GENERALIZATION OF REPETITIVE RHYTHMIC BILATERAL TRAINING

By

CLAUDIA ANN RUTTER SENESAC

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

2006

This document is dedicated Emily Salles Senesac, Robert Edward Senesac and *in Memory* of Ashley O'Mara Senesac and Robert Basil Rutter

ACKNOWLEDGMENTS

I thank my family for their patience and understanding as I pursued a dream to learn more about the body and mind. With their love and encouragement I complete this journey and begin another.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF OBJECTS

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

GENERALIZATION OF REPETITIVE RHYTHMIC BILATERAL TRAINING

By

Claudia Ann Rutter Senesac

May 2006

Chair: Lorie Richards
Major Department: Rehabilitation Science

Background and purpose: Bilateral training (BT) is an alternative approach in neurorehabilitation for individuals post stroke. Bilateral training activities may increase the activity of the affected hemisphere and decrease the activity in the unaffected hemisphere providing a balancing effect between hemispheric corticomotorneuron excitability. One bilateral approach, repetitive rhythmic bilateral training, developed and researched by Whitall, has shown improved motor function after intervention post stroke. Yet, an important question is whether this type of practice will result in improvements in untrained movements. The ability to perform related untrained motor tasks is generalization. The purpose of this study is to determine if repetitive rhythmic bilateral training will promote spatial generalization to a novel task.

Methods: Fourteen participants with hemiparesis completed the study. The intervention used an arm training machine–BATRAC–consisting of two paddles mounted in nearly frictionless tracks. The participants moved the handles back and forth in a rhythmic manner for 5-minute blocks. Half of the blocks were in-phase; the other half of the blocks were anti-phase. Practice sessions were 4 days/week, 2:25 hours/day, for 2 weeks, for a total of 18 hours of training. We measured movement time, time to peak velocity, hand path trajectory, peak velocity, and acceleration using the Vicon motion analysis system during 2 reaches to target tasks pre- and post- training. Each participant gave informed consent according to University of Florida Institutional Review Board and North Florida/South Georgia Subcommittee for Clinical Investigation requirements prior to participation.

Results: Improvements were found at post-test only for hand path trajectory and peak velocity. They were equivalent across similar and dissimilar tasks. Movement time 2 was less for novel task #1 compared to novel task #2 but equivalent across pre- and post- testing periods. No interaction effects were found.

Conclusion: Unlike Whitall, our kinematic results suggest that repetitive rhythmic BT alone is not sufficient to change motor control, specifically generalization to similar, but untrained tasks. However, the small and heterogeneous study sample precludes definitive conclusions regarding the usefulness of this practice paradigm for promoting motor skills post-stroke.

CHAPTER 1
INTRODUCTION

Stroke strikes 700,000 persons each year in the United States resulting in varying degrees of permanent disablement.[1] Many of the people affected by stroke will have a residual upper extremity (UE) motor and sensory deficit that will influence their ability to participate in life roles. These deficits typically involve decreased UE use and coordinative control of the arm and hand for activities of daily living, gesturing, and bilateral activities and will affect 78% of those individuals surviving stroke.[2] Furthermore the vast majority of those with severe UE paresis will not recover full function of their arm and hand after 6-11 weeks of “traditional” therapy. [3] The effectiveness of current rehabilitation approaches for restoration of UE function has not identified one intervention as being superior to others in gaining function in the UE.[3, 4] Scientific evidence now suggests that to enhance motor recovery post stroke, one of the critical components in an intervention protocol is practice.[5, 6] Thus finding effective UE motor rehabilitative interventions is an important goal.

Development of new, more effective rehabilitation techniques depends upon understanding the neural, physical and behavioral expression of movement.[7] Specifically, an understanding of the CNS’s ability to recover in the face of injury, and the extrinsic factors that can influence that recovery, is essential for successful neurorehabilitation. Key to motor recovery following stroke is the CNS’ ability to learn or relearn motor behaviors. This recovery can occur spontaneously, or more likely, will require practice of the lost motor abilities to facilitate reorganization of the motor cortex.[5, 7, 8]

Re-training and practicing every motor behavior that the individual will be called upon to use in everyday life is unrealistic. Motor control theory suggests that all movement behaviors, or tasks, contain essential features that can be entrained with practice.[9] Motor learning theory further suggests that these features, once trained, can be transferred to another task that requires the same features(s). This is called a generalization effect.[9]Taking advantage of this effect could have a significant impact on UE rehabilitation post-stroke.

Bilateral training is an emerging approach in neurorehabilitation for individuals post-stroke. Bilateral movements form a tight phasic relationship organizing the behavior to perform as a functional synergy.[9-11] Animal and human research has supported the notion that both hemispheres are active during bilateral activties.[12-14] During the acquisition phase of learning a bilateral skill, there is a functional coupling of motor areas in both cerebral hemispheres.[15] In persons post-stroke, bilateral activities have increased activity of the damaged hemisphere and decreased activity in the undamaged to facilitate a more balanced effect of between-hemisphere corticomotorneuron (CMN) excitability.[16, 17] For example, repetitive bilateral arm training increased activation in the contralesional cerebrum and ispsilesional cerebellum after 18 hours of training.[18] The response of the motor cortex to bilateral training with reorganization is encouraging. Bilateral training may lay a foundation in individuals post stroke for engaging coordinative structures allowing the execution of basic motions and movement even though the practice is not real life task practice.

The basic motions provided in bilateral training may entrain both hemispheres and provide the essential features necessary to generalize to similar tasks not specifically trained in the intervention. Generalization of a task should be optimal when the neural demands and conditions are similar.[9] However, because functional tasks are not directly trained, test of the generalization is important. The purpose of this study is to determine if repetitive bilateral training will promote spatial generalization to a novel task.

The following literature review is composed of five main sections and will serve to orient the reader to foundation principles underlying the purpose and hypotheses of this project. The sections will include the following: 1) stroke and UE rehabilitation; 2) theoretical basis; 3) neuroplasticity and use-dependent plasticity; 4) motor learning: practice and generalization, and 5) bilateral training in stroke rehabilitation. First, the traditional view of stroke and rehabilitation will be compared and contrasted with more recent views based upon new scientific evidence. Second, conceptual frameworks for studying UE recovery following stroke will be reviewed. In the third section, basic elements of CNS neuroplasticity and training effects on CNS plasticity will be reviewed. Motor learning principles including generalization, and practice and their relevance to stroke rehabilitation will then be discussed in the fourth section. Finally, the use of bilateral training incorporating key motor learning principles will be discussed as a potential new therapeutic approach.

Stroke and UE Rehabilitation

Each year 700,000 persons will suffer a new or recurrent stroke in the United States resulting in varying degrees of permanent disablement.[19] Many of the people affected by stroke will have a persistent upper extremity (UE) motor and sensory deficit that will influence their ability to participate in activities of daily living and life roles. Motor and sensory deficits typically involve decreased coordinative movement of the arm and hand and UE use for activities encountered in a person's daily environment including self-help skills, gesturing and bilateral activies.[2] Furthermore, the vast majority of those with severe UE paresis will not recover complete function of their arm and hand after 6-11 weeks of “traditional” therapy. [3] In fact, use of the UE is so important that subjective measures of “well being” are directly related to perceived motor impairments of the arm affecting quality of life. [19] Thus, developing effective UE motor rehabilitative interventions is extraordinarily important, especially in light of current rehabilitative approaches to UE treatment that lack clear consensus, and are conflicted and unsubstantiated. [3, 4]

Upper extremity interventions in the stroke population have historically focused on treatment of single limb movements; treating the intact and affected arm separately.[20-24] Methods designed to restore motor skill in the affected UE are influenced by facilitation models of motor recovery and emphasize handling or guidance to achieve more normal movement patterns. Practice under these conditions improves performance, but improved performance of a task does not necessarily lead to relatively permanent changes, which characterize motor learning.[7, 9] Performance during motor skill learning is a temporary change in behavior that is observed during practice sessions but may not be retrieved at a later time for execution.[9] This may be because practice under traditional motor rehabilitative approaches allows for few errors, and little problem solving (by the learner) of the criteria inherent in the task.[25] In addition many of these traditional therapy approaches were based on the hierarchical-reflex theory, which has not held up under the scrutiny of the current motor control and motor learning literature. Nonetheless, these facilitory models continue to be used as traditional standard of care for rehabilitation.[26-29]

Theoretical Basis

The hierarchical-reflex model suggests that motor learning in rehabilitation is a stepwise sequence of motor recovery and motor development from lower levels to higher levels of control.[30] Treatment based on this theory of motor control often will focus on the movements that are most automatic requiring sensory stimulation from the therapist, progressing to more skilled voluntary tasks. This approach is often referred to as a "traditional" approach utilizing facilitation from the therapist to accomplish goals. New approaches to rehabilitation are beginning to surface based on the concepts of neuroplasticity and motor learning theories.

Bernstein first proposed the systems theory in the early to mid 1900's although it was not incorporated into rehabilitation until the early 1980's. [9, 25, 31] Bernstein viewed the nervous system as one of many contributors to movement execution but not the controller of movement. Movements are seen as a result of an interaction among many systems including internal and external environments, organized around behavioral goals with distributed control.

Bernstein noted that there were many degrees of freedom (df) available to produce a movement. Different df are characteristic of a task, environmental demands, and the performer. These df need to be controlled for effective movement to be accomplished. He purposed that the formation of synergies (groups of muscles and joints constrained together) could control the multiple df problem. This model can describe how learning of a new motor skill takes place. In the early stages of learning a new task the movement may be simple. Movement at one joint may be allowed to vary with intermediate joints held stiffly utilizing cocontraction of muscles to control the df. Once the movement is learned muscle cocontraction is reduced and the movement becomes more fluid indicating the ability of the central nervous system to use multiple resources to accomplish a task. In stroke, these synergies are constrained in a pathological manner with stereotypical movements observed with attempts to move.[21, 22] Difficulty is noted in the ability to control the multiple df that are available in the extremities and trunk. This inability to form normal synergies of movement leads to compensation and decreased fluidity of movement in persons post- stroke.[24]

Neuroplasticity and Use-dependent Plasticity

Brain infarction results in a semi-reversible set of pathophysiological events including swelling of the affected area, impaired circulation and pyramidal cell injury or death.[8] Recovery from brain infarction involves plasticity–the ability of the central nervous system to reorganize after brain injury. [32] Developing an understanding of the post-ischemic plasticity and its effect on motor control and motor learning has become the focus of current rehabilitative efforts.[9] The CNS post-stroke begins a process of spontaneous recovery which involves neurological reorganization. In contrast to individuals with intact nervous systems, attempts to move after stroke result in decreased activation in the affected motor cortex with increased activity in the non-affected hemisphere.[8, 33, 34] These findings suggest even though crossed motor pathways are damaged, after stroke recruitment of preexisting uncrossed motor neural pathways may be accessed.[34] Ipsilateral motor unit activity can be induced when the ipsilateral dorsal premotor cortex area is stimulated by TMS. This stimulation has demonstrated shorter latencies when compared to contralateral stimulation of the premotor cortex when the hand is moved in stroke patients.[35] Even in individuals who have recovered from stroke, there is an increased activation of the CMN pool in the undamaged hemisphere when compared to persons with intact nervous systems performing a finger tapping movement.[33, 36] However, recovery from stroke is associated with decreasing activation in the contralesional hemisphere and increasing activation in the lesioned hemisphere; a more normal balance of activation is seen.

Motor recovery post stroke is augmented by rehabilitation. Rehabilitation of individuals post-stroke involves *motor learning.* Motor learning is characterized by a set of processes that are associated with practice. These processes influence change in the internal state of the central nervous system and become relatively permanent, capable of being retrieved from long-term memory centers into working memory for motor execution.[5, 7, 9] In the case of the individual with stroke, rehabilitation is concerned with the relearning of once familiar motor skills using new motor pathways. Coordinative patterns of movement must be practiced to create these new motor pathways during recovery for the execution of motor skills. The capability by which the brain modifies structure and function in response to learning or brain damage is neuroplasticity.[5, 7]

Several mechanisms of reorganization of cortical areas after stroke or brain injury have been proposed. Unmasking is a term used to indicate decreased inhibition of pre-existing excitatory synapses allowing for functionally inactive connections to become active. Changes that are rapidly induced during spontaneous recovery after injury are believed to be unmasking.[5] Synaptogensis refers to growth of new neural connections and is related to environment and practice.[8] Long term potentiation (LTP) involves the increasing sensitivity of synapses pre-synaptically through constant stimulation with a resultant larger postsynaptic output. Long term potentiation and synaptogensis are believed to occur over longer time periods, coming into play during intense practice.[5] Sparing refers to the areas of the brain that were not damaged during the injury and may be adjacent or interconnected to the damaged area. These areas of sparing have been shown to play a role in reorganization of cortical maps.[5, 37-39]

Nudo et al. has demonstrated in a study with squirrel monkeys that the motor cortical areas of the brain can reorganize after brain injury.[32] Further investigation by this group of researchers suggest that reorganization of cortical maps is dependent on rehabilitation and practice.[38, 40-42] Use-dependent plasticity relies on activation of the brain during periods of practice. [5, 7] Calautti and Baron reviewed neuroimaging studies of individuals post-stroke and found reorganization of motor areas with enhanced activity in existing neural networks. In this review, both motor training and pharmacological interventions were found to induce this increased activity in the damaged hemisphere associated with recovery of function and improved motor skills.[43] Calautti and Baron observed significant changes in neuromapping in individuals involved in intense practice of specific tasks. For example, neuroplasticity associated with motor rehabilitation has been documented with the treatment paradigm constraint-induced movement therapy (CIMT).[44-46] Cortical reorganization in motor output areas of the damaged hemisphere and in areas adjacent to the damaged site have been demonstrated as a result of intense practice. [37, 47, 48] Jang et al. demonstrated cortical reorganization by fMRI after 4 weeks

(4 days/week, 40 minutes/day) of task oriented training (practicing of functional tasks). This training consisted of six tasks to improve UE function in 4 individuals with chronic stroke. Cortical reorganization was evident with changes in the activation of the primary sensory motor cortex (decrease in activation of the unaffected hemisphere and increase activation in the affected hemisphere).[49] These studies indicate that practice is an

important component of the motor rehabilitative process as it facilitates neuroplasticity of the cortical motor areas.

Motor Learning

Motor learning and the underlying neuroplastic changes are dependent on practice. [5, 7] In the face of neuropathology, persons post-stroke must confront relearning skills that once were part of their daily routine. Determining the conditions for optimal learning in persons post-stroke requires an understanding of the different types of practice available during a rehabilitation program. The type of practice schedule that is selected during therapy has a strong effect on the process of motor learning effecting the basic components of movement and building the specifics of coordination for activities.[9] Certain principles of motor learning are well established in healthy adults but not well understood in stroke.

Mass practice builds capacity (skillfulness, ability) by utilizing longer practice periods and short rest periods between trials. However, this type of practice can lead to fatigue resulting in detrimental results for actual motor learning, transfer (generalization), and retention.[9] Practicing under conditions of fatigue may affect the synergies that are engaged during the learning of the task, and ultimately the ability to retrieve the appropriate information for the execution of the task at a later time (retention and transfer) is reduced. *Distributed practice* provides shortened practice sessions and equal or longer rest periods than the actual task trials. This type of practice improves performance without the complication of fatigue and has demonstrated positive effects on motor learning as measured by transfer trials. [9]

The sequence of practice is also an essential component to motor learning. Practice that repeats one task for a set number of trials before moving on to the next task is referred to as *blocked practice*. This type of practice has low contextual interference (learning within the context of only one task) as the person learns the criteria for the task and performs several repetitions in the acquisition phase before moving on to another skill. Blocked practice enhances performance but may be detrimental to retention or permanent learning as there is a low demand on problem solving once the criteria of the skill are understood. Blocked practice is used in therapy when the task is just being introduced and the participant is becoming familiar with the criteria of the movement. *Random* practice intermixes trials so that no task is repeated on two consecutive trials. The order of presentation of trials is varied presenting a high degree of contextual interference (learning one task in the context of other tasks). Random practice provides different patterns of coordination with different underlying motor programs with a range of solutions for motor tasks.[50] This type of practice can be detrimental to performance during the acquisition phase but beneficial to motor learning and retention with the continual demand on retrieving the criteria of the task.[51, 52]

During rehabilitation, therapists attempt to help the individual with stroke build the ability to produce coordinative movements. Because it is impossible during rehabilitation to practice every motor task the person will encounter in daily activity, it is believed that the basic coordination gained by practicing some tasks during rehabilitation will generalize to unpracticed motor tasks the individual will encounter in his/her everyday life. The concept of “generalization” or transfer allows for the execution of other, related skills apart from the specific practiced task (new skill or new environment). [7, 9] The critical aspect of generalization of a motor task appears to be whether similar neural processing requirements of the tasks are incorporated. The more closely linked the conditions and demands of the new skill or new environment are to the practice environment, the better the transfer.[53, 54] This ability to retrieve information for retention and generalization is directly linked to practice and the type of invariant features that constitute the motor skill.[9]

Choosing the right practice schedule and sequence are dependent on the stage of learning that the individual is in and the classification of the motor skill that is to be practiced. When a person who is neurologically intact is learning a new task he/she begins by gaining an understanding of the rules and strategies inherent in performing the task. Systems theory suggest that learning the invariant features of the task is accomplished by engaging coordinative structures (muscles, joints, neural components, arousal, and gravitational influences).[7, 31] The learning of a coordinative movement involves components of the internal and external environment all of which contribute to the pattern of coordination that emerges. Skilled movements require parameters that make the task unique and different from other tasks. The unique features contain rules that are particular to that task. Learning these rules and the invariant features of the task is often referred to as the cognitive phase of learning.[9] Each phase of learning allows for the complexity of the task to increase and the motor skill to be refined until it is automatic.

In the early stages of recovery after stroke many people have difficulty initiating any movement. This lack of movement, related to a decrease of the CMN pool, makes activation and muscular recruitment a difficult task.[55] Rehabilitation post stroke at this level is concerned with gaining an ability to move, learning the basic interjoint coordination and activation pattern of muscles, which gives feedback about movement and how to recruit muscles for motor tasks. In persons post-stroke this stage of learning is coupled with building the physiological capacity to move and is usually very cognitively demanding, requiring high levels of concentration.

What do we know about *practice* and *therapy intervention* post-stroke? There are few studies examining motor practice parameters post-stroke. Many of the studies that are cited in the literature mention practice but fail to elaborate on the specifics of the practice conditions using traditional therapy as the intervention.[27-29]There are limited studies on UE practice protocols in stroke that have shown positive results paying attention to the specifics of practice. Some of these studies have demonstrated that some of the same principles of motor learning and practice as established in healthy individuals apply to motor learning post-stroke. Others have not. For example, Hanlon[52] 1996 studied 24 subjects with chronic hemiparesis to determine the effect of different practice schedules for the acquisition and retention of a functional movement sequence for the involved UE. Subjects were randomized into three groups: control, blocked, and random practice groups. The movement sequence involved a serial task that was alternated with trials on three other tasks in the random group. The movement sequence was practiced in two blocks of five trials in the blocked group. A significant difference was found between random and blocked practice groups with random practice being more effective for retention over time in individuals post stroke.[52] These results in the stroke population follow the principles of motor learning, retention and transfer in healthy adults.[9]

In contrast, Cauraugh[56] 2003 compared blocked and random practice sequences combined with active neuromuscular stimulation trials in subjects with stroke. The movements practiced included: wrist/finger extension, elbow extension, and shoulder abduction. The results indicated motor improvement in both groups without a difference between the two practice sequences. This study did not support what we know about contextual interference associated with random practice in healthy individuals.[56] It is difficult to compare these studies as they used different types of tasks. However, the results of these studies illustrate how little is known about the effects of practice protocols, type of task practiced, in combination with the level of recovery of the individual participating in practice. The rules for practice in individuals post stroke are unclear and the factors affecting the results of practice in this population have not been established.[35] Are the concepts of motor learning based on neurologically intact individuals relevant when persons post-stroke have difficulty initiating movement and use pathological synergies to accomplish the movements that they do execute?

Principles of generalization post-stroke have had even less science. First, let's examine what is known about generalization in healthy individuals in relation to UE movement tasks. Generalization is an ability to execute another motor task not specifically practiced. The ability to dissociate a learned motor skill utilizing coordinative structures and features of the practiced task that are similar to but not part of the practiced task would be an example of generalization. In a study by Sainburg et al.[57] hand movement directions were reported to generalize for movements made up to 36 degrees to either side of the trained direction in individuals without neurological deficits. Generalization beyond the region of training has been documented successfully when a tight coupling of angle of gaze (visual field) and the position of the hand and shoulder are provided.[58] In both studies, the nervous system demonstrated an ability to use sensory information to recalibrate the internal model formed by the practiced task. This recalibration allows for a limited amount of adaptation by the musculoskeletal system to a novel task. This agrees with our knowledge that the best generalization occurs when the neural processing requirements are similar to that of the practiced task. Which parameters of the task that are critical are not clear. Understanding the parameters that enhance generalization following stroke can contribute to the design of treatment protocols.

Acquiring interventions that would generalize to skills not specifically trained in practice sessions (trials) would be advantageous therapeutically. Identifying particular intervention protocols and pairing them with the stage of recovery or learning that the individual may be in could enhance their rehabilitation. By building capacity early on in recovery and layering more complex skills as individuals post-stroke gain an ability to move could lessen their overall UE disablement. Introducing the right intervention at the right time may enhance motor learning, retention and generalization.

Bilateral Training

A new approach to UE stroke rehabilitation; bilateral training is beginning to be investigated systematically and demonstrating some positive results. [16, 59-62] Protocols in these studies have used functional and non-functional tasks practiced bilaterally with similar temporal and spatial requirements.[60, 61, 63] What do we know about the brain and bimanual coordination?

Researchers believe that bilateral training may be a good approach in stroke rehabilitation based on what we know about the brain and bimanual coordination. Bilateral movements form a tight phasic relationship causing them to perform as a functional synergy.[10, 11]The establishment of such coordinative structures during bilateral movement may serve as a template and entrain the paretic arm during the movement phase with the uninvolved hemisphere providing a pattern of firing for the involved hemisphere.[64] Generalization of task performance from one arm to the other is not a new concept. For example, reaching movements generalize from the dominant arm to the non-dominant arm in healthy individuals.[65] How does reaching with one arm improve function in the contralateral arm? When learning the dynamics of a reaching task the neural representation for the dominant arm in the contralateral hemisphere may engage neural elements for both arms. To assess the dependence of generalization on callosal inter-hemispheric communication, Criscimagna-Hemminger et al.[65] further investigated transfer of the dominant UE to the non-dominant UE in a person with a commissurotomy. The results were similar with generalization from dominant to nondominant arm (unaffected UE to affected UE).[65] What is the relationship to individuals with stroke? Conceivably bilateral training may have a similar effect on individuals post-stroke with improved transfer from the uninvolved UE to the affected UE. Bilateral practice may also be beneficial because both hemispheres are active during bilateral actions perhaps activating uncrossed tracts.[12-14, 34, 35, 66] Evidence from animal and human research supports the notion that a temporal interaction between hemispheres occurs in the motor cortex.

Gerloff et al.[15] reviewed the functional coupling of the motor areas of both cerebral hemispheres during bilateral learning. Interhemispheric interaction is particularly important during the acquisition phase of the skill.[15] Bilateral training may be an appropriate starting place for rehabilitation after stroke.

There are three studies using *repetitive rhythmic bilateral training*, which have demonstrated some transfer effects to other tasks incorporating specific critical elements of the original training task. In these studies training involved non-functional tasks performed bilaterally with similar spatial and temporal parameters for each extremity using “rhythmic” synchronized inphase and antiphase movements. However, many of the bimanual tasks that are used in daily life require a different contribution from each extremity. Thus, it is critical to show generalization of this type of training to other useful coordinative patterns utilized in daily activities as our arms are not always performing with similar patterns of movement. *One of the missing components to our understanding of this intervention in stroke is generalization of the bilateral training.*

The **Whitall,** et al.[61]study investigated the hypothesis that bilateral upper extremity training with auditory cueing of a metronome would improve motor function in persons who had suffered from stroke. The intervention involved a custom designed arm-training machine (BATRAC-bilateral arm training with rhythmic auditory cueing), which allowed for elbow and shoulder flexion and extension coordinated to a metronome set at a self-selected speed. This study concentrated on a proximal effector system involving shoulder and elbow joints while limiting trunk forward lean during reaching by a chest restraint. The design was a single group pilot study with 14 subjects consisting of 20-minute training sessions, 3 times per week for a 6-week period of intervention with a total of 18 sessions. Each session consisted of four 5-minute periods alternating inphase and antiphase movements using the BATRAC interspersed with 10-minute rest periods for distributed practice. Results indicated significant improvement in motor performance on the Fugl Meyer (FM) upper extremity section, significant improvement in performance time on the Wolf Motor Function Test (WMFT) and significant increase in daily use of the affected extremity on the Maryland Arm Questionnaire for Stroke after six weeks of training with sustained improvement at 8 weeks after training cessation. [61]

In a follow-up study, fMRI demonstrated increased hemispheric activation during paretic arm movement with changes in the contralesional cortex and ipsilesional cerebellum after training utilizing the BATRAC.[18] Cerebellar activity has been identified as a principal region for the control of bimanual coordination.[14] Although the numbers of subjects (6) who demonstrated changes in the Luft et al.[18] study are small, it is encouraging data that supports repetitive bilateral training. Bilateral training as a potential therapeutic intervention has been bolstered by evidence of reorganization of the motor cortex in individual's using BATRAC post stroke.

Stinear and Byblow [16] had individuals with stroke perform active movement of the unaffected wrist, which drove passive wrist flexion-extension of the affected UE using a manipuladum at a self-paced rhythm. Focus was placed on the distal effector system, the wrist joint. Nine subjects of a heterogeneous group of stroke participants practiced for 60 minutes a day for a total of 4 weeks with a random assignment into groups of synchronous and asynchronous practice. Five of the nine participants demonstrated improvement in motricity scores as measured by the wrist, hand and coordination components of the upper limb section of the FM Assessment of Motor Function. Postintervention transcranial magnetic stimulation (TMS) revealed a decrease in the unaffected cortical map volume in the subgroup of five patients that improved in motricity. The subjects that demonstrated significant results were a mix of persons with cortical and subcortical lesions, acute and chronic stroke, mild and severe disability, and had a combination of synchronous and asynchronous training. The results of this study suggest that bilateral training promotes a balancing of between-hemisphere corticomotor excitablility.[16]

Although these studies have suggested that motor learning has occurred after bilateral training they have not delineated the parameters or limits of motor skill generalization with this practice. Schmidt[9] suggests that the more similar the neural demands are during novel tasks the greater the transfer.[54] Specifics of the basic neural elements involved in repetitive bilateral training for individuals post-stroke have not been assessed in a transfer test. There are only a couple of studies on bilateral coordination that delineated parameters important for generalization of a novel task in individuals who were neurologically intact.[67, 68]

Little is known about the principles of generalization of bilateral coordination in healthy individuals except the studies mentioned above and to date there is nothing in the literature involving the stroke population. In neurologically intact individuals Temprado and Swinnen demonstrated generalization of a bilateral coordination pattern to a novel pattern when the spatial relative phase (RP) (a variable that characterizes the spatial relationship between two limbs) of the transfer task was similar but not to a task with a different spatial RP.[67] Muscle synergies engaged during interlimb coordination tasks are influenced by spatial orientation. The symmetry of movement may be an important factor in improving coordination in bilateral tasks.[68] Determining the relationship of training task parameters (spatial, angle of gaze, joint angles) to generalization in individuals post stroke has not been specifically investigated.

Biomechanics of Reaching

Reaching is a functional task that requires control of multiple joints through space.[69] Kinematic measures of reaching have been utilized in studies of generalization to document change in the pattern of reaching.[58, 67, 70] Biomechanical evaluations are capable of capturing interjoint coordination, and movement composition thus indicating quality of the reaching pattern.[69, 71, 72] Biomechanical measures assessing temporal aspects of reaching include but are not limited to; movement time, time to peak velocity, peak velocity which indicates symmetry of the reach, strategy for reaching, and acceleration. Kinematic spatial parameters of reaching include hand path trajectory (how straight is the path to the target) during the reach.[71] The literature on the biomechanics of reaching has documented that reaching post-stroke is slower, discontinuous with many movement reversals (stops and starts during the movement to the target), and the trajectories are curved to the target.[69, 71-73] Reliability and validity of these biomechanical measures in the stroke population are not established to date.[71] However biomechanical assessment of reaching may provide an understanding of motor control and assist in the evaluation of new therapies.

Summary

Motor learning and neuroplasticity are dependent on practice. The appropriate type, duration, intensity, and frequency of practice to enhance motor learning, generalizability, and motor recovery have yet to be determined in the stroke population. What parameters should be emphasized in rehabilitation during practice sessions to maximize generalization? It is not clear if task specific training is important in laying a foundation for coordinative movement in persons after stroke. Persons post stroke have difficulty moving and must relearn coordinative patterns to execute motor tasks. Perhaps the focus should be on engaging coordinative structures that might provide a general motor template to build physiological capacity and complex movements. Establishing a motor capacity to move post stroke may provide the framework for generalization of a practiced task. Supportive evidence on bilateral training and generalization suggests that engaging similar spatial and temporal synergies may have positive effects on motor learning in persons post stroke.[16, 18, 61, 63, 67, 68, 70]

Utilizing Whitall's protocol for repetitive bilateral training: can a "general framework" of coordinative synergies be created divorced from a particular skill or task that would underlie the basics of motion and movement capabilities? Whitall's protocol used an arm training machine (BATRAC) for repetitive bilateral training in one orientation with inphase and out-phase movements. The repetitive movement of the UE's in this protocol engages similar synergies as real life reaching tasks bilaterally accomplished in the workspace directly in front of the person. Stinear and Byblow using a distal effector system demonstrated a balancing effect between hemispheres of corticomotor excitability. How functional is repetitive bilateral training and to what degree if any will this type of training assist an individual with stroke to execute tasks that were not specifically trained but similar?

Therapy interventions have focused on simulation of tasks that would be performed in the home and community. Therapists have emphasized building a repertoire of movement skills that incorporate components necessary for other unpracticed motor skills. Practicing every task that will be encountered by an individual once they are discharged from rehabilitation is impossible. Identifying intervention protocols that generalize to tasks unpracticed in the rehabilitation arena is essential. Generalization of learned motor skills would enhance a person's ability to participate in life roles at home and in the community by increasing the number of conditions and solutions to a host of motor problems. Bilateral training may lay a foundation in individuals post-stroke for engaging coordinative structures allowing the execution of “basic” motions and movement even though the practice is not variable or with real life tasks. Collecting kinematic data for assessment of generalization of this training may help us to understand which reach parameters might change after bilateral training. Repetitive bilateral training is distributed blocked practice, which avoids fatigue but allows for the criteria of the skill to be learned without building endurance. This combination of practice may build a “physiological capacity” for movement in persons post-stroke. The entrainment of both hemispheres during bilateral training provides a functional coupling of the motor cortexes especially during the acquisition phase of learning a bilateral task.[15] Yet, the ability of such training to transfer to functional tasks awaits testing.

The **aim of this study** is to determine if repetitive rhythmic bilateral training (using the BATRAC as outlined in the Whitall et al.[61] study) will generalize to a novel task that is performed with similar neural demands.

Specific Aims

To test the hypotheses that repetitive bilateral training using blocked-distributed practice will demonstrate spatial generalization to a novel task with similar neural demands in joint angles, workspace, visual gaze angles, and muscle timing. The following research questions will be addressed in a single group repeated measures design employing a pre-test and post-test period. Outcome measures will be taken prior to intervention and at the end (completion) of 2 weeks of proximal repetitive bilateral intervention.

Research Aims and Hypotheses

General aim 1

To determine spatial generalization to a novel task after proximal bilateral training for the affected upper extremity.

Specific aim 1a and 1b

1a. To determine if proximal bilateral training generalizes to a novel task (#1) that is similar in shoulder/elbow joint angles, constraints of muscles and joints (coordination), visual gaze angles and a workspace identical to the training.

1b. A secondary novel task (#2) will be tested with different joint angles, visual gaze angles and workspace from the training motion.

Primary hypotheses 1a and 1b for spatial parameter

1a. Generalization will occur for novel task (#1) when tested in the same workspace with similar joint angles as practiced for the proximal bilateral training intervention. At the end of week two of proximal bilateral training: kinematic data for hand path trajectory to the target. <u>will demonstrate generalization for novel task (#1</u>). Data will be compared to baseline data with improvement for the above kinematic outcome predicted. Hand paths to the target in stroke are variable and lack continuity..[69, 71, 72] Therefore, based on the literature hand path trajectory will be straighter. 1b. Generalization will not occur for novel task (#2) that is dissimilar in joint angles and workspace to training. At the end of week two of proximal bilateral training: kinematic data for hand path trajectory <u>will not generalize for novel task (2#)</u>. Data will be compared to baseline data with no improvement for the above kinematic outcome predicted.

Secondary hypotheses 2a and 2b for temporal parameters

Temporal parameters are assessed separately in this study because neither the training nor the testing tasks emphasized speed. Therefore these parameters may not change. Individuals post-stroke do move slower when compared to healthy individuals so it is possible that the speed may be different after intervention although it was not emphasized.[69]

2a. Improvement in movement time, time to peak velocity, peak velocity and acceleration will occur for novel task (#1) when tested in the same workspace with similar joint angles as practiced for the proximal bilateral training intervention. At the end of week two of proximal bilateral training: kinematic data for movement time, time to peak velocity, peak velocity and acceleration (the percent of the reach that is acceleration) will change. Data will be compared to baseline data with improvement for the above kinematic outcomes predicted. Individuals post-stroke move slower during reaching and often demonstrate a skewed profile in reaching with a shorter relative duration in the acceleration phase, peak velocity is often lower compared to healthy individuals and absolute time to peak velocity is shorter.[69, 71]Therefore, based on the literature movement time will decrease, time to peak velocity will increase, peak velocity will be higher and the percentage of reach that is acceleration will approach 50% of the acceleration curve.

2b. Improvement in movement time, time to peak velocity, peak velocity, and acceleration will not occur for novel task (#2) that is dissimilar in joint angles and workspace to training. At the end of week two of proximal bilateral training: kinematic data for movement time, time to peak velocity, peak velocity, and acceleration (the percentage of the reach that is acceleration) will not change for novel task #2. Data will be compared to baseline data with no improvement for the above kinematic outcomes predicted. Movement time, time to peak velocity, peak velocity, and the percentage of reach that is acceleration will not improve.

CHAPTER 2
METHODS

Experimental Design

This study employed a single group, repeated measures design that included a pre-test baseline and post-testing at the completion of two weeks of proximal bilateral training.

Subjects

Fifteen participants with hemiparesis and UE motor deficits were recruited from the Brain Rehabilitation Research Center's stroke database at the North Florida/South Georgia Veterans Health System. One subject dropped out of the study due to unrelated medical reasons. This database consists of individuals with stroke who have been recruited to participate in rehabilitation studies from the North Florida/South Georgia VA, Shands Hospital at the University of Florida, Shands Rehabilitation Hospital, Shands Hospital at Jacksonville, Brooks Rehabilitation Hospital and the Brooks Center for Rehabilitation Studies in Jacksonville. Nine of the subjects were male and 5 were female with a mean age of 64.4 (sd = 13.3) years and a mean of 5.5 (sd = 3.9) years post-stroke. Five of participants had right-sided lesions and nine had left-sided lesions. Demographic and clinical data for the subjects are summarized in Table 2-1. Whitall[1], Luft,[2] and Stinear and Byblow[3] all demonstrated treatment effects with sample sizes of 9-14 subjects.

Inclusion criteria were: 1) single unilateral stroke at least 6 months prior, 2) no active drug or alcohol abuse, 3) able to follow 2-step commands, 4) no history of a clinical ischemic or hemorrhagic event affecting the other hemisphere, and no CT or MRI evidence of more than a lacune or minor ischemic demyelination affecting the other hemisphere, 5) no history of more than minor head trauma, subarachnoid hemorrhage, dementia, learning disorder, drug or alcohol abuse, schizophrenia, serious medical illness, or refractory depression, 6) some active movement in shoulder and elbow with palpable extrinsic forearm finger muscle recruitment. Exclusion criteria: 1) no movement in UE or no palpable muscle recruitment in extrinsic finger extensor muscles, 2) scores > 3 on the Motor Activity Log, indicating a high level of UE function, 3) spasticity greater than 2 on the Modified Ashworth Scale.

Each participant gave informed consent according to University of Florida Institutional Review Board and North Florida/South Georgia Subcommittee for Clinical Investigation requirements prior to participation.

Procedure

UE motor function for novel task (#1) and (#2) was tested at the beginning of the baseline period prior to intervention and after two weeks of proximal bilateral training. All participants performed a session of baseline testing immediately prior to starting the intervention (see **Outcome Measures** section below). The two-week intervention period was followed immediately by post-testing of UE generalization of training to a novel task. As in Whitall et al.,[1] training was provided for 18 hours. However believing that intensity is important,[4-6] these hours were provided in 8 sessions of 2.25 hours each across 2 weeks for a total of 18 hours. Short term upper extremity practice has been shown to be effective in improving upper extremity motor function in persons post-stroke.[7, 8]

Table 2-1. Subject demographic data

Subject	Age (years) sd = 13.3	Gender	Years poststroke sd = 3.9	Side of Lesion	Lesion site	Fugl-Meyer* Pre
1	80	M	1	L CVA	L MCA, parietal/post frontal	24
2	49	M	1	L CVA	L subcortical infarct w/ hemorrhage conversion-basal ganglia internal capsule	51
3	80	F	3.5	R CVA	R MCA hemorrhage, hematoma R basal ganglia	48
4	59	M	7.4	R CVA	R MCA ischemic event	33
5	62	M	5.4	R CVA	R MCA posterior	51
6	68	M	11	R CVA	R cortical infarct	46
7	40	F	5.5	L CVA	L putamen hemorrhage	37
8	72	M	11.3	L CVA	L MCA posterior infarct	59
9	67	F	4.7	R CVA	R superior hyrus, striatocapsular infarct	64
10	67	M	4.8	L CVA	L frontal lobe hemorrhage w/atrophy	52
11	80	M	1.7	L CVA	L subcortical lacunar periventicular	43
12	38	F	1.8	L CVA	L MCA infarct, deep white matter insula frontal lobe, cortex F/P junction	35
13	64	F	3.8	L CVA	L infarct insula F/Temp/P convexity	18
14	75	M	13.5	L CVA	L MCA infarct	33

*Based on Fugl-Meyer scale (maximum score) =66,
CVA= cerebrovascular accident

Proximal bilateral training: The proximal bilateral exercise was identical to that performed in the study by Whitall and colleagues.[1] In this paradigm, participants were seated facing a table on which was placed the arm training machine-BATRAC consisting of two paddles mounted in nearly frictionless tracks.[1] The handles of the device are horizontally oriented and cylindrical in shape. The participants grab the handles of the paddles (with the affected hand strapped on as needed) and move the handles back and forth in a rhythmic manner for 5-minute blocks with 10-minute breaks between blocks to minimize fatigue. There was a chest plate that prevented the participant from leaning forward with trunk flexion when the handles were pushed away from the person's body. This chest plate was set at a distance of six inches from the table and the participant was asked to keep his/her trunk against this plate during the intervention periods. The distal stop on the BATRAC was lined up to the metacarpalphangeal joint (MCP) when the intact arm and fingers were extended directly in front of the body over the track. This corresponded to 80% of the reach. When active range of motion was limited at the elbow joint the distal stop on the BATRAC was set at the wrist joint initially and progressed to the MCP joint the second week. For half of the blocks, the participants moved the handles symmetrically (in-phase); while in the other half of the blocks the participants moved the handles 180˚ out of phase. These trials were alternated and balanced across subjects and sessions. Because movement of one paddle is independent of the other paddle, participants had to coordinate the movements of both UE's in order to achieve the correct temporal and spatial movement relationships. Participants were encouraged to move the full range of the exerciser and were assisted as needed by the researchers. Participants were asked to assume a comfortable self paced movement speed at the first session, which was maintained throughout the daily training session with the use of auditory cues provided by a metronome set at the self-selected frequency. The metronome was set at the beginning of each day of training to the participant's comfortable pace to prevent holding the individual back from making progress.

Object 2-1. BATRAC Inphase.

Object 2-2. BATRAC Antiphase

Outcome Measures

The primary hypothesis stated that in individuals with chronic stroke, bilateral training would generalize to a novel task that was *similar* in neural demands to the training but not to the *dissimilar* novel task. The dependent variables were divided into primary and secondary based on differences in spatial and temporal parameters. Knowing from the literature that movements in the upper extremity are affected by abnormal synergies post-stroke, we believed that the intervention (synchronous and alternating movements bilaterally) would effect the spatial parameter to a greater extent than temporal parameters by breaking up the abnormal synergies through more normal interlimb coupling.[8, 9] Therefore, the primary goal was to assess spatial generalization after bilateral training. The primary spatial dependent variable was HPT. The secondary hypothesis stated that bilateral training would improve the temporal dependent variables (MT1, MT2, TPV, PV and acceleration) after 2 weeks of intervention. The procedures for testing pre- and post-intervention follow.

Kinematic analysis of reaching

Participants were seated on a bench with the hip and knee angle at 90 degrees and the feet flat on the floor. Each participant was asked to position their buttocks and back against a straight edge held behind them to assure the same start position on the bench each testing period. The affected UE was positioned at rest, palm down, on a table placed in front of the person at the same distance as the intervention table including the chest plate distance of six inches. The UE was in neutral shoulder flexion/extension, rotation and adducted. The elbow was flexed as in the start position for the arm-training machine.

Novel Task #1(Similar)

The start position on a table in front of them was identical to the start position used for the training with the BATRAC however the arm-training machine was not used during novel task #1 nor was there a chest restraint. End targets at approximately 80% of reach were marked on the table at the same arm reach length (elbow extension in front of the body as measured to the metacarpalphalangeal joint or wrist joint determined during intervention) as in the arm-training machine (BATRAC). A reflective marker was placed on the target so the vicon motion analysis system could pick up the end point. Participants moved their arm and hand to the target and returned to the start position five times (Figure 2-1). The participants were not asked to point to the target but to simple reach to the target. To minimize fatigue, there was a 30 second rest break between reaches.

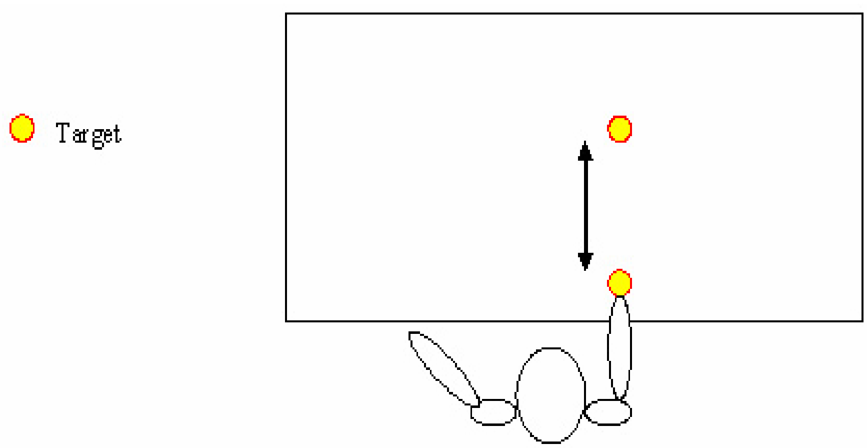

Figure 2-1. Illustration of testing conditions for similar spatial orientation novel task #1 (similar task)

Novel Task #2(Dissimilar)

The start position was on a table aligned with the paretic shoulder directly in front of the subject's body at the same distance from the trunk as in the BATRAC during intervention. The subjects were asked to move their arm and hand to a target on the table that was aligned horizontally with the start position and with the non-paretic shoulder at the near edge of the table and then return to the start position five times (Figure 2-2). A reflective marker was used so that the vicon motion analysis system could pick up the end point. There was no trunk restraint used during this testing condition. To minimize fatigue, there was a 30 second rest break between reaches.

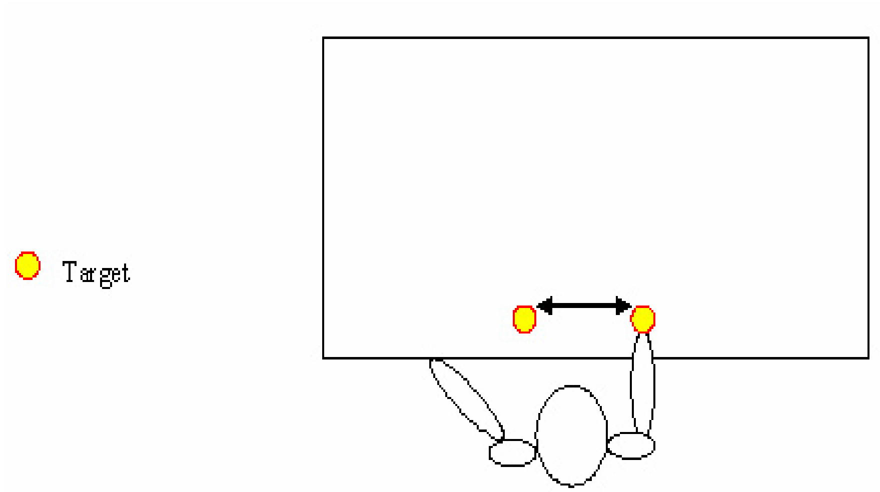

Figure 2-2. Illustration of testing conditions for dissimilar spatial orientation novel task #2 (dissimilar task)

Kinematics of reaches were videotaped using a 3-D movement recording system (8 camera Vicon system). Retro-reflective markers were placed on C_7 and T_{10} vertebrae, the acromion process, clavicle, sternum, upper arm, lateral epicondyle of the elbow, medial epicondyle of the affected UE, forearm, wrist condyles, dorsum of the hand, MCP joint of the index finger, and the index fingertip of the affected UE. The data was collected at 100 Hz. All data was averaged using the middle 3 trials for each novel task.

Kinematics were analyzed for hand path trajectories (end point paths measuring straightness of the hand path), movement time, time to peak velocity, peak velocity and acceleration as in Cirstea, et al., Cunningham et al., and McCrea et al.[9-12] Posteriori analysis of the velocity profiles to assess movement smoothness changes were performed as described by Rohrer et al.[13]

Primary Spatial Dependent Variable

1. To determine **hand path trajectory** (HPT), the ratio of the length of the actual path traveled by the index finger in three-dimensional space to the length of an ideal straight line joining the initial and final index finger positions was computed. If the participant was unable to extend the index finger, the trajectory was measured from a marker on the metacarpalphalangeal joint of the 2nd digit. The length index rather than the more usual perpendicular distance between the trajectory better captures trajectories that may deviate from the ideal straight line and may even intersect with that ideal line. Reach accuracy was computed as the root mean squared error of the absolute distance between the final endpoint position and the position of the target.

Secondary Temporal Dependent Variables

Temporal parameters in reaching post-stroke are significantly slower than healthy adults.[10-12] Therefore, although subjects were not asked to reach as quickly as possible during the testing tasks, the predictions are based on the assumption that the training intervention would increase their usual speed.

1. Movement time was the difference in time from movement onset to movement offset. Movement time 1 (MT1) was defined as the onset of movement from the start position to the touch of the target. A mark was made with tape to delineate the start position and target area based on the intervention position of the BATRAC arm-training machine. Movement time 2 (MT2) was defined as the movement onset from the target back to the start position. **2. Time to peak velocity** (TPV) was a measure of absolute time measured in seconds from the point of movement onset to peak velocity.

3. Peak velocity (PV) corresponds to a moment in time when the highest velocity is reached where acceleration is at or near zero at the changeover from the acceleration to the deceleration phase. PV is calculated from the rate of change over time.

4. Acceleration was calculated from the slope or inclination of the velocity curve and includes the percent of reach within this curve. Acceleration corresponds with the time period of movement onset to peak velocity.

Posteriori of velocity profiles

The following metrics were analyzed posteriori to assess the movement smoothness of the velocity profiles during the novel reaching task pre- and post-test.

1. Jerk metric – was calculated from the average value of the absolute jerk divided by the peak velocity of the corresponding trial (Jerk is defined as the rate of change of acceleration). Jerk metric is assigned a negative value so as the smoothness increases, the jerk metric also increases.

2. Speed metric – was calculated from the average velocity divided by the peak velocity of the corresponding trial. As the smoothness increases, speed metric also increases.

3. Movement arrest period ratio (MAPR) – was the amount of time that the velocity profile was less than 10% of the peak velocity divided by total time of the trial. A smaller MAPR indicates a smoother velocity profile.

4. **Peaks metric** – was the number of peaks in the velocity profile greater than 0.5m/s multiplied by negative 1. As the smoothness increases, the *peaks metric* increases.

5. **Tent metric** – was calculated from the area under the velocity profile curve divided by the area of a curve draped over the top of it. The closer tent metric is to 1, the smoother the velocity profile.

Data storage conformed to HIPAA regulations. VICON-captured data was stored in a database on a secure network. Participants were assigned a participant number and this number was the only identifier stored on these databases. A list of the participants' names and participant numbers was kept in a locked file in Dr Lorie Richard's office. Only the investigator and Dr Richards had access to this list. Only study personnel had access to the participant notebooks or the database.

Data Analysis

For each dependent variable a repeated measures 2 (time) x 2 (task) ANOVA was performed with an alpha level of .05. Greenhouse-Geisser's adjustment of degrees of freedom was applied to correct for small departures from the assumption of normality and equality of variance in the two-factor design. A Bonferroni correction factor was used to correct for multiple analyzes for the primary and secondary dependent variables. The corrected alpha level for the primary dependent variables was .05, secondary dependent variables was .01, and .01 for the posteriori analysis of the metrics. Lastly, a descriptive analysis of the individual data was performed post-hoc. The sample of this study was made up of a heterogeneous group of individuals with various levels of severity at baseline; therefore we decided to examine the data descriptively at the individual level, conjecturing that this could provide information on subgroups of individuals that may have benefited, but would not have been detected in the group analyses.

CHAPTER 3
RESULTS

Data Analysis

Kinematic outcomes were analyzed with a repeated measure ANOVA for each of the primary dependent variables. The within subjects factors were time (pre-test/post-test) and task condition (novel task #1 and novel task #2). The primary dependent variable was hand path trajectory. The secondary dependent variables were: 1) movement time, 2) time to peak velocity, 4) peak velocity and 5) the percentage of the reach that was acceleration.

An alpha value was set at .05 and corrected with Bonferroni to account for multiple analyses on the secondary and posteriori analysis. The corrected alpha levels on dependent variables were .01 for the secondary and the posteriori analysis of the velocity profiles. Individual data will be reported last to identify individual differences that may account for a pattern in the data.

Primary Spatial Dependent Variable

Table 3-1 displays the means and standard deviations for all outcome measures for primary and secondary dependent variables. Table 3-2 displays the ANOVA summary table.

Hypothesis 1a and 1b HPT will become straighter after intervention for novel task #1 (generalization of similar task). No change will be noted for HPT on novel task #2 (no generalization to dissimilar task).

Hand path trajectory

HPT was calculated as the ratio of the actual path traveled to the ideal straight line joining the initial and final positions for the index finger or metacarpalphalangeal joint of the 2nd digit (when subjects could not extend the index finger). There was a significant main effect of time for HPT with hand path trajectories straighter at posttest (Figure 3-1). However, there was no main effect of task nor interaction between the two variables. The increase in straightness was found for both novel task #1 and novel task #2. Therefore control of the spatial parameters of reach gained with intervention generalized to both similar and dissimilar tasks.

Secondary Temporal Dependent Variables

The main effects are reported below and means and sd are displayed in Table 3-1. The ANOVA summary table for the secondary dependent variables is displayed in Table 3-3.

Hypothesis 2a and 2b Generalization to novel task #1 following intervention will be evident with decreased movement times. No improvement in movement times will be demonstrated on novel task #2.

Movement time

Contrary to expectations, the time to touch the target (MT1) was not significantly different post compared to pre-intervention, nor across tasks. MT2, although shorter for novel task #1 compared to novel task #2, also did not change with intervention (Figure 3-2). There were no significant interaction effects of time and task on either variables.

The data for MT1 and MT2 did not support the hypothesis that there would be improvement in motor control on an untrained task with similar joint angles to the training task. Movement time at post-test was no shorter than at pre-test. Bilateral training did not appear to improve motor control during the performance of a task that was similar in terms of joint angles to the training task. Not surprisingly, no improvements in movement time were found for novel task #2, a task with dissimilar joint angles to the training task which was in support of the hypothesis.

Hypothesis 2a and 2b TPV will increase for novel task #1 following intervention: TPV will not change with novel task #2.

Time to peak velocity

TPV was measured from the point of movement onset to peak velocity. There was no difference in TPV across time or tasks. There were no significant interaction effects. Therefore, the training had no effect on the TPV.

Hypothesis 2a and 2b: PV will increase for novel task #1 and will not change for novel task #2 following 2 weeks of intervention.

Peak velocity

PV was the highest velocity that occurred during the reach. It typically occurs at the moment of changeover from acceleration to deceleration in reaching to a target. There was a significant main effect of time for PV (Figure 3-3) with PV larger following intervention for both novel tasks. There was no main effect of task nor interaction between time and task. Therefore, generalization of training was seen for similar and dissimilar tasks.

Hypothesis 2a and 2b The acceleration phase of the reach will approach 50% of the curve for novel task #1 and will not change for novel task #2 following 2 weeks of intervention.

Acceleration

There were no main effects or interaction effects noted for percentage of the reach in acceleration.

Posteriori of velocity profiles

Although this analysis was performed posteriori, changes in the smoothness of the velocity curve could be beneficial in interpreting data collected on the reaching pattern of individuals post stroke. An ANOVA summary table for the post hoc analysis is displayed in Table 3-4.

Changes in the metrics of the velocity profile would point toward a smoothing of the velocity curve following intervention indicating fewer stops and starts in the reaching pattern toward the target. Smoothness of the curve would infer that the coordination of the motor pattern for reaching has improved. There was a significant main effect of time for the Peaks Metric with improvement post-intervention however no main or interaction effects for task (Figure 3-4). In addition, there were no main or interaction effects for the remaining smoothness metrics.

Descriptive Individual Data

Although this analysis is posteriori, this individual data could be beneficial in planning future trials. Table 3-5 displays the individual data pattern of change across primary and secondary variables for each subject.

Individual differences were analyzed comparing the raw score difference from pre- to post-test with the pre-test sd for each dependent variable. Individuals who demonstrated a change at post-test greater than the sd for the dependent variables at pre-test are reported below. No subject improved in all variables with intervention. Interestingly in three of fourteen subjects no change for any dependent variable was noted and 4/14 subjects demonstrated a change in only one dependent variable. Five of fourteen subjects demonstrated differences greater than the sd of the pre-test on three or more variables. Thus, the descriptive individual data shows no general pattern across subjects or subsets of subjects. Training did not frequently foster change in similar tasks (novel task #1), but sometimes did in dissimilar tasks (novel task #2). In actuality change was infrequent across the board.

Object 3-2. Testing conditions for generalization indicated some individuals changed. Pre-test.

Object 3-3. Testing conditions for generalization indicated some individuals changed Post-test

Table 3-1. Displays the means and standard deviations (sd) for task condition # 1 and #2 for all dependent variables pre- and post-intervention.

		Task #1 *Similar* Mean (sd)	**Task #2** *Dissimilar* Mean (sd)
HPT	Pre	1.500 (.348)	1.406 (.350)
	Post	1.519 (.298)	1.264 (.114)
MT1	Pre	2.050 (1.692)	1.620 (.749)
	Post	1.976 (2.30)	1.275 (.512)
MT2	Pre	1.913 (.837)	2.838 (2.552)
	Post	1.666 (.885)	2.139 (1.828)
TPV	Pre	.446 (.190)	.431 (.153)
	Post	.368 (.618)	.403 (.153)
PV	Pre	.432 (.151)	.1.146 (1.389)
	Post	.497 (.284)	.887 (.258)
Accel	Pre	.332 (.213)	.314 (.112)
	Post	.317 (.147)	.374 (.153)

Table 3-2. Summary ANOVA model for the primary dependent variable. Significant p-value = 0..05

Dependent variable after two weeks of intervention

Source		**Mean Square**	**$F_{(1,13)}$**	**p-value**
HPT	Time	.426	8.132	.014
	Task	5.197	1.700	.215
	Time*Task	9.072	.901	.360

Table 3-3. Summary of ANOVA model the secondary dependent variables. Significant p-value = 0.01.

Dependent variables after two weeks of intervention

Source		**Mean Square**	**$F_{(1,13)}$**	**p-value**
MT 1	Time	4.48	2.248	.158
	Task	.614	.726	.410
	Time*Task	.260	.280	.606
MT 2	Time	6.84	1.897	.192
	Task	3.14	8.167	.013
	Time*Task	.714	1.076	.319
TPV	Time	1.491	.126	.728
	Task	4.022	3.439	.086
	Time*Task	1.143	.659	.427
PV	Time	4.274	8.205	.013
	Task	.130	.212	.653
	Time*Task	.767	.767	.397
Accel	Time	5.207	.392	.542
	Task	6.864	1.114	.311
	Time*Task	1.931	1.590	.229

Table 3-4. Summary ANOVA model for posteriori analysis of velocity profiles. Significant p-value = 0.01.

Source		**Mean Square**	**$F_{(1,13)}$**	**p value**
Jerk Metric	Time	1481.091	2.829	.116
	Task	659.802	1.033	.328
	Time*Task	415.415	.333	.574
Speed Metric	Time	2.5885	2.888	.113
	Task	1.355	3.663	.078
	Time*Task	8.377	.595	.454
MAPR	Time	1.779	.007	.936
	Task	1.525	.477	.502
	Time*Task	2.500	.396	.540
Peaks Metric	Time	4.767	16.476	.001
	Task	4.939	.470	.505
	Time*Task	1.796	.376	.550
Tent Metric	Time	4.408	1.053	.324
	Task	1.475	.093	.765
	Time*Task	4.378	2.021	.179

Table 3-5. Summary of individual change at post-test greater than the pre-test sd for each dependent variable (x > sd)

Subjects	FM-UE Pre/post	MT1	MT2	TMT	TPV	PV	HPT	Accel
1								
Task #1	24/28	**X**						
Task #2		**X**	**X**	**X**				
2								
Task #1	51/49		**X**	**X**	**X**	**X**		
Task #2		**X**				**X**		**X**
3								
Task #1	48/44							
Task #2								
4								
Task #1	33/38					**X**		
Task #2								
5								
Task #1	51/53							
Task #2								
6								
Task #1	46/45					**X**	**X**	**X**
Task #2								**X**
7								
Task #1	37/38	**X**			**X**			
Task #2						**X**		
8								
Task #1	59/62							
Task #2					**X**			
9								
Task #1	64/59							
Task #2								
10								
Task #1	52/61				**X**			
Task #2					**X**	**X**		
11								
Task #1	43/45				**X**			
Task #2					**X**			**X**
12								
Task #1	35/34				**X**		**X**	**X**
Task #2					**X**			
13								
Task #1	18/23							
Task #2				**X**				**X**
14								
Task #1	33/35							
Task #2					**X**			
% Change								
Task 1		2/14 (14%)	1/14 (7%)	1/14 (7%)	5/14 (36%)	3/14 (21%)	2/14 (14%)	2/14 (14%)
Task 2		2/14 (14%)	1/14 (7%)	2/14 (14%)	5/14 (36%)	2/14 (14%)	0/14 (0%)	4/14(29%)

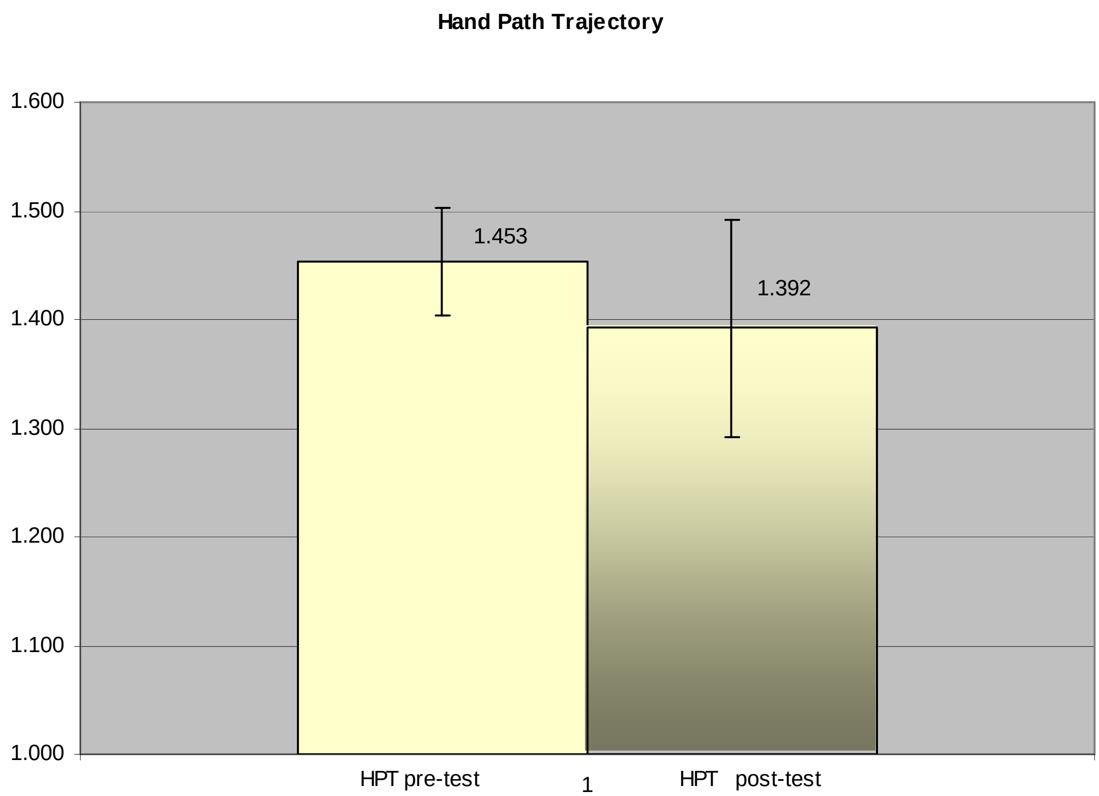

Figure 3-1. Significant main effect displayed for HPT for post-test. A value of 1 equals a straight line.

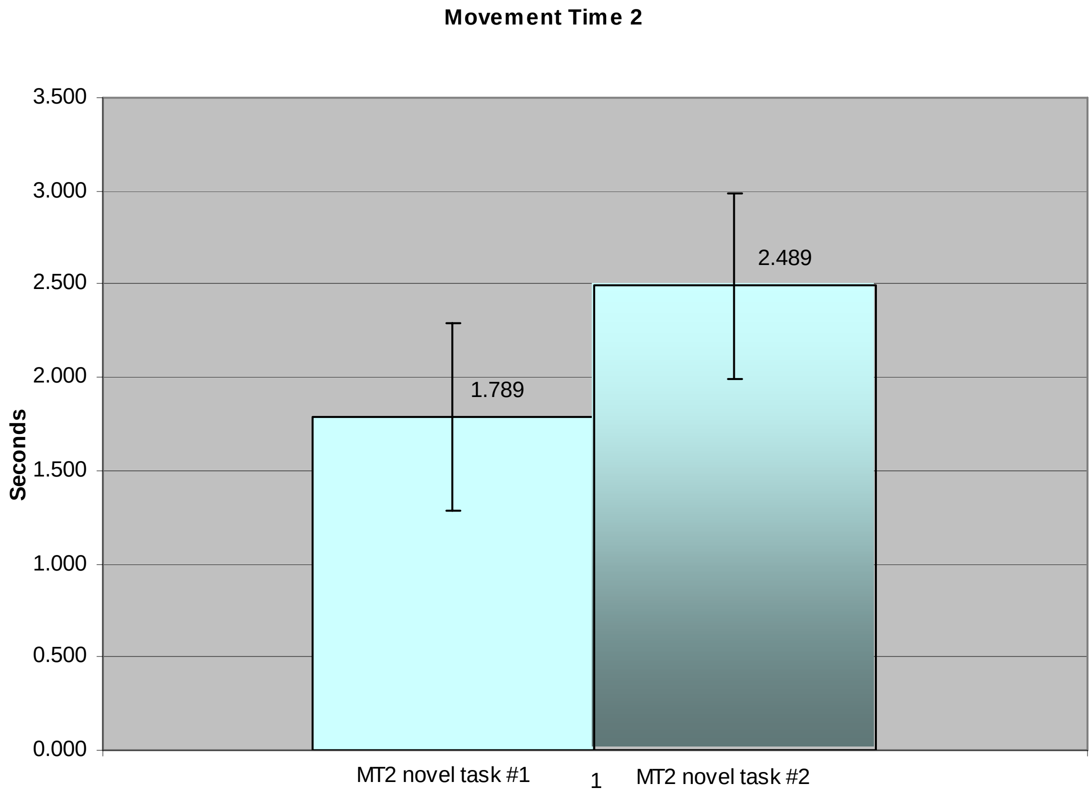

Figure 3-2. Significant main effect displayed for MT2 novel task #1.

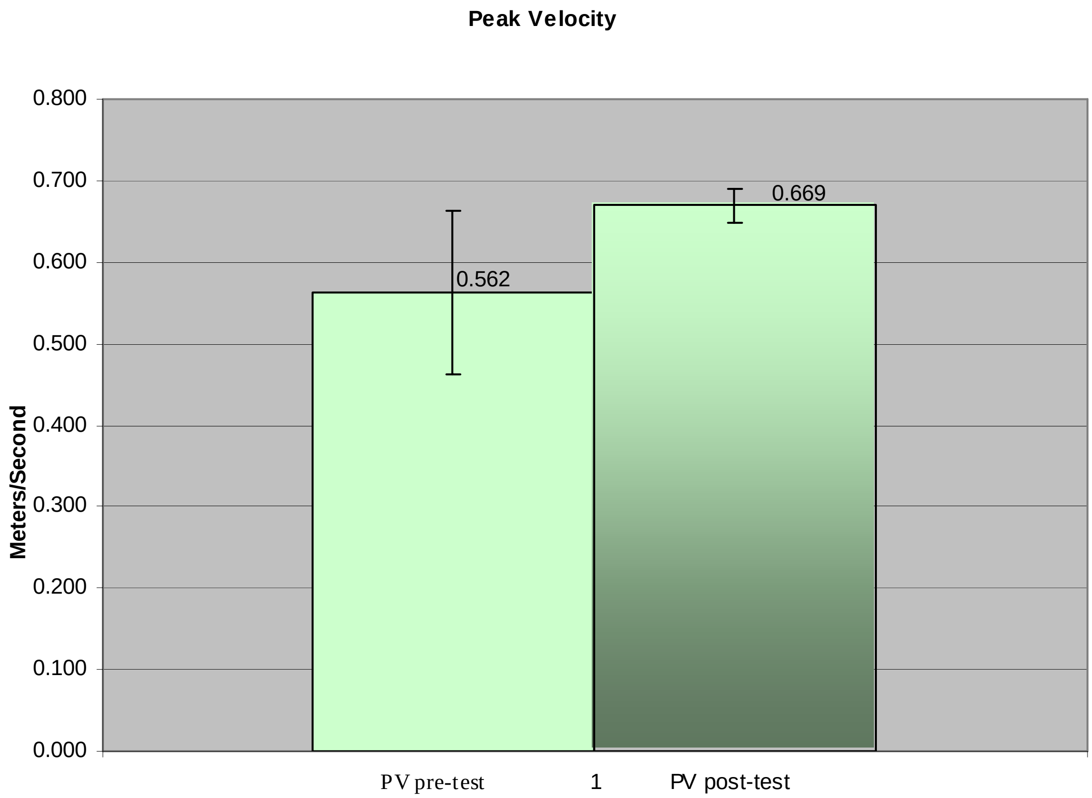

Figure 3-3. Significant main effect displayed for PV on the post-test.

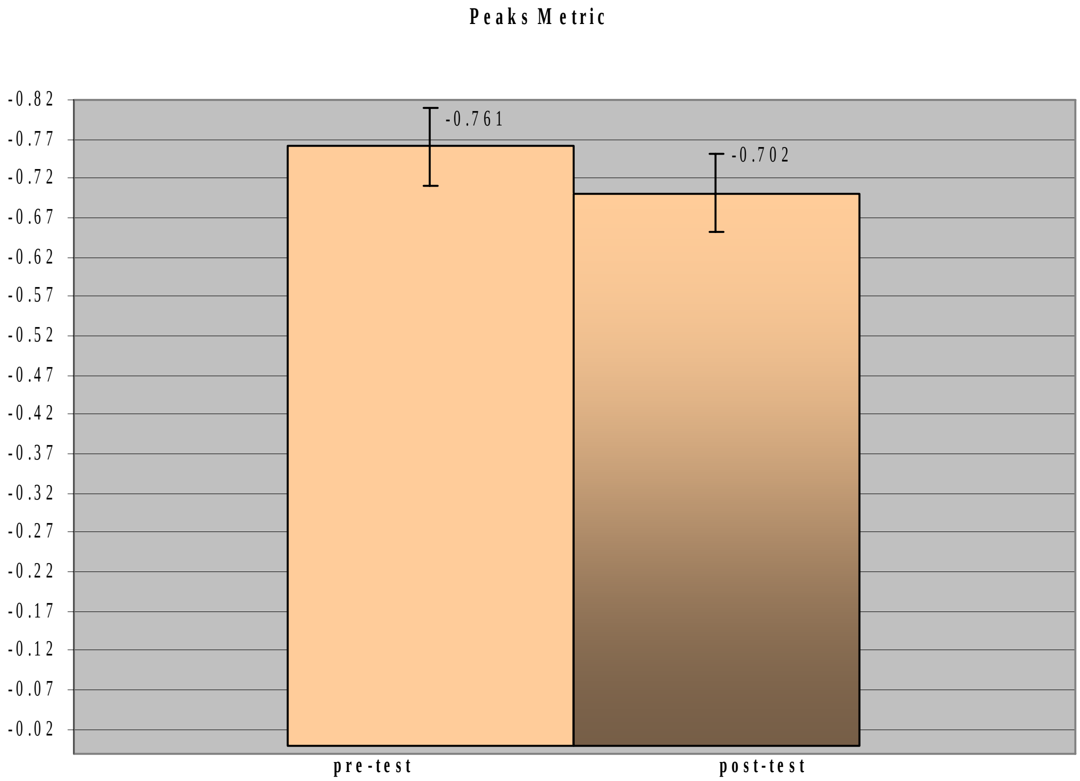

Figure 3-4. Significant main effect displayed for posteriori Peaks Metric post-test.

CHAPTER 4
DISCUSSION

Generalization is the ability to perform similar motor skills that were not specifically practiced as part of the training intervention. Generalization is directly related to the amount of practice on a particular task and how much motor learning occurred during the acquisition phase of the new the task. In addition, for neurologically intact individuals learning specific motor patterns, generalization occurs only under highly similar spatial conditions that have similar neural processing elements and demands.[1-3] We do not know if this is also true for the *basic* coordination skills that persons relearn after stroke. Persons post-stroke are just regaining the capacity to move and learning how to perform tasks with a decreased CMN pool output often their movements are influenced by pathological synergies. The critical components of invariant task features necessary for generalization of a motor skill in individuals with stroke under these conditions have not been clearly delineated in the literature. [1]

The specific aim of this study was to test spatial generalization of repetitive rhythmic bilateral training to two novel reaching tasks in individuals with stroke. The training task was a set of repetitive continuous movement reversals constrained by the BATRAC equipment which allowed only reaching forward in front of the body within a limited range (80% of the available reach). The transfer task (novel task #1) had similar neural demands for joint angles, workspace, visual gaze angles, and muscle timing compared to the training task but was not performed on the BATRAC. The second transfer task (novel task #2) had dissimilar joint angles, workspace, and visual gaze angles to the training task. It was predicted that improvements in kinematic parameters of movement gained through two weeks of intervention would generalize to the similar novel task #1 at post-test but not to the dissimilar novel task #2. Generalization occurred at post-test for HPT but surprisingly was equivalent across the similar and dissimilar tasks.. Generalization of training was further supported posteriori by the Peaks Metric that was also significant at post-intervention. The changes in dependent variables taken together indicate improved coordination with decreased stops and starts in the novel reaching tasks.

We also predicted that movement speed might also improve with training. In fact, peak velocity was also significant at post-test, with similar changes noted for both testing tasks. Perhaps, novel task #1 and novel task #2 did not present task features that were dissimilar enough to delineate a change between them kinematically post-intervention

The remaining temporal dependent variables of MT1, MT2, TPV, and acceleration did not generalize to either task. The lack of change in these particular temporal parameters may have been because speed of movement was not emphasized in the training or testing tasks. On the other hand, the higher PV suggests that for at least some of the reach, movements were faster. Perhaps subjects moved faster during parts of the reach, but slowed their movements in the remaining sections of the reach, resulting an overall unchanged movement time. Only a more detailed analysis of the reaching strategy would allow firm conclusion on this issue. Thus, the results of this study offer only weak evidence that repetitive rhythmic bilateral training may generalize to untrained tasks. Unfortunately there was no measure of actual intervention task learning in this study to delineate the lack of motor learning from the lack of generalization. Instrumentation of the BATRAC equipment would allow for measurement of the temporal coordination of the UE's providing more accurate measures of motor learning on the training task. This information could then be utilized to make further assumptions about motor learning of the intervention task compared to generalization of the novel transfer task.

Neuroscience Rationale for Repetitive Rhythmic Bilateral Training

The rationale for the potential of the BATRAC as an UE training tool post-stroke has been theorized to tap into basic neurophysiological mechanisms that stimulate coordinative structures priming the nervous system and firing up the CMN pool. Studies have shown activation of both hemispheres with bilateral movements that are organizing in a tight phasic relationship.[4-8]The symmetrical temporal relationship between the hemispheres during bilateral activities may assist in laying down a template for basic movement components necessary for reaching. However, neither the specific movement characteristics of bilateral practice necessary for generalization nor the level of severity of individuals post-stroke that would be most responsive to this type of therapy have been determined.[9]

The inconclusive findings of this present study are in contrast with the preliminary data regarding bilateral utilization presented in the literature.[10, 11] Using the BATRAC, Whitall et al.,[10] demonstrated significant improvement in UE motor performance on the FM and WMFT. The results in the Whitall et al.[10] study could be interpreted as generalization to untrained tasks since the items on these testing measures were not trained specifically in the bilateral intervention.

Luft et al.[11] showed that repetitive rhythmic bilateral training using the BATRAC influences neural mechanisms underlying motor skill in a small number of subjects. They found increased hemispheric activation during paretic arm movements after training.

Although the motor skill assessed by fMRI in this study was not a reaching task as was the transfer task in the present study, increased activity of the contralesional hemisphere was observed. The Luft et al.[11] study suggests that the BATRAC intervention induces reorganization of motor networks in persons post stroke and Whitall's[10] work further suggests that reaching post bilateral intervention may improve.

Differences in our subject population and the kinematic parameters selected as dependent variables could account for the different results observed in this study. Whitall et al.[10] used the FM and the WMFT to measure efficacy of bilateral training. These assessments are a composite of summary scores over multiple items. Looking more closely at the items that make up the assessments reveals that some items increase and some items do not, while other items may even decrease a little. Therefore the overall score can show improvement, while individual items themselves may not. This study focused on the kinematic measures of one single task only 2 tasks, one that was similar to the bilateral training. It is hard to compare the results of performance on only 2 tasks with summary scores on tests made up of many tasks. Perhaps had we chosen different tasks, we would have also found improvement across our subject sample. The task that was chosen demonstrated variability between subjects and overall did not show change across the multiple dependent variables, perhaps a different task or set of tasks may have. Ideally a combination of clinical, kinematic, and kinetic measures would give a more complete understanding of movement behaviors. Therefore, it is difficult if not impossible to compare the results of the Whitall et al.[10-12] studies with the present study due to the differences the nature of the outcome measures.

Factors Potentially Affecting the Study Results

Practice schedules are known to affect motor learning, and could possibly have played a role in our results.[13, 14] This study utilized a distributed model of practice as did Whitall et al.[10] Distributed practice allows for a rest period equal to or greater than the intervention period. In this study the intervention period equaled 5 minutes and the rest period 10 minutes. Studies by Lee and Genovese[15] have demonstrated in healthy individuals that transfer performance was increased for groups that had longer rest periods versus work periods. Other studies have also shown that distributed practice has a large positive effect on learning.[16, 17]

The intervention in this study was also delivered in a blocked manner (grouping like trials together) however, while blocked practice improves acquisition of a task, random practice appears to be superior for true learning: retention and generalization of the skill when tested after the training period of an intervention.[18-20] Although, Whitall et al.[10] demonstrated improved upper extremity functional measures with this type of practice (distributed blocked practice) during bilateral training on the BATRAC. The blocked practice schedule perhaps limited the degree of motor learning that occurred during the intervention and therefore, limited generalization to motor skills not practiced directly in the training. Introducing a distributed random practice schedule for the in/anti phase trials or randomly changing the metronome frequency on trials may have enhanced the amount of motor learning and thus generalization following this intervention. Random practice schedules increase the degree of problem solving during execution of the task by introducing variability in the practice and in turn enhance retention and generalization ultimately improving the amount of motor learning.[1]

Providing practice in a more condensed format (2 weeks versus 6 weeks) may have contributed to the study results. Whitall et al[10-12] provided the same training but distributed the practice over a longer period of time. Currently it is not known if condensed practice offers differential benefits compared with more distributed practice. Dettmers[21] found that CIMT distributed over 3 weeks with a shorter trial per day (3 hours/day) demonstrated improved UE function and quality of life in persons post-stroke. Page et al[22] also showed improved motor skills with a modified form of CIMT provided in a distributed fashion. However, no study has directly tested a condensed version against a more distributed version of an identical therapy to determine whether such practice distribution influences the amount of motor gains experienced in therapy. The difference in the distribution of practice between this study and Whitall's[10] may prove to be a critical factor in the resultant study outcomes and should be directly investigated in future research. The distribution and dose of practice to effect a change in motor learning in individuals post-stroke is clearly not understood.

Several additional aspects of this training may not have been optimal for motor learning. First, repetitive rhythmic bilateral training may not serve as a robust learning model since problem solving and the development of a reference of correctness of movement are not inherently strong or emphasized in the training. The environmental constraints of the BATRAC (the track and chest restraint) and repetitive nature of the practice may have resulted in low neural demands and little problem solving. The training was performed on a track that guided the spatial trajectory of the movements furthermore; sensory cueing was provided from a metronome, which was self-paced to a comfortable speed for the participant. This auditory cueing set up a temporal template for the individuals to match guiding the temporal parameters of the movements. Each end point stop provided kinesthetic cueing assisting with the timing of the reversal and indicated the proper extent of movement. Thus, the environment provided specific spatial and temporal features with predictable consequences, minimizing demands for problem solving.

 (A)  (B)

Figure 4-1. BATRAC invariant features, (A) in-phase and (B) anti-phase.

Introducing a margin for potential errors during the intervention might allow for increased problem solving during task learning which would facilitate the development of the capability to produce more effective movements and the ability to assess ones own movement behaviors. Error correction builds movement strategies and a larger repertoire of available movements to accomplish a task. Schmidt [1] has suggested that these aspects of motor learning are necessary to retrieve information from long-term memory for executing a motor skill. Shadmehr[23] would argue these components are critical for the formation of an internal model that would represent the physical dynamics of the limb and the workspace environment (where the motor skill is performed in relationship to the body/trunk/ upper extremities). Errors experienced in the training would influence the performance of the motor skill in an untrained but similar task, contributing to the performance of the generalization task after intervention. [1]

One could argue that learning to coordinate the two upper extremities for in-phase and anti-phase movement patterns as well as matching the metronome beat was practice that afforded some degree of problem solving with this intervention. In fact, observing participants during intervention revealed that indeed there was some difficulty in coordinating the two limbs to obtain and maintain the temporal phasing of the movement patterns as well as temporal matching with the metronome. However, temporal phasing and matching were often accomplished with manual guidance of the therapist which has been shown to improve performance during the task but not improve motor learning.[1, 3] Thus, the degree of problem solving and development of a reference of correctness during the intervention may not have been sufficient enough for motor learning and generalization to a novel untrained similar task. If this is true, it is not surprising that little generalization was found.

Another potential factor affecting the results was that perhaps subjects were not very engaged in the learning task. The nature of repetitive rhythmic bilateral training on the BATRAC was similar to an exercise with multiple repetitions versus meaningful functional task practice. Practicing real life tasks that are motivating to the individual has been shown to improve acquisition of a motor skill. Wu et al.[24]demonstrated better kinematic performance of reaching movements to real objects when compared to movements without relevant objects in persons post-stroke. Nelson et al.[25] studied the effects of an occupationally embedded exercise on bilaterally assisted supination in persons post-stroke. Significant results were found for the group receiving real life (meaningful) practice compared to rote exercise of the same task. Because the BATRAC lacked meaningful practice, the intervention may have held little motivation for the participants. Perhaps the results of this intervention would be strengthened if such bilateral, repetitive exercise were combined with functional task practice that provides motivation and meaning for the participants for real life skills improving their motor learning outcome.

Generalization is bolstered when the invariant features are similar between the training intervention and the novel transfer task. Invariant features of a motor task consist of the unique traits and rules that are particular to that task. The components chosen as critical in this study: similar neural demands, joint angles, workspace, angle of visual gaze, and muscle and joint synergies, may not have been similar enough for generalization to consistently occur across the selected kinematic outcome measures. Motor learning, generalization, and retention of a task are strengthened when the training is varied.[1, 3] The movement of the upper extremities on the BATRAC did not allow for diversified movement and therefore there was little room for error detection and the development of a reference of correction. This intervention involved little to no interaction with the environment since the objects in the environment did not change from one attempt to the next. The subject held a handle or was strapped to the handle on the BATRAC, which offered some degree of weight bearing on the apparatus, and therefore training motions were closed chain movements. The individual was assisted to the end point stops if they were unable to complete the task independently. The trunk of the individual was blocked from forward flexion by a chest plate and proximal arm motion was encouraged to complete the task. The demands of the task were externally paced, predictive; the movement was fixed within a particular range and repetitive in nature requiring minimal monitoring by the participant. Although most subjects attempted to stay in time with the metronome they were assisted with verbal cues and occasional manual assistance to coordinate their movements with the beat of the metronome.

Novel transfer task #1 was chosen because it had many of the characteristics thought to be important for generalization to occur. The workspace, visual gaze angles to the target, and joint angles required during the test reaches were identical to the training intervention utilizing similar muscle and joint synergies to perform the task (novel task #2 was dissimilar in these parameters). Schmidt[1] et al have demonstrated that these components are necessary for a motor skill to generalize to a novel untrained task.[1] While the lack of generalization may have been due to a lack of learning altogether, the similar transfer task had other features that were different from the intervention task, which possibly contributed to the limited generalization.

The transfer task may have required different processing compared to the training task. Unlike the training intervention there was no track or chest restraint utilized in the generalization task. The transfer task was a discrete unilateral reaching movement made in free space with the affected upper extremity to the target and back to the start position. The only environmental sensory cues were visual in nature: the target and the start position. No auditory cueing was used other than a verbal cue to begin the movement. The transfer task required transport of the upper extremity through space against gravity to the target and back to the start position. One could postulate that both transfer tasks required greater muscle force to move the limb against gravity then was needed in the training task although these data were not collected in this study. Certainly more variations in the movement pattern were available as there were an increased number of df at upper extremity joints as with the trunk in order to control the transfer task. Controlling such increased df in the transfer task was quite different than during training with the BATRAC as an environmental constraint and the chest plate limiting trunk forward lean. Allowing diversified movement within the execution of the novel task may have increased the requirements for attentional demands, neural control, problem solving, and error correction which were not inherent in the intervention. The transfer task required focused attention on the target, control of the upper extremity through space, and proprioception (to avoid over or under reaching) unlike the training on the BATRAC where movements were guided by the track and kinesthic cues were provided by the distal stops.

Summary

Examination of the invariant features reveals differences in the intervention-training task and the transfer task that may help to account for the lack of generalization across the dependent variables. Moving the arm fully through space required controlling many df which was clearly not something that was trained. Although some of the environmental constraints were similar: workspace, visual gaze angles; the change from a closed chain movement in the training intervention to an open chain movement and increased movement possibilities on the transfer task introduced an increased demand on the muscular and neural systems as well as the need to problem solve the execution of the task against gravity.

Identifying the specific features of the repetitive rhythmic bilateral intervention that will foster generalization to an untrained motor skill in stroke has yet to be determined. The training may not have provided a strong enough training stimulus or the components chosen as critical in this study: similar neural demands, joint angles, workspace, angle of visual gaze, muscle and joint synergies may not have been similar enough for generalization to consistently occur across the selected kinematic outcome measures. A lack of complexity in this intervention in regard to decreased demands to problem solve and lack of development of a reference of correctness may have influenced the amount of motor learning and further restricted generalization of the intervention to a similar reaching task.

Limitations to the Study

This study was composed of a heterogeneous group of subjects therefore the statistical power was influenced by the variance between the subjects (Tables 3-2 and 3-3). A small sample size (n=14) makes it difficult to draw conclusions about the population in the study and results in a substantial reduction in power. Multiple analyses on dependent variables were performed but adjusted with a Bonferroni correction resulting in a more conservative alpha value further reducing the power. Previous bilateral studies have used small sample sizes and demonstrated significant results on motor outcome measures but kinematic outcomes have not been reported. Calculating power at .80 for subsequent studies of this type of bilateral training with the same dependent variables would require 1050 subjects for significant results. To counter the violations to the assumption of normality a larger sample size and homogenous sample would be beneficial in subsequent studies. A homogenous sample in the stroke population may be difficult to achieve due to the variability of the insult to the CNS.

The inclusion criteria for this study were broad including subjects that had only palpable extrinsic forearm finger muscle activity and some active shoulder and elbow motion. Although this intervention was focused on proximal joint and muscle effector systems and did not train grasp, perhaps the criteria should be modified to include some degree of finger and hand motion indicating more motor recruitment in the upper extremity. The inclusion criteria also did not include the ability to move the UE against gravity a specified degree, which was an inherent part of the transfer tasks and may have affected the amount of generalization measured at posttest.

Future Studies

Some individuals may have improved with the intervention however delineating the variables that would discriminate those who might improve from those who might not improve were limited. Measures to assess multiple factors that potentially could influence each subjects' baseline and post-testing should be considered: 1) strength in the upper extremity, 2) coordinative patterns /muscle joint synergies during movement 3) spasticity, 4) praxis 5) executive functioning, 6) motor learning style (spatial/temporal), and 7) sensory/proprioceptive status of the affected limb. Collecting the above data of the participants' capability would further help to assess which subjects were able to benefit the most from this therapy. Although the side of the lesion was not used as exclusionary criteria in this study, it has been documented that individuals with a left-sided lesion have more difficulty with rhythm keeping. [26-29] However, McCombe Waller and Whitall[12]demonstrated that persons post-stroke with left-sided lesions improved greater than persons with right-sided lesions during intervention with the BATRAC. Use of a metronome in the intervention training sessions may affect the results for particular subjects by cueing a temporal pace or disadvantageous by creating interference during the acquisition period of learning where abstract neural signals are transformed into long-term memory for retrieval at a later time for execution.[1, 23] In our study, nine subjects had left-sided lesions and five had right-sided lesions (Table 2-1). Although no clear pattern of interference or advantage was evident from the individual data this should be a consideration in future studies. Assessing the issue of interference of the metronome or other rhythm keeper used in interventions during the acquisition stage of learning may be advantageous and revealing when evaluating the results.

Models of the relationship of the dependent variables to each other are not clearly developed in the field of movement science for the typical population and are evolving for the stroke population. The numbers of possible kinematic variables and lack of a model make it difficult to pick just one or two that are expected to change or which would be the most important for function. The reliability and validity of kinematic measures in the stroke population has not been established and therefore the stability of the measures has not been substantiated.[30] There was no obvious pattern among individuals in regard to severity of involvement that predicted which subjects would improve and on what kinematic outcomes in this study. Several investigators have theorized that smoothness of the velocity profile demonstrates improved coordination of the reaching movement with a decrease in stops and starts in the pattern of reaching in healthy individuals and persons post-stroke.[31-34] This supposition would connect the kinematic variables of PV, HPT, and smoothness metrics, all contributing to the understanding of coordination and quality of reaching ability in persons post-stroke.[30, 35-37] Investigation into the correlation among these kinematic variables related to performance on reaching tasks might allow selection of the most sensitive measures and the prediction in their change after intervention.

Conclusions

This study specifically tested generalization of repetitive rhythmic bilateral training to a similar novel task rather than the overall efficacy or motor learning in upper extremity function. The kinematic results suggest that at a basic level repetitive rhythmic bilateral training in and of itself are not enough to effect a change in motor control, specifically generalization to an untrained novel motor skill across multiple dependent variables. The novel task may not have held enough of the invariant features of the training task to truly test generalization of this intervention. The importance of task analysis of the invariant task features defined for the intervention versus the transfer task cannot be underestimated. Identification of the critical components of the invariant features necessary for generalization in the stroke population has yet to be determined. The adequacy of the intervention in providing an opportunity for motor learning involving problem solving and the development of a reference of correction without the connection of real life practice should be scrutinized further. Lastly, the distribution of practice on a continuous task may affect motor learning and the resultant outcomes and should be investigated to determine optimal dosage during interventions post-stroke.

LIST OF REFERENCES

1. American Heart Association. Know the facts/Get the Stats. Available at: http://www.americanheart.org. (Last accessed, April 2006)

2. Mayo NE, Wood-Dauphinee S, Ahmed S, Gordon C, Higgins J, McEwen S, Salbach N. Disablement following stroke. *Disability and Rehabilitation.* May-Jun 1999;21(5-6):258-268.

3. Nakayama H, Jorgensen HS, Raaschou HO, Olsen TS. Recovery of upper extremity function in stroke patients: the Copenhagen Stroke Study. *Archives of Physical Medicine Rehabilitation.* Apr 1994;75(4):394-398.

4. Duncan P, Studenski S, Richards L, Gollub S, Lai SM, Reker D, Perera S, Yates J, Koch V, Rigler S, Johnson D. Randomized clinical trial of therapeutic exercise in subacute stroke. *Stroke.* Sep 2003;34(9):2173-2180.

5. Chen R, Cohen LG, Hallett M. Nervous system reorganization following injury. *Neuroscience.* 2002;111(4):761-773.

6. Hallett M. Plasticity of the human motor cortex and recovery from stroke. *Brain Res Brain Res Rev.* Oct 2001;36(2-3):169-174.

7. Shumway-Cook A, Woollacott MH. *Motor control : theory and practical applications*. 2nd ed. Philadelphia: Lippincott Williams & Wilkins; 2001.

8. Kandel ER, Schwartz JH, Jessell TM. *Principles of neural science*. 4th ed. New York McGraw-Hill, Health Professions Division, c2000.; 2000.

9. Schimidt R, Lee TD. *Motor control and learning: a behavioral emphasis*. 4th ed. Champaign, IL: Human Kinetics; 2005.

10. Kelso JA. Phase transitions and critical behavior in human bimanual coordination. *Am J Physiol.* Jun 1984;246(6 Pt 2):R1000-1004.

11. Kelso JA. On the oscillatory basis of movement. *Bulletin of the Psychonomic Society.* 1981;18:63.

12. Tanji J, Okano K, Sato KC. Neuronal activity in cortical motor areas related to ipsilateral, contralateral, and bilateral digit movements of the monkey. *Journal of Neurophysiology.* Jul 1988;60(1):325-343.

13. Debaere F, Wenderoth N, Sunaert S, Van Hecke P, Swinnen SP. Changes in brain activation during the acquisition of a new bimanual coodination task. *Neuropsychologia.* 2004;42(7):855-867.

14. Debaere F, Wenderoth N, Sunaert S, Van Hecke P, Swinnen SP. Cerebellar and premotor function in bimanual coordination: parametric neural responses to spatiotemporal complexity and cycling frequency. *Neuroimage.* Apr 2004;21(4):1416-1427.

15. Gerloff C, Andres FG. Bimanual coordination and interhemispheric interaction. *Acta Psychology (Amst).* Jun 2002;110(2-3):161-186.

16. Stinear JW, Byblow WD. Rhythmic bilateral movement training modulates corticomotor excitability and enhances upper limb motricity poststroke: a pilot study. *J Clin Neurophysiol.* Mar-Apr 2004;21(2):124-131.

17. Byblow WD, Lewis G, Stinear J, Carson RG. The modulation of excitability in corticospinal pathways during rhythmic movement. In: Swinnen SP, Duysens, eds. *Neuro-behavioral determinants of interlimb coordination - A multidisciplinary approach*. Boston: Kluwer Acdemic publishers; 2004:155-185.

18. Luft AR, McCombe-Waller S, Whitall J, Forrester LW, Macko R, Sorkin JD, Schulz JB, Goldberg AP, Hanley DF. Repetitive bilateral arm training and motor cortex activation in chronic stroke: a randomized controlled trial. *Jama.* Oct 20 2004;292(15):1853-1861.

19. Wyller TB, Sveen U, Sodring KM, Pettersen AM, Bautz-Holter E. Subjective well-being one year after stroke. *Clinical Rehabilitation.* May 1997;11(2):139-145.

20. Umphred D. Merging neurophysiologic approaches with contemporary theories: setting the stage for discussion. In: Lister MJ, ed. *Contemporary management of motor control problems: proceedings of the II STEP conference*. Alexandria, Va: Foundation for Physical Therapy; 1991:127-140.

21. Bobath B. Treatment of adult hemiplegia. *Physiotherapy.* Oct 1977;63(10):310-313.

22. Brunnstrom S. *Movement therapy in hemiplegia; a neurophysiological approach*. Philadelphia, PA: Harper and Row; 1970.

23. Adler S, Beckers D, Buck M. *PNF in practice: an illustrated guide*. 2nd ed. New York: Springer; 2000.

24. Davies P, M. *Steps to follow: the comprehensive treatment of patients with hemiplegia*. 2nd ed: Springer; 2000.

25. Singer R. *Motor learning and human performance*. 3rd ed. New York: Macmillan; 1980.

26. Winstein CJ, Merians AS, Sullivan KJ. Motor learning after unilateral brain damage. *Neuropsychologia.* Jul 1999;37(8):975-987.

27. Brown G, Burns S. *The efficacy of neurodevelopmental treatment in paediatrics: A systematic review*. 2001.

28. Fetters L, Kluzik J. The effects of neurodevelopmental treatment versus practice on the reaching of children with spastic cerebral palsy. *Phys Ther.* Apr 1996;76(4):346-358.

29. Salter J, Y C, LL P, LC M. Rehabilitation nursing approaches to cerebrovascular accident: A comparison of two approaches. *Rehabilitation Nursing.* Mar-Apr 1991;16:2(62).

30. Waganaar R, Meijer O, van Wieringen P, Kuik D, Hazenberg G, Lindeboom J, Wichers F, Rijswijk H. The functional recovery of stroke: A comparison btween neuro-developmental treatment and the brunnstrom method. *CScand J Rehab Med.* 1990;22:1-8.

31. Horak F. Assumptions underlying motor control for neurologic rehabilitation. In: Lister MJ, ed. *Contemporary management of motor control problems: proceeding of the II STEP conference*. Alexandria, Va: Foundation for Physical Therapy; 1991:11-27.

32. Cech D, Martin S, eds. *Functional movement development across the life span.* 2nd ed. Philadelphia W.B. Saunders; 2002.

33. Nudo RJ, Wise BM, SiFuentes F, Milliken GW. Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct. *Science.* Jun 21 1996;272(5269):1791-1794.

34. Cramer SC, Nelles G, Benson RR, Kaplan JD, Parker RA, Kwong KK, Kennedy DN, Finklestein SP, Rosen BR. A functional MRI study of subjects recovered from hemiparetic stroke. *Stroke.* Dec 1997;28(12):2518-2527.

35. Cao Y, D'Olhaberriague L, Vikingstad EM, Levine SR, Welch KM. Pilot study of functional MRI to assess cerebral activation of motor function after poststroke hemiparesis. *Stroke.* Jan 1998;29(1):112-122.

36. Matthews PM, Johansen-Berg H, Reddy H. Non-invasive mapping of brain functions and brain recovery: Applying lessons from cognitive neuroscience to neurorehabilitation. *Restor Neurol Neurosci.* 2004;22(3-5):245-260.

37. Donchin O, Cardoso de Oliveira S. Electrophysiological approaches to bimanual coordination in primates. In: Swinnen S, Duysens J, eds. *Neuro-behavioral determinants of interlimb coordination: a multidisciplinary approach*. Dordrecht, The Netherlands: Kluwer Academic Publishers; 2004:131-153.

38. Liepert J, Bauder H, Wolfgang HR, Miltner WH, Taub E, Weiller C. Treatment-induced cortical reorganization after stroke in humans. *Stroke.* Jun 2000;31(6):1210-1216.

39. Nudo RJ. Adaptive plasticity in motor cortex: implications for rehabilitation after brain injury. *J Rehabil Med.* May 2003(41 Suppl):7-10.

40. Nudo RJ. Functional and structural plasticity in motor cortex: implications for stroke recovery. *Phys Med Rehabil Clin N Am.* Feb 2003;14(1 Suppl):S57-76.

41. Friel KM, Heddings AA, Nudo RJ. Effects of postlesion experience on behavioral recovery and neurophysiologic reorganization after cortical injury in primates. *Neurorehabilitation and Neural Repair.* 2000;14(3):187-198.

42. Kleim JA, Barbay S, Nudo RJ. Functional reorganization of the rat motor cortex following motor skill learning. *Journal of Neurophysiology.* Dec 1998;80(6):3321-3325.

43. Nudo RJ, Friel KM. Cortical plasticity after stroke: implications for rehabilitation. *Rev Neurol (Paris).* 1999;155(9):713-717.

44. Calautti C, Baron JC. Functional neuroimaging studies of motor recovery after stroke in adults: a review. *Stroke.* Jun 2003;34(6):1553-1566.

45. 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.* Mar 17 1999;10(4):807-810.

46. Schaechter JD, Kraft E, Hilliard TS, Dijkhuizen RM, Benner T, Finklestein SP, Rosen BR, Cramer SC. Motor recovery and cortical reorganization after constraint-induced movement therapy in stroke patients: a preliminary study. *Neurorehabil Neural Repair.* Dec 2002;16(4):326-338.

47. 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.* Feb 2003;14(1 Suppl):S77-91, ix.

48. Liepert J, Miltner WH, Bauder H, Sommer M, Dettmers C, Taub E, Weiller C. Motor cortex plasticity during constraint-induced movement therapy in stroke patients. *Neuroscience Letters.* Jun 26 1998;250(1):5-8.

49. Levy CE, Nichols DS, Schmalbrock PM, Keller P, Chakeres DW. Functional MRI evidence of cortical reorganization in upper-limb stroke hemiplegia treated with constraint-induced movement therapy. *Am J Phys Med Rehabil.* Jan 2001;80(1):4-12.

50. Jang SH, Kim YH, Cho SH, Lee JH, Park JW, Kwon YH. Cortical reorganization induced by task-oriented training in chronic hemiplegic stroke patients. *Neuroreport.* Jan 20 2003;14(1):137-141.

51. Magill R, Hall K. A review of the contextual interference effect in motor skill acquistion. *Hum Mov Sci.* 1990;9:241-289.

52. Winstein C. Designing practice for motor learning: Clinical implications. *Contemporary management of motor control problems: proceedings of the II STEP conference.* Alexandria, VA: Foundations in Physical Therapy; 1991:65-76.

53. Hanlon RE. Motor learning following unilateral stroke. *Arch Phys Med Rehabil.* Aug 1996;77(8):811-815.

54. Winstein CJ. Knowledge of results and motor learning--implications for physical therapy. *Phys Ther.* Feb 1991;71(2):140-149.

55. Schmidt RA. Motor learning principles for physical therapy. *Contemporary management of motor control problems. proceedings of the II Step conference.* Alexandria, VA: Foundation for Physical Therapy; 1991:49-63.

56. Turton A, Fraser C, Flament D, Werner W, KMB B, Lemon RN. Organisation of cortico-motoneuronal projections from the primary motor cortex: evidence for task-related funciton in monkey and man. In: Thilmann, al e, eds. *Spasticity: Mechanisms and Management*. Berlin: Springer-Verlag; 1993:8-24.

57. Cauraugh JH, Kim SB. Stroke motor recovery: active neuromuscular stimulation and repetitive practice schedules. *Journal of Neurology, Neurosurgery, and Psychiatry.* Nov 2003;74(11):1562-1566.

58. Cauraugh JH, Kim SB. Stroke motor recovery: active neuromuscular stimulation and repetitive practice schedules. *J Neurol Neurosurg Psychiatry.* Nov 2003;74(11):1562-1566.

59. Sainburg RL, Ghez C, Kalakanis D. Intersegmental dynamics are controlled by sequential anticipatory, error correction, and postural mechanisms. *J Neurophysiol.* Mar 1999;81(3):1045-1056.

60. Shadmehr R, Moussavi ZM. Spatial generalization from learning dynamics of reaching movements. *J Neurosci.* Oct 15 2000;20:7807-7815.

61. Hesse S, Schulte-Tigges G, Konrad M, Bardeleben A, Werner C. Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects. *Arch Phys Med Rehabil.* Jun 2003;84(6):915-920.

62. Mudie MH, Matyas TA. Can simultaneous bilateral movement involve the undamaged hemisphere in reconstruction of neural networks damaged by stroke? *Disability and Rehabilitation.* Jan 10-20 2000;22(1-2):23-37.

63. 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.* Oct 2000;31(10):2390-2395.

64. Platz T, Bock S, Prass K. Reduced skilfulness of arm motor behaviour among motor stroke patients with good clinical recovery: does it indicate reduced automaticity? Can it be improved by unilateral or bilateral training? A kinematic motion analysis study. *Neuropsychologia.* 2001;39(7):687-698.

65. Stinear JW, Byblow WD. Disinhibition in the human motor cortex is enhanced by synchronous upper limb movements. *Journal of Physiology.* Aug 15 2002;543(Pt 1):307-316.

66. Kelso JA, Holt KG, Ruben P, Kugler P. Patterns of human interlimb coordination emerge form the properties of non-linear limit cycle oscillatory proceses: theory and data. *Journal of Motor Behavior.* 1981;13:226-261.

67. Criscimagna-Hemminger SE, Donchin O, Gazzaniga MS, Shadmehr R. Learned dynamics of reaching movements generalize from dominant to nondominant arm. *J Neurophysiol.* Jan 2003;89(1):168-176.

68. Werhahn KJ, Conforto AB, Kadom N, Hallett M, Cohen LG. Contribution of the ipsilateral motor cortex to recovery after chronic stroke. *Ann Neurol.* Oct 2003;54(4):464-472.

69. Temprado JJ, Swinnen SP. Dynamics of learning and transfer of muscular and spatial relative phase in bimanual coordination: evidence for abstract directional codes. *Exp Brain Res.* Jan 2005;160(2):180-188.

70. Welsh TN, Almeida QJ, Lee TD. The effect of postural stability and spatial orientation of the upper limbs on interlimb coordination. *Exp Brain Res.* Mar 2005;161(3):265-275.

71. Sainburg RL, Wang J. Interlimb transfer of visuomotor rotations: independence of direction and final position information. *Exp Brain Res.* Aug 2002;145(4):437-447.

72. Sunderland A, Tinson DJ, Bradley EL, Fletcher D, Langton Hewer R, Wade DT. Enhanced physical therapy improves recovery of arm function after stroke. A randomised controlled trial. *Journal of Neurology, Neurosurgery, and Psychiatry.* Jul 1992;55(7):530-535.

73. Sterr A, Elbert T, Berthold I, Kolbel S, Rockstroh B, Taub E. Longer versus shorter daily constraint-induced movement therapy of chronic hemiparesis: an exploratory study. *Archives of Physical Medicine and Rehabilitation.* Oct 2002;83(10):1374-1377.

74. Ouellette MM, LeBrasseur NK, Bean JF, Phillips E, Stein J, Frontera WR, Fielding RA. High-intensity resistance training improves muscle strength, self-reported function, and disability in long-term stroke survivors. *Stroke.* Apr 22 2004;35:1404-1409.

75. McCrea PH, Eng JJ, Hodgson AJ. Biomechanics of reaching: clinical implications for individuals with acquired brain injury. *Disabil Rehabil.* Jul 10 2002;24(10):534-541.

76. Cunningham CL, Stoykov ME, Walter CB. Bilateral facilitation of motor control in chronic hemiplegia. *Acta Psychol (Amst).* Jun 2002;110(2-3):321-337.

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

78. Cirstea MC, Mitnitski AB, Feldman AG, Levin MF. Interjoint coordination dynamics during reaching in stroke. *Experimental Brain Research.* Aug 2003;151(3):289-300.

79. Rohrer B, Fasoli S, Krebs HI, Hughes R, Volpe B, Frontera WR, Stein J, Hogan N. Movement smoothness changes during stroke recovery. *J Neurosci.* Sep 15 2002;22(18):8297-8304.

80. McCombe Waller S, Whitall J. Hand dominance and side of stroke affect rehabilitation in chronic stroke. *Clin Rehabil.* Aug 2005;19(5):544-551.

81. Shea CH, Kohl RM. Specificity and variability of practice. *Res Q Exerc Sport.* Jun 1990;61(2):169-177.

82. Shea CH, Kohl RM. Composition of practice: influence on the retention of motor skills. *Res Q Exerc Sport.* Jun 1991;62(2):187-195.

83. Lee TD, Genovese ED. Distribution of practice in motor skill acquisition: different effects for discrete and continuous tasks. *Res Q Exerc Sport.* Mar 1989;60(1):59-65.

84. Ammons R. Acquisition of motor skill: III. Effects of initiallly distributed practice on rotary pursuit performance. *Psychology.* 1950;40:777-787.

85. Reynolds B, Bilodeau I. Acquisition and retention of three psychomotor tests as a function of distribution of practice during acquisition. *Journal of Experimental Psychology.* 1952;44:19-26.

86. Tsutsui S, Lee TD, Hodges N. Contextual interference in learning new patterns of bimanual coordination. *Journal of Motor Behavior.* 1998;30:151-157.

87. Newell KM, McDonald P. Practice: A serach for task solutions. *American Academy of Physical Education, Enhancing human performance in sport: New concepts and developments.* Vol 25. Champaign, IL: Human Kinetics; 1992:51-59.

88. Shadmehr R. Generalization as a behavioral window to the neural mechanisms of learning internal models. *Hum Mov Sci.* Nov 2004;23(5):543-568.

89. Wu C, Trombly CA, Lin K, Tickle-Degnen L. A kinematic study of contextual effects on reaching performance in persons with and without stroke: influences of object availability. *Arch Phys Med Rehabil.* Jan 2000;81(1):95-101.

90. Nelson DL, Konosky K, Fleharty K, Webb R, Newer K, Hazboun VP, Fontane C, Licht BC. The effects of an occupationally embedded exercise on bilaterally assisted supination in persons with hemiplegia. *Am J Occup Ther.* Sep 1996;50(8):639-646.

91. Alcock KJ, Wade D, Anslow P, Passingham RE. Pitch and timing abilities in adult left-hemisphere-dysphasic and right-hemisphere-damaged subjects. *Brain Lang.* Oct 15 2000;75(1):47-65.

92. Mavlov L. Amusia due to rhythm agnosia in a musician with left hemisphere damage: a non-auditory supramodal defect. *Cortex.* Aug 1980;16(2):331-338.

93. Murayama J, Kashiwagi T, Kashiwagi A, Mimura M. Impaired pitch production and preserved rhythm production in a right brain-damaged patient with amusia. *Brain Cogn.* Oct 2004;56(1):36-42.

94. Vignolo LA. Music agnosia and auditory agnosia. Dissociations in stroke patients. *Ann N Y Acad Sci.* Nov 2003;999:50-57.

95. Krebs HI, Hogan N, Aisen ML, Volpe BT. Robot-aided neurorehabilitation. *IEEE Trans Rehabil Eng.* Mar 1998;6(1):75-87.

96. Platz T, Denzler P, Kaden B, Mauritz KH. Motor learning after recovery from hemiparesis. *Neuropsychologia.* Oct 1994;32(10):1209-1223.

97. Trombly CA, Wu CY. Effect of rehabilitation tasks on organization of movement after stroke. *Am J Occup Ther.* Jul-Aug 1999;53(4):333-344.

BIOGRAPHICAL SKETCH

Claudia Ann Rutter Senesac, PT, MHS, PCS, has over 27 years of pediatric clinical experience. She is the owner and administrator of a pediatric physical therapy private practice since 1984 and is a board certified clinical specialist in pediatrics. She received her bachelor’s degree in physical therapy and master’s degree in health science from the University of Florida. She is graduating with a Doctor of Philosophy in rehabilitation science with her research interest focused on *motor learning* and *motor control* in neurological and neuromuscular impaired populations: adult individuals who have suffered a stroke, pediatric individuals that have suffered a SCI, cerebral palsy and neuromuscular diseases. Investigations have included constraint induced movement therapy, upper extremity intervention protocols for recovery, and locomotor training in the pediatric population. She has been an adjunct faculty member of the Physical Therapy Department at the University of Florida since 1979 and faculty Lecturer since 2003. Her primary teaching responsibilities in the entry-level doctorate program include Functional Anatomy I and II and Pediatrics in Physical Therapy.