;32:57-71

46. Davids K, Bennett S, Kingsbury D, Jolley L, Brain T. Effects of postural constraints on children's catching behavior. *Res Q Exerc Sport*. 2000;71:69-73

47. Saltzman E, Kelso JA. Skilled actions: A task-dynamic approach. *Psychol Rev*. 1987;94:84-106

48. Crawford D, Godbey G. Reconceptualizing barriers to family leisure. *Leisure Sciences*. 1987;9:119-127

49. Crawford D, Jackson E, Godbey G. A hierarchical model of leisure constraints. *Leisure Sciences*. 1991;13:309-320

50. Glazier PS, Davids K. Constraints on the complete optimization of human motion. *Sports Med*. 2009;39:15-28

51. Newell KM. Constraints on the development of coordination In: M.G.Wade, Whiting HTA, eds. *Motor development in children: Aspects of coordination and control*. Boston: Martinus Nijhoff; 1986:341-360.

52. Newell KM, McDonald PV, Baillargeon R. Body scale and infant grip configurations. *Dev Psychobiol*. 1993;26:195-205

53. Newell KM, Scully DM, McDonald PV, Baillargeon R. Task constraints and infant grip configurations. *Dev Psychobiol*. 1989;22:817-831

54. Wu CY, Wong MK, Lin KC, Chen HC. Effects of task goal and personal preference on seated reaching kinematics after stroke. *Stroke*. 2001;32:70-76

55. Davids K, Glazier P, Araujo D, Bartlett R. Movement systems as dynamical systems: The functional role of variability and its implications for sports medicine. *Sports Med*. 2003;33:245-260

56. Mark LS, Nemeth K, Gardner D, Dainoff MJ, Paasche J, Duffy M, Grandt K. Postural dynamics and the preferred critical boundary for visually guided reaching. *J Exp Psychol Hum Percept Perform*. 1997;23:1365-1379

57. Volman MJ, Wijnroks A, Vermeer A. Effect of task context on reaching performance in children with spastic hemiparesis. *Clin Rehabil*. 2002;16:684-692

58. Adamovich SV, Archambault PS, Ghafouri M, Levin MF, Poizner H, Feldman AG. Hand trajectory invariance in reaching movements involving the trunk. *Exp Brain Res*. 2001;138:288-303

59. Armbruster C, Spijkers W. Movement planning in prehension: Do intended actions influence the initial reach and grasp movement? *Motor Control*. 2006;10:311-329

60. Cirstea MC, Levin MF. Improvement of arm movement patterns and endpoint control depends on type of feedback during practice in stroke survivors. *Neurorehabil Neural Repair*. 2007

61. Corradini ML, Gentilucci M, Leo T, Rizzolatti G. Motor control of voluntary arm movements. Kinematic and modelling study. *Biol Cybern*. 1992;67:347-360

62. Foroud A, Whishaw IQ. Changes in the kinematic structure and non-kinematic features of movements during skilled reaching after stroke: A laban movement analysis in two case studies. *J Neurosci Methods*. 2006;158:137-149

63. Gentilucci M, Negrotti A. Planning and executing an action in parkinson's disease. *Mov Disord*. 1999;14:69-79

64. Jakobson LS, Goodale MA. Factors affecting higher-order movement planning: A kinematic analysis of human prehension. *Exp Brain Res*. 1991;86:199-208

65. Levin MF, Michaelsen SM, Cirstea CM, Roby-Brami A. Use of the trunk for reaching targets placed within and beyond the reach in adult hemiparesis. *Exp Brain Res*. 2002;143:171-180

66. McCombe Waller S, Whitall J. Fine motor control in adults with and without chronic hemiparesis: Baseline comparison to nondisabled adults and effects of bilateral arm training. *Arch Phys Med Rehabil*. 2004;85:1076-1083

67. Messier J, Adamovich S, Berkinblit M, Tunik E, Poizner H. Influence of movement speed on accuracy and coordination of reaching movements to memorized targets in three-dimensional space in a deafferented subject. *Exp Brain Res*. 2003;150:399-416

68. Messier J, Kalaska JF. Comparison of variability of initial kinematics and endpoints of reaching movements. *Exp Brain Res*. 1999;125:139-152

69. Micera S, Carpaneto J, Posteraro F, Cenciotti L, Popovic M, Dario P. Characterization of upper arm synergies during reaching tasks in able-bodied and hemiparetic subjects. *Clin Biomech (Bristol, Avon)*. 2005;20:939-946

70. Krakauer JW, Ghilardi MF, Ghez C. Independent learning of internal models for kinematic and dynamic control of reaching. *Nat Neurosci*. 1999;2:1026-1031

71. Schmidt RA LT. *Motor control and learning: A behavioural emphasis*. Champaign, IL: Human Kinetics; 1999.

72. Winstein CJ, Pohl PS, Lewthwaite R. Effects of physical guidance and knowledge of results on motor learning: Support for the guidance hypothesis. *Res Q Exerc Sport*. 1994;65:316-323

73. Jeannerod M. The timing of natural prehension movements. *J Mot Behav*. 1984;16:235-254

74. Gentilucci M, Daprati E, Gangitano M, Saetti MC, Toni I. On orienting the hand to reach and grasp an object. *Neuroreport*. 1996;7:589-592

75. Lang CE, Wagner JM, Bastian AJ, Hu Q, Edwards DF, Sahrmann SA, Dromerick AW. Deficits in grasp versus reach during acute hemiparesis. *Exp Brain Res*. 2005;166:126-136

76. Tretriluxana J, Gordon J, Winstein CJ. Manual asymmetries in grasp pre-shaping and transport-grasp coordination. *Exp Brain Res*. 2008;188:305-315

77. Chieffi S, Gentilucci M. Coordination between the transport and the grasp components during prehension movements. *Exp Brain Res*. 1993;94:471-477

78. Chieffi S, Gentilucci M, Allport A, Sasso E, Rizzolatti G. Study of selective reaching and grasping in a patient with unilateral parietal lesion. Dissociated effects of residual spatial neglect. *Brain*. 1993;116 (Pt 5):1119-1137

79. Stelmach GE, Castiello U, Jeannerod M. Orienting the finger opposition space during prehension movements. *J Mot Behav*. 1994;26:178-186

80. Paulignan Y, Frak VG, Toni I, Jeannerod M. Influence of object position and size on human prehension movements. *Exp Brain Res*. 1997;114:226-234

81. Lundy-Ekman L. *Neuroscience: Fundamentals for rehabilitation*. Philadelphia: PA: W.B. Saunders Company; 1998.

82. Feys H, Hetebrij J, Wilms G, Dom R, De Weerdt W. Predicting arm recovery following stroke: Value of site of lesion. *Acta Neurol Scand*. 2000;102:371-377

83. Bernhardt J, Bate PJ, Matyas TA. Accuracy of observational kinematic assessment of upper-limb movements. *Phys Ther*. 1998;78:259-270

84. Chieffi S, Gentilucci M, Castiello U, Scarpa M. [kinematic study of the temporal coupling between the components of transport and manipulation during reaching and grasping movements]. *Boll Soc Ital Biol Sper*. 1991;67:723-729

85. Beer RF, Given JD, Dewald JP. Task-dependent weakness at the elbow in patients with hemiparesis. *Arch Phys Med Rehabil*. 1999;80:766-772

86. Daly JJ, Sng K, Roenigk K, Fredrickson E, Dohring M. Intra-limb coordination deficit in stroke survivors and response to treatment. *Gait Posture*. 2007;25:412-418

87. Desrosiers J, Malouin F, Richards C, Bourbonnais D, Rochette A, Bravo G. Comparison of changes in upper and lower extremity impairments and disabilities after stroke. *Int J Rehabil Res*. 2003;26:109-116

88. Mackey AH, Walt SE, Stott NS. Deficits in upper-limb task performance in children with hemiplegic cerebral palsy as defined by 3-dimensional kinematics. *Arch Phys Med Rehabil*. 2006;87:207-215

89. Rice MS, Newell KM. Upper-extremity interlimb coupling in persons with left hemiplegia due to stroke. *Arch Phys Med Rehabil*. 2004;85:629-634

90. Feys H, De Weerdt W, Nuyens G, van de Winckel A, Selz B, Kiekens C. Predicting motor recovery of the upper limb after stroke rehabilitation: Value of a clinical examination. *Physiother Res Int*. 2000;5:1-18

91. Tresilian JR, Stelmach GE. Common organization for unimanual and bimanual reach-to-grasp tasks. *Exp Brain Res*. 1997;115:283-299

92. Jeannerod M. The hand and the object: The role of posterior parietal cortex in forming motor representations. *Can J Physiol Pharmacol*. 1994;72:535-541

93. Lang CE, Wagner JM, Edwards DF, Sahrmann SA, Dromerick AW. Recovery of grasp versus reach in people with hemiparesis poststroke. *Neurorehabil Neural Repair*. 2006;20:444-454

94. Nowak DA, Grefkes C, Dafotakis M, Kust J, Karbe H, Fink GR. Dexterity is impaired at both hands following unilateral subcortical middle cerebral artery stroke. *Eur J Neurosci*. 2007;25:3173-3184

95. Haaland KY, Harrington DL, Yeo R. The effects of task complexity on motor performance in left and right cva patients. *Neuropsychologia*. 1987;25:783-794

96. Leonard CT, Gardipee KA, Koontz JR, Anderson JH, Wilkins SA. Correlation between impairment and motor performance during reaching tasks in subjects with spastic hemiparesis. *J Rehabil Med*. 2006;38:243-249

97. Messier S, Bourbonnais D, Desrosiers J, Roy Y. Kinematic analysis of upper limbs and trunk movement during bilateral movement after stroke. *Arch Phys Med Rehabil*. 2006;87:1463-1470

98. Krakauer JW, Mazzoni P, Ghazizadeh A, Ravindran R, Shadmehr R. Generalization of motor learning depends on the history of prior action. *PLoS Biol*. 2006;4:e316

99. Murphy MA R-WD. A review of motor performance measures and treatment interventions for patients with stroke. *Topics in Geriatric Rehabilitation*. 2003;19:3-42

100. Kopp B, Kunkel A, Muhlnickel W, Villringer K, Taub E, Flor H. Plasticity in the motor system related to therapy-induced improvement of movement after stroke. *Neuroreport*. 1999;10:807-810

101. Krakauer JW. Arm function after stroke: From physiology to recovery. *Semin Neurol*. 2005;25:384-395

102. Uswatte G, Taub E, Morris D, Vignolo M, McCulloch K. Reliability and validity of the upper-extremity motor activity log-14 for measuring real-world arm use. *Stroke*. 2005;36:2493-2496

103. Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S. The post-stroke hemiplegic patient. 1. A method for evaluation of physical performance. *Scand J Rehabil Med*. 1975;7:13-31

104. Bezeau RGaS. Statistical power and effect sizes of neuropsychological research. *Journal of Clinical Experimental Neuropsychology*. 2001;23:399-406

105. Browne R. Using the sample range as a basis for calculating sample size in power calculations. *The American Statistician*. 2001;55:293-298

106. Richards L, Senesac C, McGuirk T, Woodbury M, Howland D, Davis S, Patterson T. Response to intensive upper extremity therapy by individuals with ataxia from stroke. *Top Stroke Rehabil*. 2008;15:262-271

107. Rab G, Petuskey K, Bagley A. A method for determination of upper extremity kinematics. *Gait Posture*. 2002;15:113-119

108. Woodbury ML, Howland DR, McGuirk TE, Davis SB, Senesac CR, Kautz S, Richards LG. Effects of trunk restraint combined with intensive task practice on poststroke upper extremity reach and function: A pilot study. *Neurorehabil Neural Repair*. 2009;23:78-91

109. Wyrwich KW, Tierney WM, Wolinsky FD. Further evidence supporting an sem-based criterion for identifying meaningful intra-individual changes in health-related quality of life. *J Clin Epidemiol*. 1999;52:861-873

110. Bland JM, Altman DG. Measurement error. *BMJ*. 1996;313:744

111. Portney MWL. *Foundations of clinical research: Applications to practice*. Upper Saddle River: Prentice Hall Health; 2000.

112. Stratford PW. On "Test-retest reliability and minimal detectable change on balance..." Steffen t, seney m. Phys ther. 2008;88:733-746. *Phys Ther*. 2008;88:888-890; author reply 891

113. Mendes MPA. Type i error rate and power of three normality tests. *Pakistan Journal of Information and Technology*. 2003;2:135-139

114. Norusis M. *Spss 16.0 guide to data analysis*. Upper Saddle River: NJ: Prentice Hall; 2008.

115. Rau G, Disselhorst-Klug C, Schmidt R. Movement biomechanics goes upwards: From the leg to the arm. *J Biomech*. 2000;33:1207-1216

116. Ronnqvist L, Rosblad B. Kinematic analysis of unimanual reaching and grasping movements in children with hemiplegic cerebral palsy. *Clin Biomech (Bristol, Avon)*. 2007;22:165-175

117. Gladstone DJ, Danells CJ, Black SE. The fugl-meyer assessment of motor recovery after stroke: A critical review of its measurement properties. *Neurorehabil Neural Repair*. 2002;16:232-240

118. Crow JL, Harmeling-van der Wel BC. Hierarchical properties of the motor function sections of the fugl-meyer assessment scale for people after stroke: A retrospective study. *Phys Ther*. 2008;88:1554-1567

119. Latash ML, Nicholas JJ. Motor control research in rehabilitation medicine. *Disabil Rehabil*. 1996;18:293-299

BIOGRAPHICAL SKETCH

Tara Patterson was born and raised in northern New Jersey and graduated from Immaculate Heart Academy High School in 1993. She continued her education at the Pennsylvania State University, and received her Bachelor of Science Degree in 1997 in Psychology with a minor in Human Development and Family Studies. She decided to pursue a graduate degree and received a Master's of Education within the Developmental Kinesiology division from Bowling Green State University (BGSU) in 2000. Her focus while at BGSU was motor learning and control, and she received partial funding from the NW Chapter of the National MS Society in order to complete her master's thesis; a study examining the effects of a therapeutic horseback riding experience on selected behavioral and psychological factors on ambulatory adults diagnosed with MS. This study was recognized by the community, and was featured in the local news.

Tara developed a passion for research and decided to pursue a PhD at the University of Florida within the department of Recreation, Parks and Tourism with a focus on therapeutic recreation. She was granted an assistantship within the tourism division, and was involved in numerous research projects and volunteered at a local physical therapist's practice specializing in Hippotherapy. In 2001, Tara decided to change specializations and was admitted into the Rehabilitation Science Department with a concentration in movement dysfunction. She was involved with and supported by several funded studies examining changes in individuals with stroke after Constraint Induced Movement Therapy, and was also project coordinator for a study examining gait and balance changes after a home exercise program intervention in older adults. Her primary interest became motion analysis in the upper extremity in individuals with stroke, which ultimately became her doctoral research. Tara received her Doctorate of Philosophy in May of 2009.