Adaptive Mixed Reality Rehabilitation for Stroke

by

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ABSTRACT

Millions of Americans live with motor impairments resulting from a stroke and the best way to administer rehabilitative therapy to achieve recovery is not well understood. Adaptive mixed reality rehabilitation (AMRR) is a novel integration of motion capture technology and high-level media computing that provides precise kinematic measurements and engaging multimodal feedback for self-assessment during a therapeutic task. The AMRR system was evaluated in a small (N=3) cohort of stroke survivors to determine best practices for administering adaptive, media-based therapy. A proof of concept study followed, examining changes in clinical scale and kinematic performances among a group of stroke survivors who received either a month of AMRR therapy (N = 11) or matched dosing of traditional repetitive task therapy (N = 10). Both groups demonstrated statistically significant improvements in Wolf Motor Function Test and upper-extremity Fugl-Meyer Assessment scores, indicating increased function after the therapy. However, only participants who received AMRR therapy showed a consistent improvement in their kinematic measurements, including those measured in the trained reaching task (reaching to grasp a cone) and in an untrained reaching task (reaching to push a lighted button). These results suggest that that the AMRR system can be used as a therapy tool to enhance both functionality and reaching kinematics that quantify movement quality. Additionally, the AMRR concepts are currently being transitioned to a home-based training

application. An inexpensive, easy-to-use, toolkit of tangible objects has been developed to sense, assess and provide feedback on hand function during different functional activities. These objects have been shown to accurately and consistently track hand function in people with unimpaired movements and will be tested with stroke survivors in the future.

ACKNOWLEDGEMENTS

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INTRODUCTION

Millions of people are currently living in the US with residual disabilities stemming from a previous stroke. Hundreds of thousands of people will also have a new or recurrent stroke each year.[1] While swift medical attention can lessen the effects of a stroke, many stroke survivors either cannot or do not seek prompt medical attention, resulting in a greater impact on their health. Currently, once the stroke has occurred, the most common treatment of motor impairments is physical and occupational therapy for a short period, followed by discharge to the home or to a care facility. Exercises or self-initiated physical therapy tasks may be prescribed to the patient to complete at home, but there are few resources or incentives to ensure compliance.

Many times the amount of therapy covered by the stroke survivor's insurance or by his or her own funds is inadequate to restoring enough function to live independently. The completion of activities of daily living with the affected limb at the same frequency and with the same movement quality as before the stroke is also greatly impacted. While the traditional clinical belief was that a recovery plateau (no additional improvement probable) was inevitable after approximately six months post-stroke,[2] recent research show that ongoing recovery can occur for years post-stroke.[3-7] Clinicians are being urged to reconsider the idea of a plateau and instead utilize novel, engaging therapies[8] to help stroke survivors

regain motor function in the long-term. However, most data comes from fairly small research studies and have not been sufficient to convince third-party insurance payers to continue funding therapy for stroke survivors extending beyond 6 months. Other research and clinical experience shows that providing an exciting and engaging environment for rehabilitation can help to encourage patients to be more involved in their recovery.[9-11] Many times repetitive therapy or therapy done without feedback or encouragement can become boring and if progress towards recovery is not outwardly evident, the patient may lose motivation. Traditional repetitive therapy also has the potential to be performed without full cognitive engagement by the user, which limits the possibility for active motor learning.[10]

Providing therapy for the upper-extremity is especially challenging because of highly varied combinations of impairments such as spasticity,[12] weakness, movement inefficiency,[13,14] joint discoordination,[13] limited ranges of motion, increased trunk compensation[15] and reduced movement speed[16] that may be present. Because each stroke survivor has a unique array and severity of impairments, as well as potentially confounding neurological and mobility conditions caused by the stroke or other concurrent conditions, prescribing one therapy to adequately address movement behaviors throughout the recovery period is difficult. This may also explain why there has been little conclusive evidence that any one type of rehabilitation has been consistently effective during chronic stroke.

The evidence needed to convince both the rehab community and the insurance companies that ongoing therapy is both useful and necessary will have to demonstrate improvements for a diverse group of impairments, lesion locations, and post-stroke durations. Ideally, results could be combined across research and clinical groups to create evidence-based therapy choices for each patient, as individualized medicine becomes more of the accepted norm.[17] Alternatively, therapy regimes and systems that can accurately track and adjust the therapy to the person's recovery patterns would provide similar benefits. Tracking rehabilitation improvements in a standardized, objective way could also be extremely useful in providing confirmation of progress,[18] which may help support continued funding of the therapy, as well as provide an incentive strategy to the patient receiving therapy. Standardization of therapy applications, evaluations and results can also help in creating large databases of patient characteristics, response to therapy type and therapist opinion on a variety of different therapies.

Rehabilitation systems created to address the problems above would utilize individualized therapy protocols, provide encouragement and feedback related to the therapy that promotes active learning, quantitatively and accurately track the recovery of motor impairments and demonstrate the ability to induce functional and quality of movement improvements over a diverse group of stroke survivors (in terms of age, gender, impairment, stroke site, time post-stroke, etc). A research group at

the School of Arts, Media and Engineering at ASU has developed an adaptive, mixed reality rehabilitation (AMRR) system that incorporates these key features. The AMRR system uses high-resolution motion capture and smart sensing objects to track kinematics and forces of the stroke survivor's torso, right arm and right hand while they perform a functional task. Figure 1 shows a stroke survivor using the clinical version of the AMRR system. The data collected from the person's movements are used to drive an audio and visual narrative feedback reflective of motor performance. The data are also transformed into a kinematics-based score of impairment, which can be used to track progress and create adaptations to the feedback or physical environment. An initial pilot study showed kinematic improvements in a short two-week period. This result led to a control group study performed at a local rehabilitation clinic that compared functional and kinematic outcomes of a group of stroke survivors receiving AMRR therapy to control group of stroke survivors receiving traditional repetitive reaching task therapy. This study showed that both groups had similar functional improvements, but the group receiving AMRR therapy demonstrated significantly better changes in movement quality.

Figure 1: A photo taken during one of the AMRR training sessions. The therapist, right, monitors and instructs the subject, left, during the entire interactive session.

The AMRR system has advanced from a small pilot study in a research laboratory to a control group study in a rehabilitation clinic. However, the ultimate goal of AMRR therapy is to fill the void of low-cost, easy to use, effective therapy that can be done at home. Current work is being done to scale down the size and cost, while retaining the basic feedback and task structures, to create a home-based AMRR system. Future work will include a study that will introduce stroke survivors to the adaptive mixed reality rehabilitation therapy in the clinic, under the supervision of a therapist, and continue with self-directed, self-evaluated therapy at home, while still ensuring relevant motor improvements are

being consistently made. This research will happen over three sites to demonstrate that AMRR therapy can be used in different environments with different clinical and study staff.

The work presented here focuses on how I used the outcomes of the initial pilot study to advance the way AMRR therapy is administered in a clinical setting. I also took the lead in developing the study procedures and data analysis for the control group study that explored the differences in clinical and kinematic changes seen after stroke survivors received either AMRR or traditional reaching therapy. My final contribution was in creating a physical sensing environment that utilizes tangible objects to evaluate and provide feedback on different hand functions during unsupervised AMRR therapy. The following elaborates on the three main areas of my work:

Guidelines for implementation of the AMRR system in the clinic

The system was first piloted with three stroke survivors to develop strategies for adapting the therapy procedures and evaluating outcomes during the intervention period and to measure functionally relevant changes as a result of the therapy. My work on the pilot study involved observation of therapy appointments, analysis of kinematic and clinical scale data collected before and after the intervention and data interpretation. The pilot study results demonstrated that the AMRR system had the potential to be a useful therapy tool and was easily used and understood by all three participants. However, the real-time kinematic

evaluation was too difficult to understand to be of significant use to the therapist in adapting the therapy in real time. The two-week intervention period was also too short to address the participants' full range of impairments. The system also lacked a consistent implementation protocol for using physical objects as a therapy end goal and the physical objects that were used were limited in the types of hand function they could train. Outcomes were also impossible to generalize due to the small sample size and could not be compared to outcomes from other types of therapy. Before beginning the control group study, I collaborated with the therapist to create strategies to help her understand and direct the therapy protocol based on the subject's individual abilities and the available feedback streams. This also led to developing standardized kinematic-based evaluation measures the therapist could easily use to track progress during the therapy and adapt the task based on the subject's progress. The protocol and evaluation measures are now being used to create semi-automated adaptive therapy in the home and will continue to be honed as the study expands to include different clinical locations and additional treating therapists.

Testing the outcomes of the AMRR therapy as compared to traditional reaching therapy

The pilot study results suggested that AMRR therapy could induce specific changes in a stroke survivor's kinematic performance during a reaching task. To further validate this claim and explore the specific

functional and kinematic benefits gained by AMRR therapy, a study with a group of stroke survivors who received AMRR therapy and a control group that received traditionally administered repetitive task reaching therapy was developed. During this study, I took the lead in helping the therapist understand how to administer AMRR therapy, overseeing the evaluation visits and developing the data analysis protocols. Two groups of participants with chronic stroke (6 months or more post-stroke) received either a month of AMRR therapy (N = 11) or matched dosing of traditional repetitive task therapy (N = 10). Participants were right-handed, between 35 and 85 years old and could independently reach to and at least partially grasp an object in front of them. Upper extremity clinical scale scores and kinematic performances were measured before and after treatment. Both groups showed increased function after therapy, demonstrated by statistically significant improvements in Wolf Motor Function Test and upper extremity Fugl-Meyer Assessment (FMA) scores, with the traditional therapy group improving significantly more on the FMA. However, only participants who received AMRR therapy showed a consistent improvement in kinematic measurements, including those measured in the trained reaching task (reaching to grasp a cone) and in an untrained reaching task (reaching to push a lighted button). These results offer an initial suggestion that the AMRR system may be useful in improving both functionality and reaching kinematics that quantify movement quality. However, further work is needed to determine if AMRR therapy induces

long-term changes in movement quality that foster better functional recovery.

Creating a modular physical sensing environment and tool-kit for use in a long-term, home-based AMRR system

Although results from the clinical study demonstrate that the AMRR system show promise, it is still unclear if these kinematic and functional results translate to activities of daily living. Research on mixed reality rehabilitation needed to evolve to include a system that incorporates strategies from the clinical system to provide long-term, unsupervised therapy at home. The home-based system is much lower cost, but still has the capability to provide real-time and summary feedback on kinematic parameters based on the hand's movement (e.g. trajectory efficiency, movement speed and how the hand interacts with the object). My focus has been on expanding the ability of the system to train hand function during different functional tasks through a tool-kit that integrates tangible objects and analysis software that can sense interactions with the object, evaluate the function compared to unimpaired interaction and provide feedback based on the evaluations. The physical targets were specifically designed to help the user mentally connect what she is practicing during therapy to activities of daily living, provide the correct visual input to help plan for the physical interaction and provide feedback to the user about hand posture and pressure exerted during grasp. Physical objects that can sense features related to the desired interaction (such as sensing

magnitude and spatial location of applied forces) are also important to evaluating and providing ancillary feedback on how well the task is being performed. The tool-kit of objects and related analysis software can also be utilized independently of the AMRR system in different therapy environments. The physical objects were all created from digital files through rapid prototyping techniques, which means they can be easily modified or reproduced by anyone wanting to utilize the tool-kit during therapy. The objects create unique therapy workspaces without therapist intervention, offer multiple hand functions to practice, and integrate sensing, evaluation and feedback into the physical environment.

Chapter 2

GUIDELINES FOR IMPLEMENTATION OF THE AMRR SYSTEM IN THE CLINIC

Mixed reality rehabilitation is just one of many recent rehabilitation techniques that employs novel technologies to enhance therapy. Such techniques may use advanced custom technologies, such as virtual reality scenarios and robotics, modified existing technologies, such as video game based therapy, or a combination of custom and existing hardware and software. Many of these techniques use theories similar to those employed in the AMRR therapy, such as creating an engaging, rewarding environment for training and evaluating the kinematics of the movement with high-resolution motion capture or electromechanical sensors.

One of the most popular ways to use robotic therapy is as a physically assistive device. This involves a robotic device that interfaces directly with the affected limb(s) and either assists the movement or moves the passive limb without any action from the user. Robotic devices such as these can be used as a stationary device that the person interacts with or as an ambulatory, wearable exoskeleton, or a combination of both types.[4,19-23] Assistive wearable robotic devices have been created to address issues of the hand, arm and gait. Many of these robots also use a computer screen to provide some feedback to the user and create incentive for use. The Hand Mentor (KMI) is a commercially available

repetitive task robot that passively moves or actively assists the hand in a way to practice wrist flexion/extension movements.[24,25] This product has a small computer screen associated with the exercise so the user can play a game with the movements of the hand. The same company has also created the Foot Mentor, which uses very similar principles to train ankle range of motion (http://www.kineticmuscles.com). The MIT Manus is hand and arm robot where the user grasps a cylinder and the user's forearm is strapped onto the robot. The user can perform active anti-gravity movements, or if needed, be assisted by the robot, while they are playing a rehabilitation game.[26] The Lokomat uses robotic exoskeletons around each leg that are connected to a treadmill, anti-gravity support and bar apparatus. The patient can use the Lokomat to practice walking, even if they do not yet have the strength or control to fully complete the movement on their own.[20] While assistive robotics can be extremely useful in augmenting a therapist's ability to help patients produce repetitive movements with a high frequency, they have also tended to focus on the technology, rather than the specific clinical benefit. Many robots were designed to passively move the limbs of severely impaired patients, which greatly limits the patients' opportunity to engage in active motor learning. The robots may also fail to adapt to the patient's specific movement impairments or to change the assistance based on improvements in movement or function. Because repetitive movements can become tedious even with assistive robots, robotic protocols often include visual

feedback or games to incentivize the user to practice more often and for longer time periods. The feedback can also help the patient actively self-assess and improve their movement in conjunction with the passive intervention of the robot.

Other current research focuses on creating more immersive rehabilitation experiences, with or without the aid of robotics, that use virtual reality techniques to provide real-time feedback to the user about his or her movement. Research at Rutgers has shown greater improvements in aspects of gait when a virtual feedback environment was used with their Ankle Rehabilitation robot than when the robot was used alone.[27] Another group showed improvements in gait parameters following a virtual and traditional therapy program when compared to solely traditional therapy, although the experimental group received more therapy than the control group, suggesting virtual reality should augment, rather than replace traditional therapy.[28] Other virtual reality regimes, such as that developed at USC,[29] have shown promise in improving hand function. However, the evidence in most cases is severely limited by the small cohort sizes. The current results are very promising, but more work is needed to determine exactly how and when to present the feedback, what form the feedback should take, how a reward system should be structured to entice patients to play for extended times and many other aspects of the systems before these can be widely used and accepted by clinics and by insurance companies. Questions also remain about how

virtual reality therapy differs from traditional therapy of a matched dosage and whether the improvements are sustained in the long-term.

While custom-made, advanced technologies have shown great promise, other groups have also been looking at using readily available games or environments for rehabilitation. There have been recent anecdotal reports of nursing homes and clinics using the Wii console to encourage upper body and hand movements among people who are in therapy.[30] Studies have yet to be done on the efficacy of this, but while unsupervised practice may help with general activity level functions, the movement quality will most likely not get better without specific feedback about the involved body structures. Additionally, repetitive practice without correction can lead to increased compensatory movements or strain. A group in Italy examined three types of rehabilitation video games and actually reported an increase in compensatory movements following the intervention.[31] Other groups have used commercially available video games, and modified hardware to provide rehabilitation. One such group uses a racing game and a force-feedback steering wheel controller to provide upper extremity therapy.[32,33] While the participants improved in the task, no significant clinically relevant changes were reported. This may be due to the non-specific feedback received (based only on accuracy of steering) or because of the short intervention period. Another group used the Sony Playstation and EyeToy games that involved upper extremity movements to supplement traditional rehabilitation. This group found that

significant functional improvements to the impaired side were seen immediately following the intervention, as compared to patients receiving just traditional therapy, but those changes were not retained at the 3 month follow-up.[34] Many of the therapy techniques discussed above all have potential benefits that can advance stroke rehabilitation, and mixed reality rehabilitation combines many of the benefits seen in these therapies.

Principles of adaptive mixed reality rehabilitation

My lab has developed an adaptive, mixed reality rehabilitation (AMRR) system that integrates traditional rehabilitation and motor learning theories with state of the art motion capture and sensing technologies, smart physical objects, and interactive computer graphics and sound. This unique configuration provides real-time, intuitive, and integrated audio and visual feedback representative of goal accomplishment, activity performance, and body function during a reach and grasp task. The AMRR system provides kinematic measurements derived from high-resolution motion capture data that is used to create feedback related to the movement, evaluate the participant's progress and to adapt the therapy accordingly. The therapist can adapt the system between sets of reaches to individualize the therapy based on the participant's individual impairment and progress, as informed by the therapist's observations and the quantitative assessment. During the course of the rehabilitation, the therapist can also adapt the focus of the therapy task and corresponding

audiovisual feedback. However, the nature of the audiovisual feedback places each component in the context of the full action, resulting in integrated, instead of isolated, improvements among the movement features.

Motion analysis sensing protocol

The AMRR system is driven by 3-dimensional motion capture data from 14 markers placed on the right (impaired) hand and arm and the torso, seen in Figure 2. Kinematic parameters (e.g. hand speed, elbow joint angle, etc) related to the reach and grasp task are then derived from the movement data. All of the kinematic parameters are used to assess impairment and progress throughout the therapy, and many are directly mapped to the audio and visual feedback streams as part of the AMRR therapy.

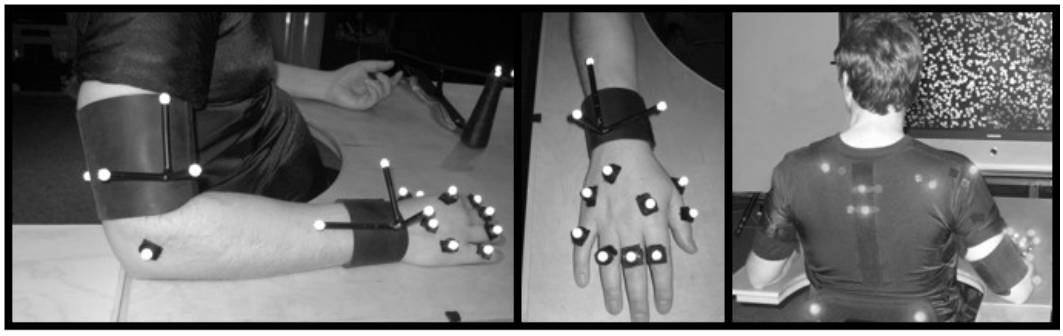

Figure 2. Marker configuration for the right hand, arm, shoulder and torso.

Kinematics-driven audio and visual feedback

The AMRR system uses audio and visual feedback to intuitively communicate to the stroke survivor levels of his performance and direction for improvement. Individual audio and visual feedback mappings

correspond to different kinematic attributes within the selected parameters related to the reach and grasp task (i.e. the action representation). While each feedback mapping communicates performance of an individual kinematic attribute, all feedback mappings together create one audiovisual narrative, which communicates the stroke survivor's overall performance in an integrated manner. Artistic and perceptual principles from interactive media, music, dance, animation and film are utilized for the design of the audio and visual feedback mappings. This integrative approach facilitates the stroke survivor's self-assessment of the reach and grasp action.

Feedback is provided on an LCD screen and two speakers. Each reach begins with a digital image appearing on the screen, which breaks apart into many minute segments of the image, called particles. As the participant moves his hand towards a target location, the hand's forward movement pushes the particles back to reassemble the image and simultaneously creates a musical composition (Figure 3). Visual feedback communicates spatial aspects of activity level movement features (e.g. trajectory deviation stretches the image in the direction of deviation – Figure 4). Audio feedback communicates temporal aspects of activity components (e.g. endpoint speed controls the musical rhythm) and provides indicators for body function (e.g. shoulder compensation activates a unique sound indicator).[35] The amount of error required to produce each type of feedback (feedback sensitivity) can be independently adjusted to fit the therapy needs of each individual.

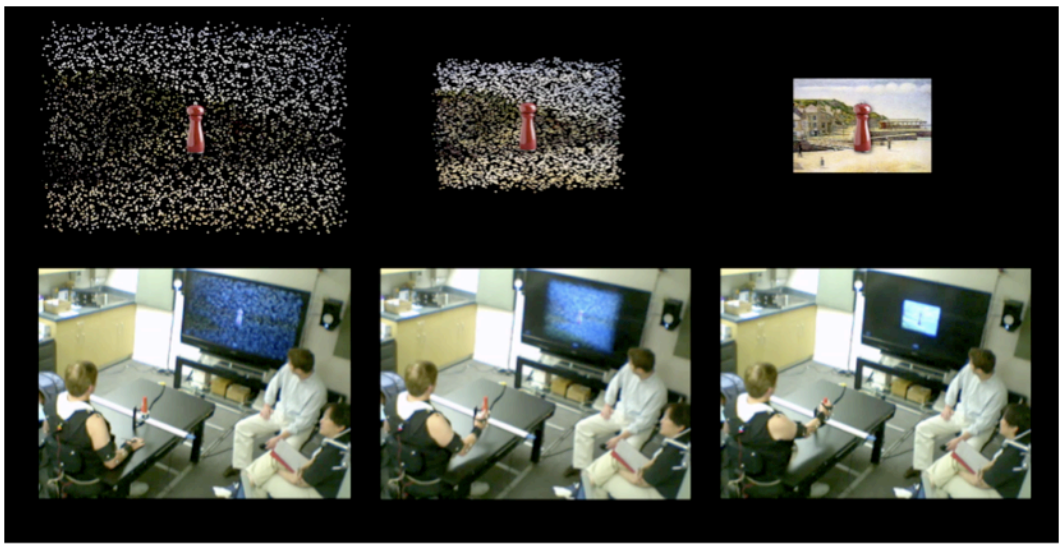

Figure 3. Correspondence between where the hand is in space during a reach and the feedback shown on the screen.

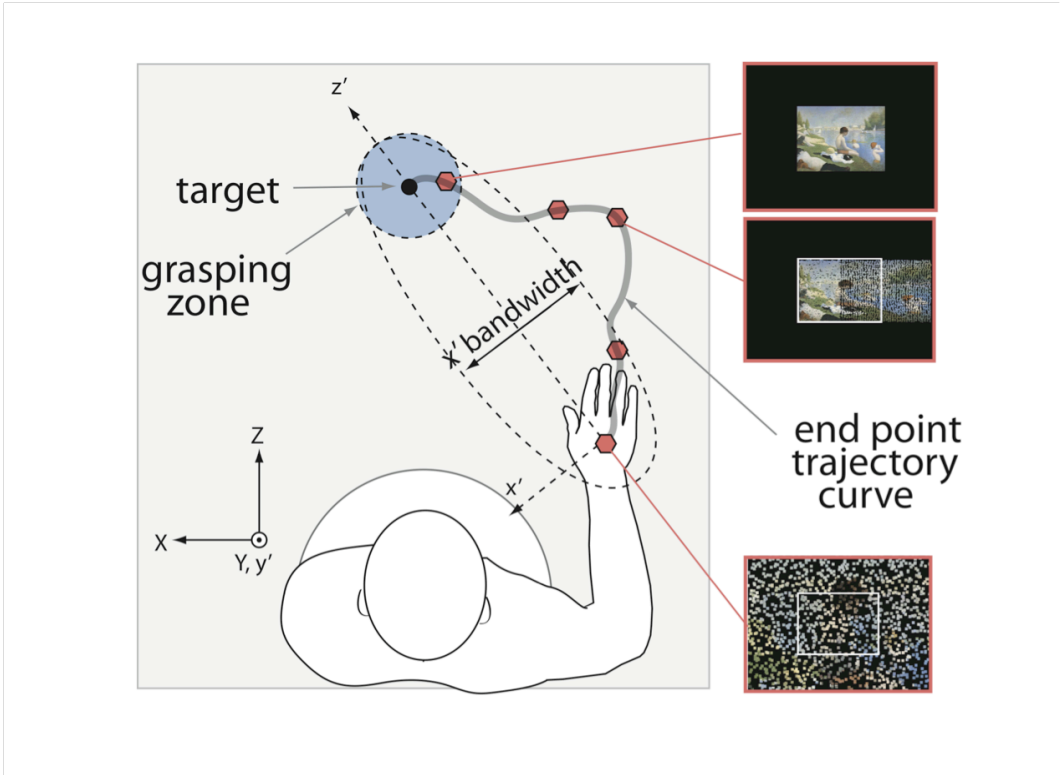

Figure 4. Visual feedback is based on how the arm moves within the bandwidth (sensitivity zone).

Although many of the aspects related to the rehabilitation of a reach and grasp movement are mapped to audio or visual feedback, others do

not have direct mappings. Some aspects may be trained by focusing on related or contributing kinematic aspects. For example, ataxia may be reduced after training trajectory efficiency and targeting. Other aspects may be trained implicitly through the combinatory training of related movements. For example, trajectory and velocity profile training may cause secondary improvements in joint correlation. The remaining aspects, such as spasticity and weakness, cannot be addressed by the feedback and incorporating these features into the AMRR system is an area of further investigation. However, regardless of the feedback mappings, the therapist is always present to provide any verbal or physical guidance necessary to address the rehabilitation requirements of the individual.

Adaptation of therapy

The AMRR system is adaptable to maintain a level of challenge and engagement appropriate for the stroke survivor's impairment and progress. Reaches are preformed in sets of 10, and the clinician can adapt each set in terms of: the target location, the virtual and physical aspects of the training environment, the kinematic attributes to be addressed by the feedback, and the sensitivities of each type of feedback. Adaptation is essential for greatly enhancing the stroke survivor's ability to create and maintain a generative plan for movement[36,37] and ultimately to transfer rehabilitation gains to various functional tasks beyond those trained within rehabilitation.[38] The clinician could use the graphic

visualizations of computed kinematic measures (e.g. trajectory, velocity, joint angles)[18] and direct observation of the stroke survivor's performance to adapt the system as necessary after every set of ten reaching trials. The therapist also uses physical or verbal cues to address therapeutic aspects not being addressed by the AMRR system or when the feedback is not clearly understood by the participant.

AMRR training can be done at four different target locations. These target locations each use unique combinations of joints, increasing from a simple to a more complex joint space. The targets are: ipsilateral and on the table (Target 1), to the participant's midline and on the table (Target 2), to ipsilateral and 6 inches above the table (Target 3), to the participant's midline and 6 inches off the table (Target 4). Targets 1 and 3 are set horizontally on a line at half the angle (alpha) between the vertical projection of the rest position and midline and vertically to 95% his or her active assisted reach to the midline. The second target is set horizontally to the midline and vertically to 85% of his or her active assisted reach. This is illustrated in Figure 5. The active assisted reaches are on the table for Targets 1 and 2 and 6 inches off the table for Target 3 and 4. The physical target may either be a cone or a large button to be pressed, both of which sense the user's touch. Purely physical (no audio or visual feedback and physical target), mixed (audio and/or visual feedback and physical target), or purely virtual (audio and/or visual feedback and no physical target) training environments may be used. Based on which

kinematic attributes are the foci of therapy, the corresponding feedback mappings are enabled, and their relative sensitivities can be adjusted.

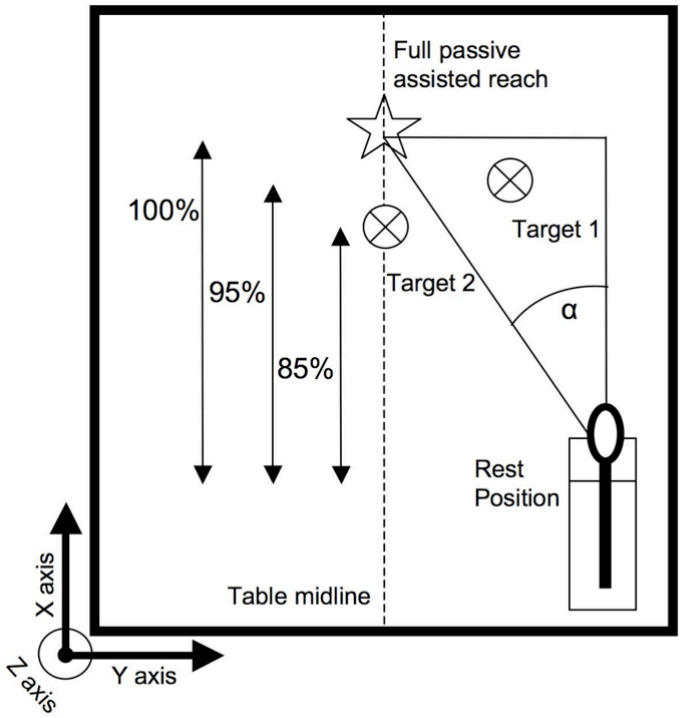

Figure 5. Target positions as calculated from each participant's active assisted reach distance (shown by the star).

One important advantage of the AMRR system is that it performs integrated training for all key aspects of the reach and grasp movement, even though the therapy generally only focuses on one or two aspects at a time. While the system does allow the therapist to focus on specific aspects of recovery, the nature of the audiovisual feedback places each component in the context of the full action, which communicates performance of the entire task in addition to the focused areas of recovery and can lead to integrated improvement.

Pilot study – spring 2008

In order to provide a proof of principle for the AMRR system, a formal study of the system was implemented to test the ability to provide beneficial therapy in a standardized way. Because each stroke survivor has a very unique baseline impairment profile and will progress at different rates, the type of therapy administered needs to be continuously adapted to their performance and ability. To test whether the AMRR system could provide this adaptation, especially in a way that was easy for the therapist to understand and implement, a small pilot study was run in the spring of 2008. This study also helped us to refine and redefine exactly what the system was trying to accomplish and how it could best meet those goals. One of the main goals of this preliminary study is to develop better guidelines for administering AMRR therapy and to make improvements to the system before a larger control group study could be performed. A picture of a participant using the system with a therapist at ASU is shown in Figure 6.

Figure 6. Photo of a stroke survivor (left) and the therapist (right) using the AMRR system at ASU.

Study Methods

Participant selection. Four participants were recruited from direct referrals from medical care providers or through previous research studies and provided informed consent. The protocol was approved by the Arizona State University Institutional Review Board (see appendix A). Participants had chronic stroke (6+ months after the stroke at recruitment) and presented clinical symptoms consistent with a left-sided motor area lesion(s) resulting in right-sided hemiparesis. Participants were categorized as having mild or mild-to-moderate impairments by an

experienced rehabilitation doctor. Specifically, the participants were required to have a right arm active range of motion that met or exceeded the following thresholds to ensure they could complete the task: shoulder flexion of at least 45°, elbow flexion/extension of at least 30° to 90°, forearm pronation or supination of at least 20°, wrist extension of at least 20°, and at least 10° extension in the thumb and any two fingers. One participant was excluded because he had nearly normal arm kinematics and had little potential benefit from the study. The three participants who completed the study had the following characteristics at the start of training: Participant 1 was a 77 year old male, 14 months post-stroke; Participant 2 was a 76 year old male, 20 months post-stroke; and Participant 3 was a 71 year old female, 32 months post-stroke. All participants were right hand dominant before the stroke, had corrected vision of at least 20/40, no confounding mental illness (verified by a score greater than 24 on the Mini Mental State Exam) and acceptable levels of audio and visual perception, as confirmed by a sensory perception test. The sensory perception test includes standard measures of perception (i.e. a standard color blindness test and the ability to detect basic properties of musical sounds, such as pitch, timbre, loudness[39]) but also tests the participant's ability to perceive structural characteristics of the feedback such as movement of images and rhythm acceleration. In addition to being used as a screening criterion, the results of this test were also used when adapting the feedback during the training. For example, a

participant with limited hearing would very rarely be trained using two concurrent audio feedback streams

Study procedures. Each participant had two evaluation visits and six training visits. The pre-training evaluation was performed immediately prior to training and the post-training evaluation was performed immediately following training. Prior to each evaluation visit, each participant and his or her caregiver were asked to complete and return the Motor Activity Log (MAL) and the Stroke Impact Scale (SIS), with study staff were available to answer any questions by phone. The MAL asks participants to rate their more affected arm on the amount of use and quality of movement of that arm during various activities of daily living. The MAL has been evaluated to be reliable and valid measure of the use of the affected arm and hand during activities of daily living in mild to moderate stroke survivors.[40] The SIS asks participants to rate aspects of their recovery such as strength, mobility, social function and emotion. This questionnaire has been validated as reliable and sensitive to change over recovery for mild to moderate stroke survivors.[41] As a standardized measure of arm function, participants performed the upper extremity Wolf Motor Function Test (WMFT). The WMFT is a series of functional tasks relevant to activities of daily living that is timed and rated for quality by a trained therapist.[42] Participants also performed eight reach and grasp movements, using a force sensitive cone for the target, to each of the four locations (SI, SM, AGI, AGM) for a total of 32 reach and grasp trials. All

reaches were self-paced, but the participant was asked to briefly rest after each reach (2 -3 seconds) to discourage mechanical rhythmic movement and aid in the segmentation of the data. Participants rested for 2-3 minutes between targets. The WMFT and reach and grasp movements were performed while recording motion capture data, as described above, and were conducted by the same therapist who performed the therapy.

Each training visit lasted 90 minutes, including 20-30 minutes of setup, and consisted of approximately 120 reaches (12 sets of 10 reaches). Each participant's therapy protocol was customized to fit their personal movement challenges as determined by both the therapist and system's evaluation of the movement. Each participant's training profile, below, shows the movement parameters that were targeted for improvement during training. Other parameters were also measured and trained as an integrated part of the therapy task, but the therapist determined the following aspects of each participant's movement to be fundamental to their rehabilitation.

Participant 1 focused on improving the efficiency of his reach to grasp movements by increasing his reaching speed, reducing jerkiness, and improving the bellness (smoother acceleration and deceleration during reaching) and the consistency of his velocity profile. He also worked on reducing torso compensation at the end stage of the reach. *Participant 2* focused on increasing the speed and the consistency of his reaches. He also worked on relaxing his elbow and shoulder before the

movement started and synchronizing his shoulder and elbow joints during the reach to improve his trajectory and target acquisition accuracy.

Participant 3 focused on increasing her shoulder and elbow ranges of motion and improving joint synergy while reducing shoulder and torso compensation.

Data Analysis. Clinical scale scores and reaching kinematic data were obtained from each participant at the pre- and post-training sessions. All kinematic parameters given in Table 1 were tracked and assessed for each participant. The differences in the kinematic performance measures from pre- and post-training were analyzed using the Wilcoxon rank-sum test. This non-parametric alternative to the t-test was used due to the small sample size of eight reaches at each target. Statistical significance was measured at two levels: $\alpha = .05$ and $\alpha = .00156$, which corrects for the multiple comparisons of eight parameters at four different targets. Because of the individual nature of each participant's impairments and therapy protocol, statistical comparisons of kinematics are made individually for each participant and are not combined across participants. Clinical scale results are presented qualitatively with no statistical comparisons.

Results

Clinical Scale Results. The MAL (scoring range 0-5, with 5 representing movement frequency or quality at pre-stroke levels) scores for participants 1 and 2 show increases in their average amount of use (AOU) of 1.08 and

1.16 points, respectively, and quality of movement (QOM) of 1.41 and .52 points, respectively after training. The third participant had a slight worsening in the amount of movement of -.56 points and slight increase in the quality of movement of .28 points after training. The SIS scores (normalized score of 0-100 with 100 representing full recovery) of all participants show an average increase of 5.7 points in their scores after training. The Wolf Motor Function Test did not show any consistent trends among the three participants. Participants 2 and 3 increased their average Functional Ability Score (scoring range 0-5, with 5 representing unimpaired movement quality) slightly during the post-test and Participant 1 decreased slightly. The total time to complete the tasks was slightly longer for both Participant 1 and 3 during the post-test while Participant 2 reduced his time by more than half during the post-test. Average scores, across the rated daily activities, for each participant's amount and quality portions of the MAL, normalized SIS scores (Participant 1's score does not include Section 8 of the SIS due to missing data), and the average Functional Ability Score (FAS) and total time of the WMFT are shown for each participant in Table 1.

Table 1. The Motor Activity Log average Amount of Use (AOU) and Quality of Movement (QOM), the Stroke Impact Scale normalized scores and the Wolf Motor Function Test average Functional Ability Score (FAS) and total time of movement.

	MAL				SIS		WMFT			
	AOU		QOM				FAS		Time, sec	
Subject	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1	2.6	3.6	2.1	3.5	76.1	82.0	3.9	3.4	60.4	70.9
2	1.4	2.5	1.6	2.1	54.9	59.0	3.1	3.3	204.9	100.7
3	2.2	1.7	2.1	2.4	43.1	50.2	3.4	3.5	41.9	46.4

Kinematic results for reach and grasp. The results presented here are for each target, comparing pre- and post-training evaluations, and are presented in the context of the participant's individual training protocol. Despite the short training period of two weeks, all three participants showed improvement trends in activity recovery combined with partial recovery of pre-morbid body function. Specific improvements are described below and results for the eight most important aspects for each participant are shown in Figure 7.

Participant 1 showed significant improvements in velocity aspects (bellness and jerkiness) and elbow and shoulder joint correlation during reaches to at least two of the targets. Torso and shoulder compensation was significantly reduced in most targets, with many of these improvements holding even with the stricter significance level. These results are shown in Figure 7a.

Target AGI was not included in any analyses for Participant 2 due to missing data during the post-training evaluation. Participant 2 demonstrated improved velocity measures (normalized adjust area, number of phases and jerkiness) at most targets, with all normalized adjust area being significant at the corrected level. This participant also significantly reduced the average reach duration at all targets. Participant 2 had mixed results for both elbow and shoulder joint correlation and compensation measurements, mainly showing significant improvements in the supported target reaching. These results are shown in Figure 7b.

Participant 3 made the most improvements in body function, both joint range of motion and correlation and shoulder and torso compensation. Participant 3 increased the extension of the elbow significantly (at the corrected level) during the reach at all four targets. Elbow and shoulder correlations were all higher during the post-training evaluation, with two targets improving significantly. Shoulder and torso compensation were significantly reduced for a majority of the targets. These results are shown in Figure 7c.

Discussion

The kinematic results show that all three participants improved their reaching movements after training with the interactive mixed reality system, especially in the targeted parameters. Due to the limited training period of only two weeks, however, significant functional changes in the clinical assessments were not expected. One possible explanation is that

the finer changes in movement that are detected by kinematic analysis are not reliably detected by the clinical tests.[43,44]

After training, two participants showed an improvement in the amount and quality in performing the activities of daily living presented on the Motor Activity Log. While the MAL is a validated measure, it may be influenced by the participant's mood or other cognitive biases at time of survey completion. The MAL also may not be sensitive to changes in recovery after a short intervention period.[45] The SIS scores also show a trend of improvement, but the underlying cause of these changes is not clear. And while improvements seen in the kinematic parameters were detected by both the therapist and system, they may not have been apparent to the participant, and therefore not reported. Further work will be done to determine how and when changes in kinematics become functionally relevant and will produce a substantial change in the participants' self-assessments. These scales also do not distinguish between compensation and recovery of pre-morbid movement patterns, whereas the kinematic and therapist evaluations do. There were no obvious trends of improvement in WMFT scores. Participant 2 decreased his time to completion by over 100 seconds during the pretest, but this was due mainly to being able to complete a task (checker stacking) that he was unable to complete during the pretest. However, when this task was removed from the totals, he still shows a decrease of about 18 seconds. The training period may have been too short to induce general

functional improvement, as the generalization of specific motor task training into functional improvement requires extensive training.[9,38]

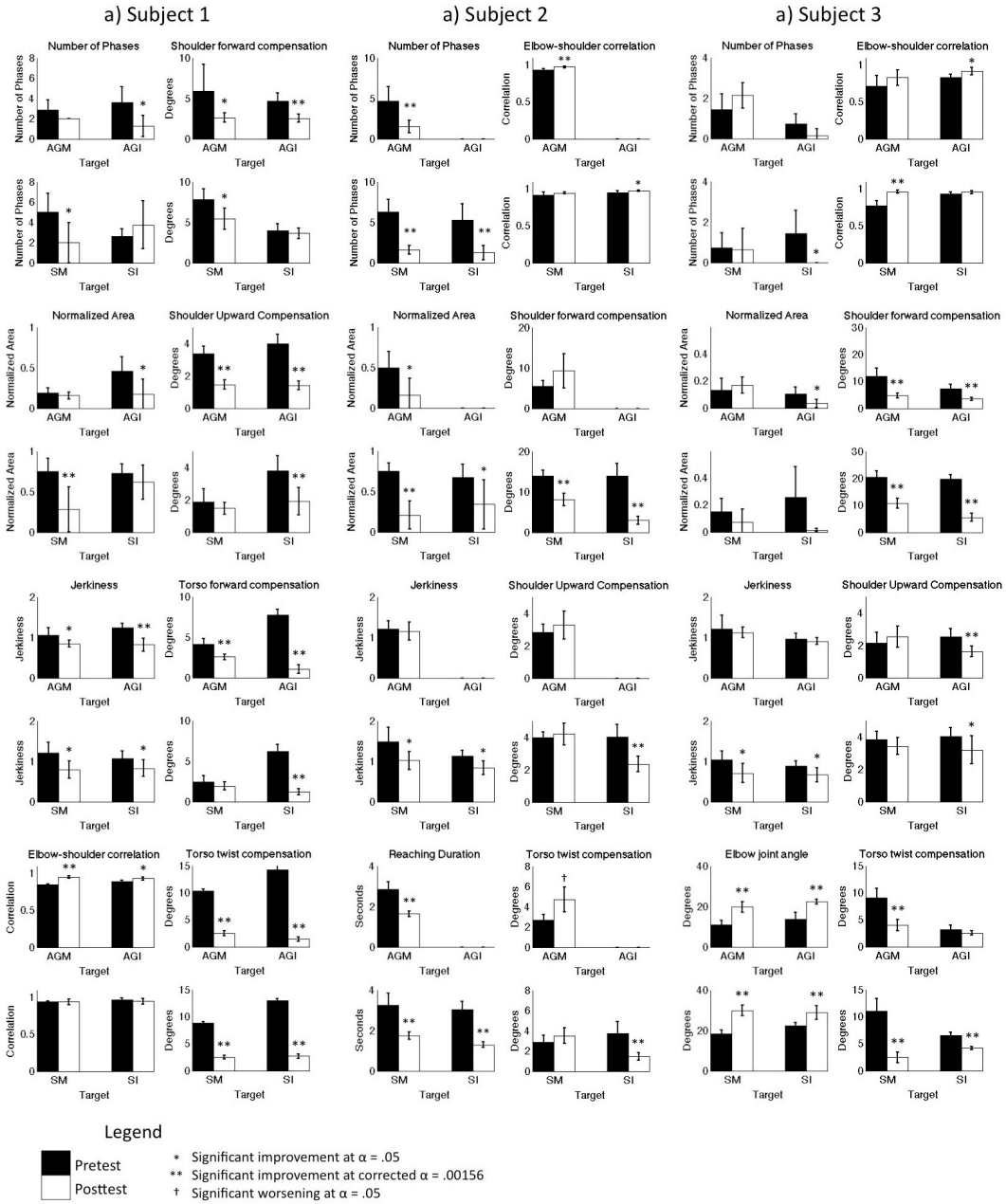

Figure 7. Comparison of kinematic parameters during reaching from pre- and post-training evaluations for Participant 1 (a), Participant 2 (b), and Participant 3 (c). AGM: reaching to a target 6” in the air aligned with the trunk midline; AGI: reaching to a target 6” in the air on the ipsilateral side; SM: reaching to a target on the table aligned with the trunk midline; SI: reaching to a target on the table on the ipsilateral side.

Each participant showed significant improvements in their reaching kinematics in merely six sessions, specifically for movement parameters on which their training was focused. This indicates that the approach of customized, adaptable and interactive feedback in a mixed reality environment is appropriate and beneficial to the rehabilitation of people who have mild-to-moderate hemiparesis resulting from stroke. While performing repetitive reaching movements alone[46,47] may have improved some parameters of the participants' end effector behavior (velocity, trajectory, etc.), each participant's improvements in activity performance were correlated to improvements in relevant body function parameters (joint synergy, compensation, etc) for which they had received targeted feedback. Furthermore, the improvements in activity recovery parameters showed a level of stylization (i.e. consistent velocity profile across targets) that can rarely be achieved simply through repetition.[46,47] This suggests participants used the mixed reality feedback to inform their motor plans and make improvements. However, the two-week training period may have been too short to fully address issues of the physical apparatus (like lack of muscle strength) or complete the full training sequence for each target location. There were also inconsistencies in the training due to concurrent system developments. For example, because the evolving experience with the study were used to finalize the implementation of mixed training, the intensity and quality of mixed training increased between Participant 1 to Participants 2 and 3. Finally, because

participants with only mild and mild-to-moderate impairments were recruited, each participant was already performing adequately in some parameters prior to training which left little room for improvement in those areas.

Other studies[48-50] have shown improvements using constraints of the unimpaired limb, trunk restraints or robotic assistive devices. However, these methods use external interventions that physically guide the participant to move in a certain way or restrain their body such that they must use the affected limb. Conversely, the approach taken with the AMRR system allows the participant to be free to move as they wish, while providing mediated incentives to the participant to move in a more efficient way and mediated deterrents from using compensatory or inefficient movements. This allows the participant to actively, yet often subconsciously, construct his or her own strategies, reducing dependencies on external constraints. The AMRR system also helps participants progressively integrate strategies learned for each kinematic parameter to form a complete movement strategy. Finally, the system effectively trains the participant to integrate the motor tasks with input from their audio, visual and tactile sensory streams, which could promote increased motor learning and neural plasticity. The enthusiastic acceptance of the system by the therapist and participants during the pilot study suggests that the mixed reality system is suited for therapeutic application in the clinic.

Alterations to AMRR administration following the pilot study

Setup

This study has also led to improvements in the system infrastructure. The setup for each visit took 20-30 minutes per participant, which became tiresome for both the participant and research team. This setup time was prohibitive to running multiple participants in one day or running participants for an extended training period. A revised setup uses predefined rigid body motion capture markers on the hand and torso, which are more easily identified by the motion capture software with less calibration (Figure 8 and Figure 9). While this change does prevent gathering data from smaller joints, such as the fingers, the smart sensing objects are being designed to detect tangible interaction without the data provided by detailed hand motion capture.

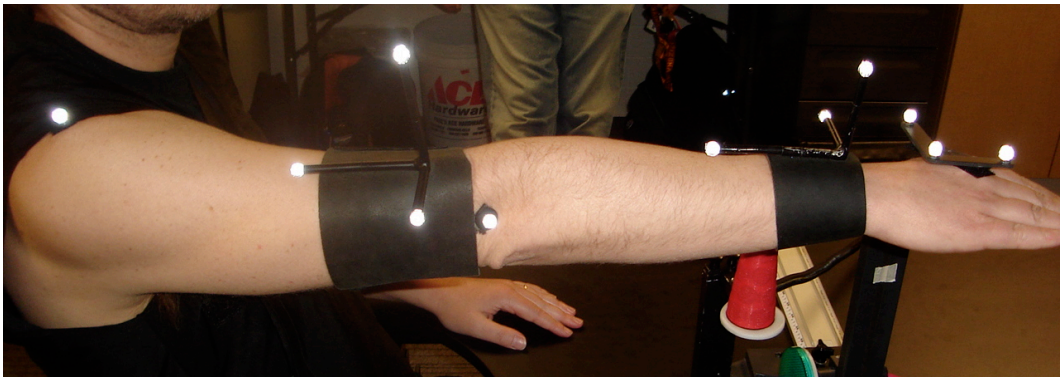

Figure 8. Revised marker configuration using rigid bodies for the right hand, arm and shoulder.

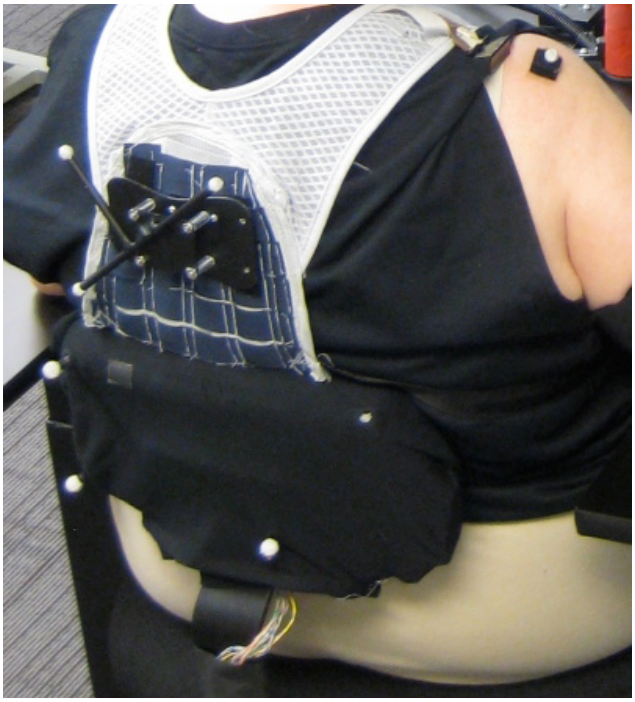

Figure 9. Revised marker configuration for the right shoulder and torso.

Physical sensing objects

The pilot study began with purely virtual environment reaches and it was quickly evident that this type of environment was not going to be successful in training a reach and grasp task and did not provide enough variation for 2 weeks of therapy. Throughout the study, the system was successful in integrating mixed (physical-virtual) environments into the training to promote motor learning bridging the virtual and physical worlds, although the later participants received a higher percentage of mixed reality training. Movement improvements made during training in the virtual and mixed environments successfully transferred to their post-training physical reaching tests. Smart physical objects that can sense touch and force and serve as the end target to the reach will also help

train a variety of interactions from the participant, ensuring the kinematic changes are transferrable to different types of tasks. The data collected from the objects can also be used to analyze the quality of interaction. The next version of the AMRR system allowed for virtual reaches (no physical target), button reaches (must touch a flat surface) and cone reaches (must grasp a cone-shaped object). These are shown in Figure 10.

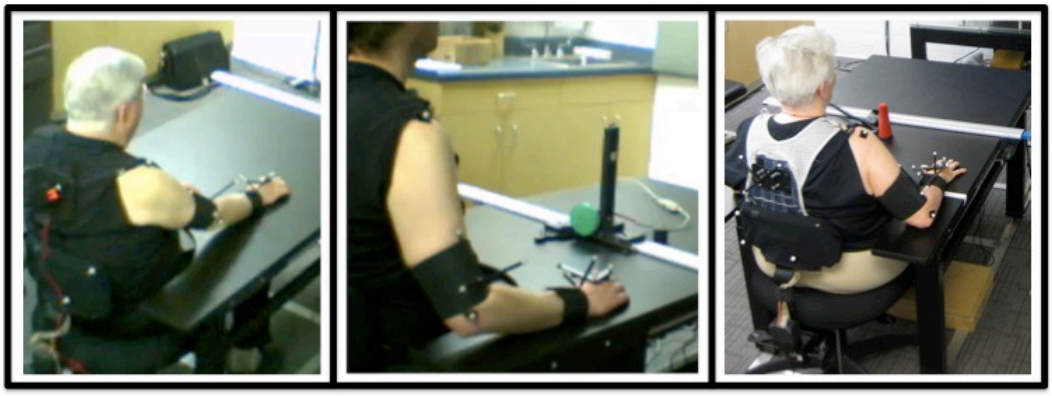

Figure 10. Left - Participant reaching for a virtual target during AMRR training. Center – Participant preparing to reach to a button target during AMRR therapy. Right – Participant preparing to reach to grasp the cone target.

Therapy administration and adaptation

More advanced control software was also developed to make adaptations to the therapy protocol and visualizing data faster and easier. This helps to better utilize the therapy time with the patient and ensure that the patient will be completely and consistently engaged in the training. There is now a formalized approach to adaptive training where the overall training structure can be repeated across participants but specific parameters of the training can be customized to each participant using quantitative data. The results suggest the feedback is intuitively and

effectively communicating measures of performance and direction for improvement to the participants.

Automated kinematic evaluation

In planning for a larger control group study, it became obvious that the kinematic parameters that were being measured were too complex and too confusing for the therapist to understand quickly. To allow the therapist to make better informed therapy decisions in real time, we developed a novel computational measure – the Kinematic Impairment Measure (KIM). Originally, each kinematic parameter being measured was presented to the therapist for evaluation as a raw number (such as, number of degrees for elbow joint angle). Due to a number of factors, such as the large number of tracked kinematic parameters, unique combination of impairments of each patient, the nature of improvement specific to each parameter, and the non-linearity of the raw data vs. the impairment level, this evaluation system was extremely difficult for the therapist to quickly and accurately understand and use the data to adapt the therapy. The data was also very difficult to present in a way that allowed easy comparisons and combinations between parameters and between different patients. The statistical comparisons also suffered, as there was no good way to get an overall sense of how much improvement was made in each of the participants or with the group as a whole. And while it was quite easy to determine the value of a certain parameter, there was no sense of *overall, objective* impairment or improvement. The KIM was

custom designed to solve a majority of the issues that arose when using purely raw data.

Kinematic feature extraction from the movement based on simplified action representation. A simplified action representation was necessary to reduce the reach and grasp movement into a manageable number of measurable kinematic attributes and to provide general relationships among those attributes relative to accomplishing the action goal. The simplified representation is derived from principles within rehabilitation practice, motor learning research, and phenomenological approaches to interactive technology.[35] Kinematic attributes were selected to represent key movement components used within clinical practice and presented in literature on stroke rehabilitation.[16,38,51,52] These attributes are organized into seven categories, grouped by operational similarities within the reach and grasp action, and described as either an activity level category or a body function level category. For example, “Compensation” is a body function level[43] category comprised of measures of shoulder and torso compensatory movements and “Temporal Profile” is an activity level category comprised of measures of hand speed and reaching duration. The categories and their relationships are shown in Figure 11. Activity level categories are depicted closer to the action goal based on their increased importance in completing the action, as compared to body function categories. This visualization presents an illustrative summary of category relationships, with overlap among categories showing the

potential generalized correlation among categories and their kinematic attributes. However, each stroke survivor's movement patterns will produce a distinct visualization (e.g. more or less overlap between categories based on the individual correlations between categories), which is an area of ongoing research. This action representation is described in greater detail elsewhere.[35]

Activity Level Categories – The four activity level categories (Temporal Profile, Targeting, Trajectory Profile, and Velocity Profile) contain kinematic attributes derived from the endpoint activity (movement of the hand over time and space). Because these categories have the greatest influence on the efficient completion of the reach and grasp action, activity attributes form the basis of the interaction design of the AMRR system. And since this system provides therapy in the context of performing an entire task-based movement, feedback may be provided on activity level attributes even when those attributes are not the primary focus of training.

Body Function Level Categories - The three body function level categories (Compensation, Joint Function, and Upper Extremity Joint Correlation) include kinematic attributes that are derived from joint angles of the torso, arm and hand. The quality of these attributes is less essential to the completion of the task, but an improvement of these attributes can reflect recovery of pre-morbid movement patterns of specific body structures. The three body function level categories are focused on during

training at the discretion of the clinician and the related feedback can be turned on and off throughout the course of the training.

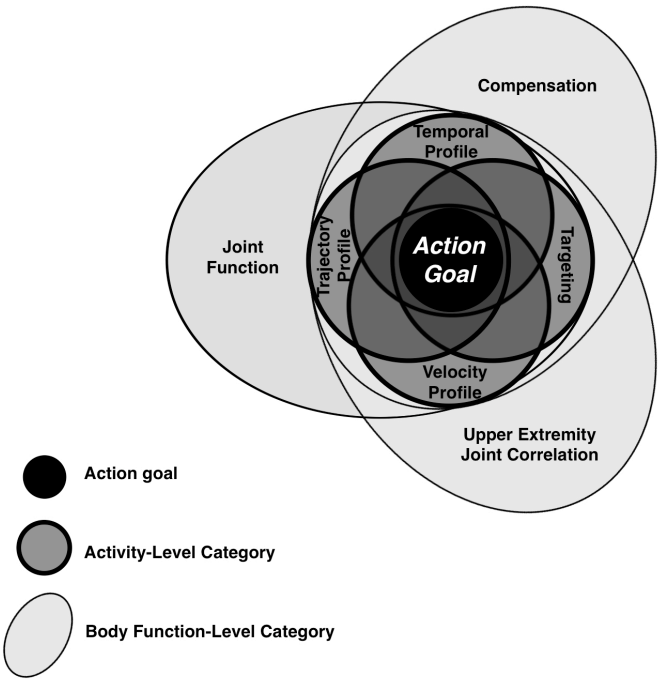

Figure 11. Simplified action representation for a reach and grasp movement. Distance relative to the center indicates the importance of each category relative to achievement of the action goal. Overlap among categories illustrates potential generalized correlation.

Calculation of the KIM. The KIM uses a database of both unimpaired person's movements and stroke survivor's movements to create a mapping function of impairment. While the KIM for each parameter is uniquely defined by the data from that parameter, the benefit is that all KIMs create a normalized number from 0 to 1 that indicates the level of impairment of that parameter. Zero is representative of the idealized (unimpaired) data and 1 represents the maximal deviation from that

idealized data during performance of the movement. Figure 12 shows how the data from the unimpaired movements and the stroke survivors' movements translate to a normalized mapping function. The top graph shows the probability density function for both groups of participants and the bottom graph shows the cumulative distribution function and modeled curves. The model curve is zeroed out where the majority of unimpaired data is grouped (at the left of the graph) since this is considered a performance level that would be considered 'normal.' The graph shows a sharp increase as the impairment gets worse and then levels out as it approaches 1. This model is based on fairly small sample of stroke survivors (n~15) so the ideal model curve may change as data from more participants with different types of impairments are collected.

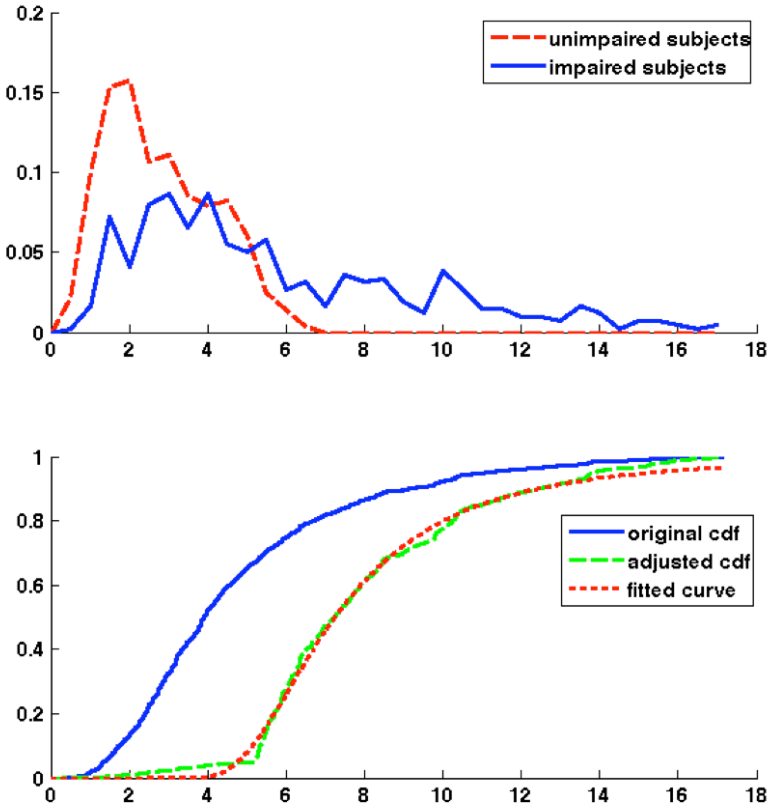

Figure 12. Top - An example probability density function of unimpaired and stroke survivor movement data. Bottom - The cumulative density function that the KIM values are based on. The red fitted curve is the model used in calculation.

The KIM also takes full advantage of the movement representation presented previously to track both individual and grouped kinematic parameters, as well as an overall impairment level. The attribute KIM measures different movement features (e.g. trajectory, compensation) and the category KIM combines attribute KIMs encompassed within that category. The 33 attribute KIMs and 7 category KIMs correspond exactly to the attributes and categories of the action representation. Ultimately, the composite KIM averages the category KIMs to create an overall assessment of the movement. The detailed attribute KIMs allow for

identification of how each component of the movement contributes to the user's functional impairment. The KIM values provide the therapist with a standard way to calculate and compare performance between and across participants and to track the rehabilitation progress quantitatively over time and across multiple kinematic dimensions. The emerging data set indicates that the KIM measure is highly correlated with clinical scales as well as clinical observations and is robust to variations in impairment and performance within and between participants. Table 2 shows example data of KIM values and raw kinematic values for three parameters. When used within the AMRR system, the KIM provides detailed, real-time information about the participant's movement and progress to the therapist, and can be used to inform the therapist's adaptation decisions.[18]

Table 2. Ranges of raw kinematic parameter values and their corresponding KIM value ranges. A KIM value of 0 means that parameter is in the unimpaired range and a KIM value of 1 indicates the maximal measured impairment. Note from this table that KIM values may increase when the raw value either increases, decrease, or both (raw value is either excessively large or small).

Attribute KIM value	Peak Speed (m/s)	Torso Flexion Compensation (deg)	Upper Extremity Joint Correlation
KIM = 0.0	0.42 - 0.60	0.0 - 3.1	0.95 - 1.0
$0.0 < \text{KIM} \leq 0.3$	0.38 - 0.42 or 0.60 - 0.64	3.1 - 5.8	0.88 - 0.95
$0.3 < \text{KIM} \leq 0.7$	0.35 - 0.48 or 0.64 - 0.67	5.8 - 8.2	0.80 - 0.88
$0.7 < \text{KIM} \leq 1.0$	< .35 or >.67	>8.2	<0.80

Evaluating the AMRR system compared to traditional therapy

While the pilot study has shown that AMRR therapy can elicit changes in important movement characteristics in three people with stroke with mild to moderate impairments, the study needed to be expanded to a larger control group study. The outcomes of the presented pilot study lay

the foundation for a clinical study at the Rhodes Rehabilitation Institute at Banner Baywood Medical Center. This study was conducted with a stable system, using a larger group of subjects and included a matched control group who received traditional repetitive task training of equal dosage. One of the main study hypotheses was that mediated rehabilitation will yield functional improvements equivalent to those seen in traditional therapy but will improve movement kinematics more because of the integrated feedback, which should also help the participants create generalizable movement strategies that can be applied to untrained tasks. Another hypothesis is that the AMRR system to be as well received by participants as traditional therapy and can be understood and utilized by a different physical therapist.

The pilot study revealed that each participant needed the therapy to be customized to his or her performance, and the clinical study quickly revealed that the customization had to be made in a complex network structure, not according to a pre-planned series of therapy options. Administering therapy in this manner has both benefits and disadvantages in terms of running a study comparing it traditional therapy in a standardized way. The benefit is that AMRR therapy is similar to traditional therapy in that the therapist has final say over what type of therapy is administered, in terms of target location, therapy focus, time spent per task, etc. This flexibility, however, leads to each participant receiving largely different therapy regimens from each other and one

aspect of the data analysis will be to determine if this greatly influenced the outcomes of that group.

Chapter 3

COMPARING THE OUTCOMES OF AMRR THERAPY AND TRADITIONAL REPETITIVE REACHING THERAPY IN PEOPLE WITH STROKE

While functional recovery is possible for people with chronic stroke,[3,53,54] the best way to administer rehabilitation to achieve this recovery is still not well understood. Specific challenges to providing therapy after stroke for the upper extremity are: addressing highly varied combinations of impairments, motivating the participant to perform repetitive therapy, promoting active learning, and balancing recovery of lost function and motor patterns.[35,43,55] The pilot study of the adaptive mixed reality rehabilitation (AMRR) system showed that this system is attempting to address these challenges using an interactive framework to train motor components related to both the completion of an activity and the quality of the movement during the task. AMRR integrates repetitive task training using a variety of smart objects with real-time motion capture and analysis to extract kinematic measurements as a useful quantification of arm motor performance[56] and provide a systematic assessment of typical upper extremity impairments. The kinematic data are also used to provide real-time and summary audiovisual feedback to the participant for self-assessment of the movement. The interactions are engaging to motivate task completion and promote generalized learning of motor elements related to the task. The tasks and feedback may be adapted to

focus on activity completion or on performing the activity within the additional context of re-establishing pre-morbid movement patterns (i.e. by improving movement quality) based on the participant's therapy needs. Feedback is presented within the context of a functional task, and the underlying principles for transitioning to different tasks or feedback streams are consistently applied to all participants. Details of the design principles of the system have been presented elsewhere.[35,55]

Other researchers have developed virtual environments to provide feedback on therapeutic tasks,[31,32,37] which have generally produced positive outcomes in people with stroke. While feedback can enhance motor learning,[57] the extent to which interactive therapies differ from traditional therapy is still under investigation. The purpose of the present study was to gather fundamental information on the value-added potential of the AMRR system by examining functional and kinematic outcomes from two groups of participants with chronic stroke, who received either traditional repetitive task reaching therapy (performance feedback provided by the therapist) or AMRR reaching therapy. While both groups should benefit from receiving a month of physical therapy, it was also hypothesized that AMRR therapy group would show greater and more generalized improvements in overall movement quality (e.g. more efficient trajectories, smoother acceleration and deceleration, reduced compensatory movements) due to active learning of associated motor elements. The kinematic evaluation paradigm also aims to address an

evasive and difficult issue - the quantification of quality of limb movement – that represents a substantial step towards discovering the relationship between the recovery of motor performance and the recovery of function.

Methods

Participants

Twenty-five participants with stroke were enrolled from Banner Baywood Medical Center and provided informed consent. The protocol was approved by the Banner Health and Arizona State University Institutional Review Boards (see appendix A). Participants were placed into the AMRR group (N= 11) or the Control group (N= 10), based upon random group assignments for the first four participants and subsequently adaptive randomization in an effort to minimize group differences in impairment severity, age, and time post-stroke. Inclusion criteria were: age between 35 and 85 years old; currently 6 months to 5 years post-stroke; right-sided hemiparesis; right hand dominant pre-stroke. Active range of motion criteria (adopted from the EXCITE trial[58]) were: shoulder flexion of at least 45°, elbow ROM of at least 30° to 90°, forearm rotation of at least 20° pronation or supination, wrist extension of at least 20°, at least 10° active extension of the metacarpophalangeal and the interphalangeal joint of the thumb and any two fingers. Exclusion criteria were: current or past seizure disorder; change in pain medication or alcohol use immediately prior to the study; current video game playing exceeding 1 hour/week; concurrent participation in another physical therapy program; injections of

anti-spasticity drugs within the past 3 months; inability to distinguish depth, shape, color, motion, pitch, timbre as measured by a sensory perception test; and ≤ 24 on the Mini-Mental State Examination. Table 3 shows participant demographics, as well as severity, baseline total upper extremity Fugl-Meyer score (maximum score of 126) and lesion location. The treating therapist and attending rehabilitation doctor determined the severity levels using: estimation of muscle tone; strength (mild: 4- to 5; moderate: 3- to 3+; and severe: less than or equal to 2+, as measured by the Manual Muscle Test); active range of motion (mild: within functional limits; moderate: significantly greater than inclusion criteria but less than functional limits; severe: meets inclusion criteria); and subjective assessment of the participant's coordination during finger-to-nose and reaching movements.

Table 3. Demographic information and baseline Fugl-Meyer Assessment (FMA) score (out of 126) for the AMRR (MR) participants and the Control (C) participants. Group summary or median values and (1st, 3rd) quartiles shown at the bottom where appropriate.

Subject	Age	Months post-stroke	Gender	Severity	FMA score	Lesion location
MR1	72	11	M	Severe	96	L pons
MR2	60	16	F	Mild-moderate	104	L pontomedullary junction
MR3	55	22	M	Moderate-severe	80	L parietal and frontal lobes and basal ganglia
MR4	66	6	M	Moderate	91	Multifocal embolic L hemispheric cerebral infarctions
MR5	74	7	M	Mild-moderate	109	Unknown
MR6	83	6	M	Moderate-severe	88	L frontal embolic infarctions
MR7	71	14	M	Mild-moderate	115	L thalamic hemorrhage
MR8	76	6	F	Mild	116	L basal ganglia and periventricular white matter infarct
MR9	71	8	M	Mild	99	L pons infarction
MR10	60	9	M	Mild	103	L pontine base and tegmentum
MR11	74	9	F	Mild	102	L internal capsule and corona radiata
C1	73	14	M	Moderate	102	L frontal lobe
C2	82	11	M	Mild	107	L parietal white matter
C3	70	11	F	Mild	104	L frontal lobe
C4	64	7	F	Mild	96	L basal ganglia
C5	55	51	M	Moderate-severe	97	Unknown
C6	74	12	M	Mild	106	L basal ganglia hemorrhagic infarct
C7	68	22	M	Moderate	107	ICH near L thalamus
C8	55	7	M	Moderate	114	Infarction in the L thalamus, L cerebral peduncle and L brain stem with subsequent hemorrhagic transformation
C9	69	11	M	Severe	89	L pons infarction
C10	67	12	F	Mild-moderate	107	Infarctions in the L corona radiata and lenticular nucleus and white matter of the L precentral gyrus
MR group	71 (61.5, 74)	9 (6.25, 13.25)	3F 8M	1 Sev. 3 Mod. 7 Mild	102 (92.25, 107.75)	
C group	68.5 (64, 73)	11.5 (11, 14)	3F 7M	1 Sev. 4 Mod. 5 Mild	105 (97, 107)	

Evaluations

While previous work (see Chapter 1) has shown that virtual or mixed reality rehabilitation environments can produce improvements in the movement that is being trained, the training should also impart on the stroke survivor a generalizable movement strategy. This means that the improvements that the stroke survivor makes during training will be seen in similar reaching movements in a context that was not previously trained. The evaluations performed on all subjects before and after therapy were designed to test both trained and untrained aspects of upper-extremity movements. The evaluations also distinguished between functionality (the ability to perform a movement) and movement quality (how well the movement is performed). Both objective measures, rated by a therapist or calculated from motion capture data, and subjective measures, having the participants rate their movements and quality of life before and after treatment, were measured. These evaluations become extremely important when trying to discover the different benefits participants receive from AMRR therapy versus traditional therapy. Each participant completed an evaluation, consisting of validated clinical tests and reaching tasks, within 5 days before starting and within 5 days after completing treatment.

Clinical outcome measures. The Wolf Motor Function Test (WMFT)[42] is a therapist-administered validated scale that rates (Functional Ability Score of 0 – could not perform to 5 – normal movement) and times complete upper extremity movements related to functional tasks. The tasks all have

a different end goal to the reach (or joint movement related to a reach), such as reaching to manipulating an object (i.e. reaching to grasp and turn a key). The movements during this test are externally cued (via a verbal 'go' by the evaluating therapist) and the participants are shown the movement and location of the object/equipment prior to starting. The subject is allowed 2 minutes to complete the task and the therapist moves on to the next task if a task cannot be completed in the allotted time. The Wolf Motor Function Test is most useful in measuring the function and general quality and time to completion of a wide variety of movements that require different joint ranges of motion and coordination.

The upper extremity Fugl-Meyer Assessment (FMA)[59,60] is a therapist-rated validated scale that includes joint range of motion, pain, sensation, and proprioception (0 – no function to 60 – full function in all areas), and motor function of the affected arm (0 – no function to 66 – full function in all areas), for a total possible score of 126. The FMA is used to provide a general rating of the physical and sensory abilities of the arm (such as feelings of sensation and pain or flexibility during range of motion exercises) and how well the arm can perform simple manipulation and movement tasks (such as different grasps). While the FM does not provide a high-resolution representation of upper arm movement, it does give a well-validated overall measure of upper-extremity impairments related to stroke.

The Motor Activity Log (MAL)[40] is a validated scale (0 – not used to 5 – used as much or as well as before the stroke) that allows stroke survivors to self-report their amount of use and quality of movement of their more impaired arm during activities of daily living (such as grooming, eating and dressing). The full Stroke Impact Scale (SIS)[41] is a normalized, validated scale (0% – no recovery to 100% – full recovery) to measure the self-reported impact stroke has had on areas such as social interaction, emotion, motor function and cognition.

The evaluating therapist who performed the FM and WMFT was blind to the treatment group designation. The researcher who administered the SIS and MAL was not blind to the treatment group.

Reaching tasks. The participants completed a trained and an untrained reaching task during which motion capture data from the right hand, right arm and torso were collected. The trained task was 4 sets of 10 reach-to-grasp movements to a stable cone object at 4 locations. The four locations used were at the midline with the cone on the table (gravity-eliminated movement) and 6 inches off the table (anti-gravity movement), and on the right side with the cone on the table and 6 inches off the table. The target distance was based on the individual participant's active-assisted reach. These targets were used for both the pre- and post-evaluation, as well as the therapy, and gave the participant a therapy goal beyond his or her active reach. All reaches started from a consistent rest position (marked with tape and monitored by the therapist) and were self-initiated at the

participant's own pace. Reaching to grasp a cone was a therapy task available to both groups, although the time spent on that task varied per person based on the therapist's discretion and was more likely to be used during AMRR sessions.

The untrained movement task was a series of reaches-to-touch one of nine 1" buttons embedded within a rectangular upright stand (button box test). The nine touch-sensitive buttons were arranged in three rows and three columns, equally spaced by 5 inches, placed so that the middle button aligned to the participant's sternal angle and provide a range of functional reaching positions both ipsilateral and contralateral to the subject's dominant side, as well as to the midline. Each button lit three times in a pseudo-random order. The light provided an external stimulus to initiate the reach and the light turned off when the button was successfully touched. The participant was instructed to reach the target as quickly as possible. The location of the target button was unknown to the participant until immediately prior to the start of the reach. The elements of this task that differentiate it from the trained tasks are unknown target location, instruction to move as quickly as possible once the button lights, triggering from an external stimulus within a defined latency, smaller targets, and greater off-sagittal target locations. A picture of a participant using the button box test can be seen in Figure 13. Technical details and further rationale for the design of the button box test can be found elsewhere.[61]

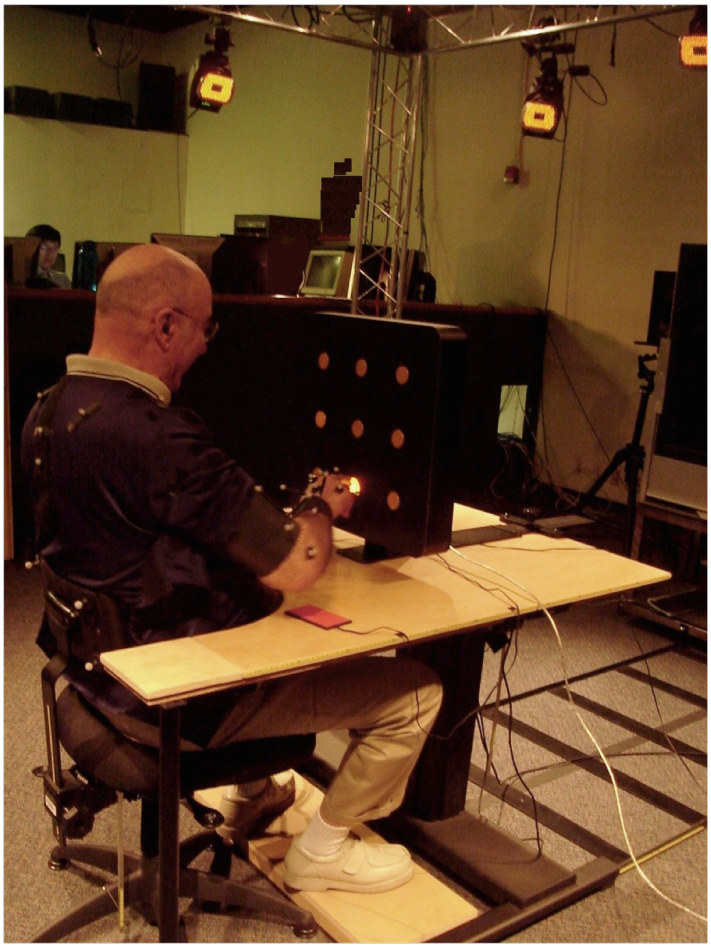

Figure 13. A stroke survivor reaching to push the lighted button while using the button box test. He is wearing motion capture markers to collect simultaneous kinematic data.

Treatment protocols

Participants from the AMRR group received 1 hour of therapy (not to exceed 120 reaches) three times a week for four consecutive weeks (12 sessions in total). Participants from the Control group received therapy of a matched amount of time on the same schedule. Tasks in both groups were performed with the right hand only. The same therapist administered treatment to both groups. The Control group received upper extremity therapy exemplified by pegboard reaching tasks, bead threading reaching

tasks, cone reaching tasks, range of motion and coordination exercises. During therapy with more severely impaired participants, the therapist focused on real-time instruction based on her perception of movement quality, while she tended to summarize feedback to higher functioning participants after they finished a set of reaches. If the participant was not improving with verbal cues, the therapist guided the arm with active-assisted movements for a few reaches. The therapist also monitored compensation by using her hand to provide a tactile cue related to excessive shoulder or torso movement.

The AMRR group performed reaching tasks to three different objects: a virtual point (no physical target), a 3” physical button, or a physical cone. The targets were either on the table or 6 inches above it. Motion capture data collected from the participant’s right hand, right arm and torso were transformed into kinematic measurements (see *Kinematic assessments*, below) and used to provide audio and visual feedback to the participant during the task, evaluate the progress of the participant, and adapt the therapy accordingly. The feedback provided real-time visual cues about trajectory error and hand rotation and real-time audio indications of the speed of the hand’s movement, elbow extension and torso and shoulder compensation. The system also provided audio and visual cues when the task was successfully completed and provided a visual summary of where the trajectory errors had occurred to aid in forward planning. A picture of a participant using the system is shown in

Figure 14. Further explanation of the feedback theories and applications[35,55] has been presented elsewhere.

Figure 14. Picture of a participant (center) using the AMRR system with the treating therapist (right) at Banner Baywood Medical Center.

Data Analysis from Pre-Post Evaluations

Kinematic assessments. The kinematic parameters calculated during the trained task (cone reaches) and untrained task (button box) cover both activity level and body function aspects of recovery[43] and are representative of key areas of impairments caused by a stroke.[18,55] The parameters for the trained task kinematic analysis were grouped by common functionality into the following seven categories: 1) Trajectory–horizontal and vertical trajectory efficiency and consistency; 2) Targeting–error and consistency of hand placement during the manipulation phase of

the reach; 3) Temporal– peak reach speed magnitude and consistency and time to target; 4) Velocity– smoothness of the reach and how well the velocity curve adheres to an ideal bell shape; 5) Compensation – excessive shoulder or torso movements during the reach; 6) Joint Function – shoulder, elbow and wrist range of motion and consistency; 7) Joint Correlation – synergy between key joint pairings of the arm.[55] The kinematic parameters were further normalized into a Kinematic Impairment Measure (KIM) score.[18] The KIM maps each parameter onto a function that ranges from 0 (within the idealized range of movement) to 1 (maximal deviation from this metric) modeled on a set of reaching data from both able-bodied people and people with stroke at different levels of impairments (i.e. mild, moderate, severe). Table 2 (see Chapter 2) illustrates of how ranges of KIM values map to raw data for three example kinematic attributes: peak hand movement speed, maximum torso flexion during the task and the correlation value between two joints. The conversion of data from attribute specific units of measurement to a common scale allows for parameters to be combined into the seven category level KIMs and for category values to be combined as a weighted average into one composite KIM, providing higher-level summaries of performance. For instance, peak speed (second column, Table 2) of the hand is considered unimpaired between .42 and .60 meters per second. When the speed either increases (e.g. due to ballistic movement) or drops (e.g. due to weakness) indicating an elevated impairment, the KIM

correspondingly increases. KIM values were calculated for each location of the cone reaches and each button location and respectively averaged together to obtain the kinematic assessment for the trained and untrained tasks. The percent change in composite KIM for the trained task after treatment [(composite KIM post – composite KIM pre) / composite KIM pre * 100%, and transformed so a positive change indicates a reduction in KIM] was calculated for each subject. This percent change gives a normalized measure of the overall change in movement quality for each participant. A subset of four parameters, chosen from the parameters comprising the seven categories, was used to evaluate the untrained task. These categories (2 activity level – Trajectory and Velocity - and 2 body function – Torso compensation and Joint correlation) were chosen to represent the data because they are most relevant to the button reach task. Composite and category KIM for the untrained task were not compared because the ideal weights for combining the parameters are still under investigation.

Statistical analysis. Due to small sample sizes, all statistical analyses were performed using non-parametric methods. The demographic data for the two groups were compared using the two-sample Wilcoxon ranked sums test to demonstrate equivalent participant groups. Data from the clinical scales were analyzed within each group using a paired Wilcoxon signed-ranks test and between groups with the two-sample Wilcoxon ranked sums test. Demographic and clinical scale data were tested for

significance withα = .05. The overall composite KIMs and each of the seven category KIMs (see previous subsection for details) derived from the trained task reach kinematic data were assessed within group using paired Wilcoxon signed-ranks tests to determine group changes after treatment. Each comparison used a significance level of α = .01875, calculated by applying a Bonferroni correction for the 8 comparisons to a maximum family-wise error of .15. The distributions of the percent change in composite KIM were compared between groups using a Kolmogorov-Smirnov two-sample test, which is used to determine if two distributions are identical in terms of location (mean/median) and variance at α = .05. The four kinematic parameters (see previous subsection for details) derived from the untrained task kinematic data were also assessed within group using paired Wilcoxon signed-ranks tests to determine changes after treatment. Each comparison used a significance level of α = .0375, calculated by applying a Bonferroni correction for the 4 comparisons to a maximum family-wise error of .15. The application of conservative Bonferroni corrections to an increased family-wise alpha of .15 was an attempt to balance the occurrence of Type 1 errors (false positives) and loss of power[63] in analyses with multiple comparisons.

Case Studies – Two subjects' journeys through using the AMRR System

In order to best understand the use of AMRR, two case studies will be presented to show the progress and therapy protocols for two

participants that had different clinical characteristics. These case studies highlight how the feedback was utilized to address certain aspects of movement quality and how the participants' kinematic results changed in response to the different types of audio and visual feedback. Individualized training plans, kinematic improvements measured over the entire therapy period, and the changes in relevant clinical scales and kinematic movement attributes before and after the month-long therapy are presented for the two participants. The substantial improvements made by both participants after AMRR therapy demonstrate that this system has the potential to considerably enhance the recovery of stroke survivors with varying impairments for both kinematic improvements and functional ability. The case studies are further explained elsewhere as well.[63]

Prior to starting the 12 therapy sessions, the attending rehabilitation physician and therapist determined the participant-specific movement impairment profile based upon their observations, clinical scale scores and the KIM scores. The movement impairment profile ranks the movement aspects (e.g. insufficient elbow extension, inefficient trajectory) that require focused training. Using the individual's impairment profile as an overall guide and starting point, the therapist and media specialist create and continually adapt a training plan during the therapy. This dynamic therapy plan is based on all prior knowledge of the participant's abilities and progress, as well as the anticipated therapy outcome for the

participant, as tracked by the therapist's observations and the KIM scores. This plan can utilize focused feedback streams, different physical environments and verbal or physical interaction by the therapist. At the start of each therapy session, the participant performed 10 reaches to the target selected by the therapist, without any audio or visual feedback. The therapist used the movement performance during these reaches to decide how to begin training that day and to track the retention of improvement from the previous sessions. Whenever a new feedback parameter was introduced during the training, the participant performed exploratory trials to learn the new mapping and the therapist and media specialist provided verbal guidance to aid in the participant's understanding. This section presents the training process and results from two stroke survivors (Participant 1 & 2) who received AMRR therapy, illustrating how the system can be used in the clinic. The participants' individualized training plans, kinematic improvements measured over the entire therapy period, and the changes in relevant clinical scales and kinematic movement attributes before and after the month-long therapy are presented. The substantial improvements made by the participant after AMRR therapy demonstrate that this system has the potential to considerably enhance the recovery of stroke survivors with varying impairments, in terms of both kinematic improvements and functional ability. The results also highlight some of the improvements that may increase the benefit provided by the AMRR therapy.

Participant 1's Movement Impairment Profile and Training Plan

Participant 1 was a 74-year-old male 7 months post stroke who had a left-sided middle cerebral artery infarct resulting in *mild to moderate* overall impairment. He is listed as MR5 in Table 3. Participant 1 could accurately reach the target, but did so with greatly reduced speed. He also had reduced elbow extension and shoulder flexion and horizontal adduction throughout the reach and compensated by using increased torso flexion and rotation. The rehabilitation doctor and therapist determined the elements and ranking of his movement impairments as follows:

1. Insufficient elbow extension
2. Insufficient shoulder flexion
3. Insufficient speed
4. Slow initiation of movement
5. Torso compensation

However, the rankings of each aspect of impairment do not necessarily indicate the sequence of training. The AMRR training is combinatorial and the progression of the training plan is completely dynamic. In this participant's training, the therapist started with an introduction to the system, which focused on the participant having a basic understanding the activity level feedback (targeting, trajectory and speed) that is present continuously throughout the therapy. After the introduction, the therapist focused on reducing torso compensation by introducing a

disruptive sound that is triggered by excessive trunk rotation or flexion. The expectation of this approach would be to concurrently increase elbow extension since excessive torso compensation is often correlated to insufficient elbow extension. To further increase elbow extension, the therapist introduced a positive audio feedback that is driven by elbow range of motion (as the elbow extension increases, so does the volume, range of pitch, and harmonic richness of accompanying orchestral music). In addition, the therapist tightened the targeting accuracy constraint for successfully reaching the target (the participant's hand needed to be very close to the target to receive an indication of reach completion) and moved the target position further from the rest position to encourage extension of the elbow. As the participant improved his elbow extension and torso compensation, the therapist changed the therapy focus to address other impairments such as insufficient speed, slow initiation and shoulder flexion/adduction. A complete summary of the training foci and sequence can be found in Figure 15b. Although the feedback given to address a specific movement attribute is expected to have a strong influence on the training of that parameter, secondary and indirect influences between movement and feedback parameters need to be considered. Because all feedback parameters are components of an integrated media composition, these secondary connections are continuously used to enhance the training.

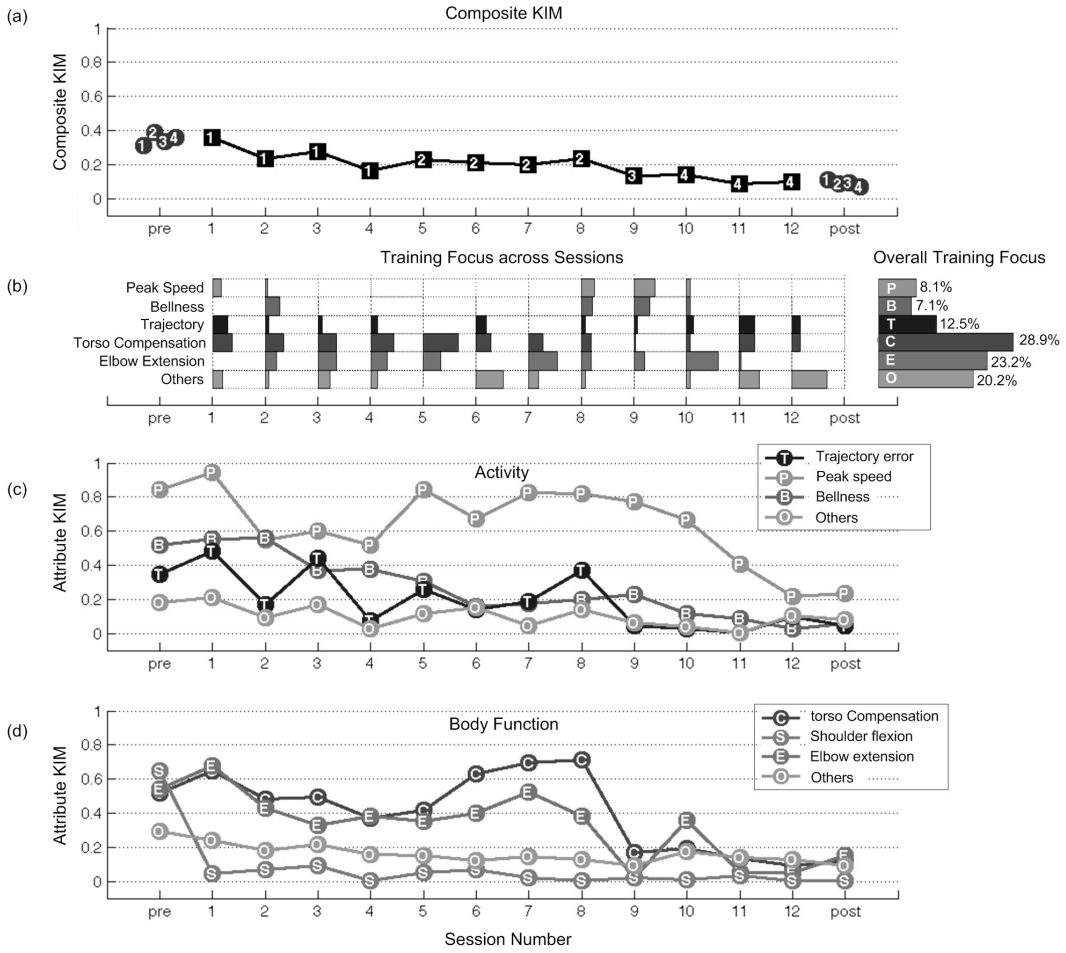

Figure 15. Participant 1 case study results: (a) composite KIM measures (numbers shown in the composite KIM graph indicate which number target was evaluated at the beginning of that session. All four targets were evaluated during the pre- and posttests and these are all shown as the grouped circles in the graph), (b) attribute focus throughout therapy, (c) activity level attribute KIMs, (d) body function level attribute KIMs throughout therapy, including the pre- and post-test evaluations. All measurements made during the initial set of 10 reaches (before training started, no audio or visual feedback).

Participant 1's training protocol and results throughout training

Participant 1 spent a majority of his training working on body function level parameters, such as elbow extension and torso compensation and the activity level parameters of speed and velocity profile bellness[18] (a measure indicative of smooth acceleration and

deceleration, without hesitations, or phases, when approaching a target). The adaptive and interconnected nature of the AMRR therapy, and the nonlinearity of motor learning[64] make extracting direct correlations between training foci and local improvements difficult. However, there is a trend for consistent improvement in his composite KIM (shown per target) throughout the therapy (Figure 15a). The percentage of each training focus used during each session, along with the overall training foci across all sessions, is shown in Figure 15b. Figure 15c shows how the three activity level parameters (Peak speed, Trajectory error and Velocity bellness) that were focused on the most during training, along with a combined measure of the remaining activity parameters, changed throughout the therapy. Figure 15d reveals how the three body level parameters (Shoulder flexion, Torso compensation and Elbow extension) that were focused on the most during training, along with a combined measure of the remaining body function parameters, changed throughout the therapy. The definitions and method of calculation of activity level parameters (e.g. Trajectory error, Peak speed, Bellness) and body level parameters (e.g. Shoulder flexion, Torso compensation and Elbow extension) can be found elsewhere.[6,18] Note that for KIM values in Figure 15, a smaller number corresponds to less impairment and therefore better movement performance. If the composite KIM value is close to zero, the participant's overall movement performance is close to an unimpaired movement.

Participant 1's kinematic and clinical scale pre- and post-test results

Participant 1 improved many kinematic parameters substantially, resulting in an overall impairment reduction (Figure 16). This participant reduced his composite KIM by almost 75% and reduced his category KIMs by at least 50% in 6 out of 7 categories. Table 4 also shows pre- and post-training raw values and KIM values for five kinematic attributes on which the training was focused. Participant 1 had a mixed result in his clinical scales (see Figure 17). Both self-reported scales, the Motor Activity Log (MAL) and Stroke Impact Scale (SIS), had reduced scores after training. The MAL amount of use decreased from an average of 3.6 to 2.1 and the quality of movement decreased from an average of 2.88 to 2.08. The SIS score changed from 67.4% recovery to 61.0% recovery. However, the Wolf Motor Function test (WMFT), which is rated and timed by a clinician, showed large improvements in both the functional activity score (from an average of 3.6 to 4.4) and the task completion time (from 110.8 seconds to 74.7 seconds). The Fugl-Meyer had small increases/decreases or no change in score, depending on the component.

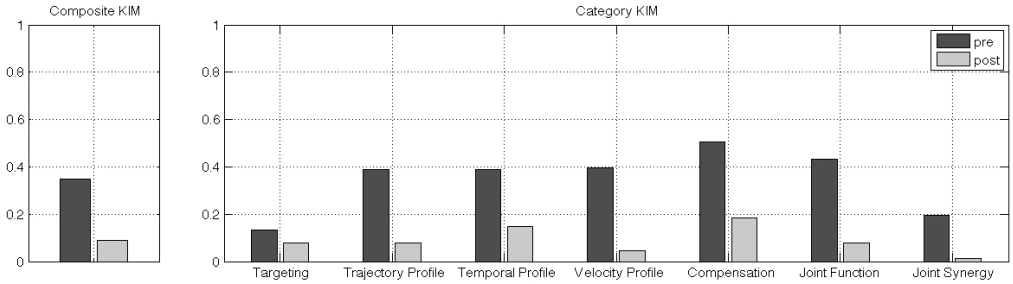

Figure 16. Left: improvement in Participant 1's composite kinematic impairment measure (KIM); right: improvement within each of the category KIMs.

Table 4. Average pre- and post-AMRR therapy raw values and KIM values for 5 attributes that were heavily focused on during the training of Participant 1 (Number of Phases refers to the number of distinct sections in the velocity profile due to hesitations while reaching and % AAR is the percentage of range of motion achieved compared to an Active Assisted Reaching).

	Peak Speed		Number of Phases		Elbow Extension		Shoulder Flexion		Torso Flexion	
	m/s	KIM	Raw #	KIM	% AAR	KIM	% AAR	KIM	Degrees	KIM
Pre	0.26	0.86	5.4	0.71	70.8%	0.53	82.2%	0.68	6.7	0.51
Post	0.38	0.24	1.2	0.08	88.4%	0.19	103.9%	0.0	3.2	0.12

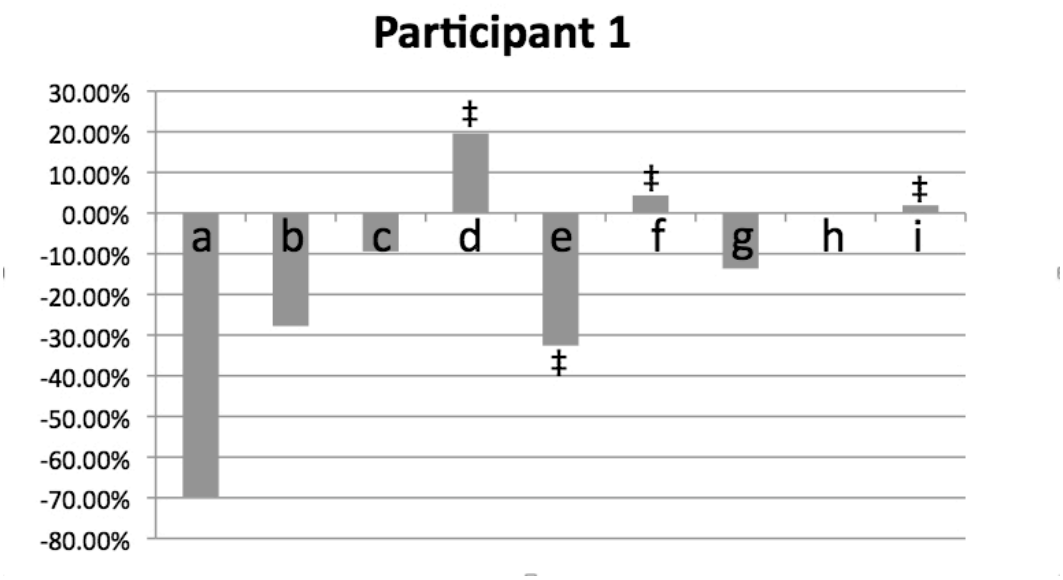

Figure 17. Participant 1's percent change from the pre-test to the post-test for four different clinical scales. (a – Motor Activity Log Amount of Use, b – Motor Activity Log Quality of Motion, c – Stroke Impact Scale, d – Wolf Motor Function Test Functional Activity Score, e – Wolf Motor Function Test task completion time, f – Fugl-Meyer Joint Range of Motion score, g – Fugl-Meyer Joint Pain score, h – Fugl-Meyer Sensation/Proprioception Score, i – Fugl-Meyer Motor Function score; ‡ indicates a change associated with improvement)

Participant 1's kinematic and clinical scale results discussion

Participant 1 initially presented with *mild-to-moderate* impairment, mainly attributed to reduced distal joint use and very slow initiation and

speed of movement. After 12 hour-long AMRR therapy sessions, he showed a substantial improvement in all kinematic parameters on which his training was focused. However, as seen in Figure 15, the key attributes (e.g. torso compensation, elbow extension, speed) appear to require 8 sessions to show consistent improvements compared to other attributes. This timeline suggests that this participant needed 8 sessions to understand what information the feedback was conveying, connect that information with how his body was moving, and initiate integrating this information into a modified motor plan. The consistency of the improvements throughout the last few therapy sessions and in the post-test indicate that the participant was no longer relying directly on the feedback to adjust his motion, but instead had created new movement patterns that already integrated those adjustments. This participant's results also highlight the importance for the therapy to adapt in real-time based on the participant's performance throughout the therapy intervention. Participant 1 presented with markedly decreased shoulder flexion during the pretest. However, the consistently low shoulder flexion KIM, indicating very low deficit in that attribute, (Figure 15d) throughout the 12 therapy sessions suggests that the initially elevated baseline measure was anomalous.

Although the magnitude and direction of the correlations between the training focus, the target location and changes to attribute KIMs are still under investigation Figure 15b-d show some clear overarching

relationships between these factors. For example, torso compensation was heavily trained during the first seven therapy sessions. While the torso compensation KIM did show an improvement during the first four sessions, when the target changed from Target 1 (ipsilateral to the right hand) to Target 2 (at the midline), shown in Figure 15d, Session number 5, torso compensation began to worsen. However, with consistent training, this attribute began to improve again after session eight and continued to be very low throughout the remainder of training and during the post-test, regardless of the target location.

Overall, the composite KIMs (shown per target in Figure 15a) improved during the month-long therapy sessions. The composite improvement was driven by improvements in a majority of measured kinematic attributes. The improvements were also consistent across all of the targets, including Target 1, which was only trained during the first four sessions, and Target 3, which was only trained during one session. These observations suggest the occurrence of a generalizable, integrated motor learning with improvement across most kinematic attributes for all target locations.

Participant 1 improved substantially on both portions of the WMFT. His average Functional Activity Score (FAS) increased by almost 20% and his total task completion time was reduced by over 30%. Both results are relevant to his training since he focused on improving his movement quality and increasing his task speed during the AMRR therapy. The FM

showed mixed results, which was not unexpected given the short one-month duration of the therapy. The FM also measures many aspects of the upper extremity that the AMRR therapy was not intended to address such as pain and sensation.

While Participant 1's kinematic and WMFT improved, he did not seem to be fully aware of his level of improvement. The self-reported scale (MAL and SIS) scores both declined from the pre-test to the post-test. The AMRR system is designed to make the participant more aware of their body, how the body is moving and the impairments related to the movements. Participant 1 may have only become aware of his body functions after receiving AMRR training, but focused more on his impairments than on other behavioral changes that could have resulted from the training. Finding intuitive and engaging means to illustrate his progress to him throughout the therapy and during the post-test evaluation could have more favorably influenced his health related quality of life impression.

Participant 2's Movement Impairment Profile and Training Plan

Participant 2 was a 66-year-old male 6 months post stroke who had multifocal embolic left hemispheric cerebral infarctions resulting in *moderate to severe* overall impairment. He is listed as MR4 in Table 3. Participant 2 presented with an inability to smoothly reach to the target, caused by a reduced range of motion, impaired inter-joint coordination, and ataxia. He had insufficient elbow extension, shoulder range of motion

and supination, and consequently demonstrated compensatory behavior of increased use of the torso and elevation and protraction of the shoulder. The attending rehabilitation doctor and therapist determined his movement impairment profile, ranked in order of importance for influencing recovery as follows:

1. Insufficient elbow extension
2. Insufficient shoulder range of motion
3. Shoulder and torso compensation
4. Ataxia
5. Targeting

This participant also started training with a system introduction that permitted him a basic understanding of how his movement could be mapped to the audio and visual feedback. Because the participant reached with multiple pauses during the movement rather than a smooth, continuous extension of the elbow, the therapist decided to focus on the audio feedback that maps end point speed to musical rhythm. This approach helped the participant concentrate on creating a smooth acceleration and deceleration of musical notes, which can lead to a bell-shaped velocity curve. The therapist also enabled the positive audio feedback linked to elbow extension so the participant would be encouraged to increase his elbow range of motion and implicitly learn the optimal spatial and temporal relationships between the elbow's joint angle and the location and speed of the hand. To further incentivize the use of

the distal joints, the therapist also used the disruptive sound linked to torso compensation to discourage usage of trunk rotation or flexion to move the hand forward. When the training moved to off-table targets (Targets 3 & 4), the trajectory error and torso compensation increased as a result of the more complex joint space and needing to work against gravity to reach the target. To address these issues, the therapist focused the training on hand trajectory (by adapting the sensitivity of image particle deviation in both the horizontal and vertical direction) and torso compensation (by adjusting the amount of torso compensation required to elicit the related audio feedback). A complete summary of the training foci and sequence can be found in Figure 18b.

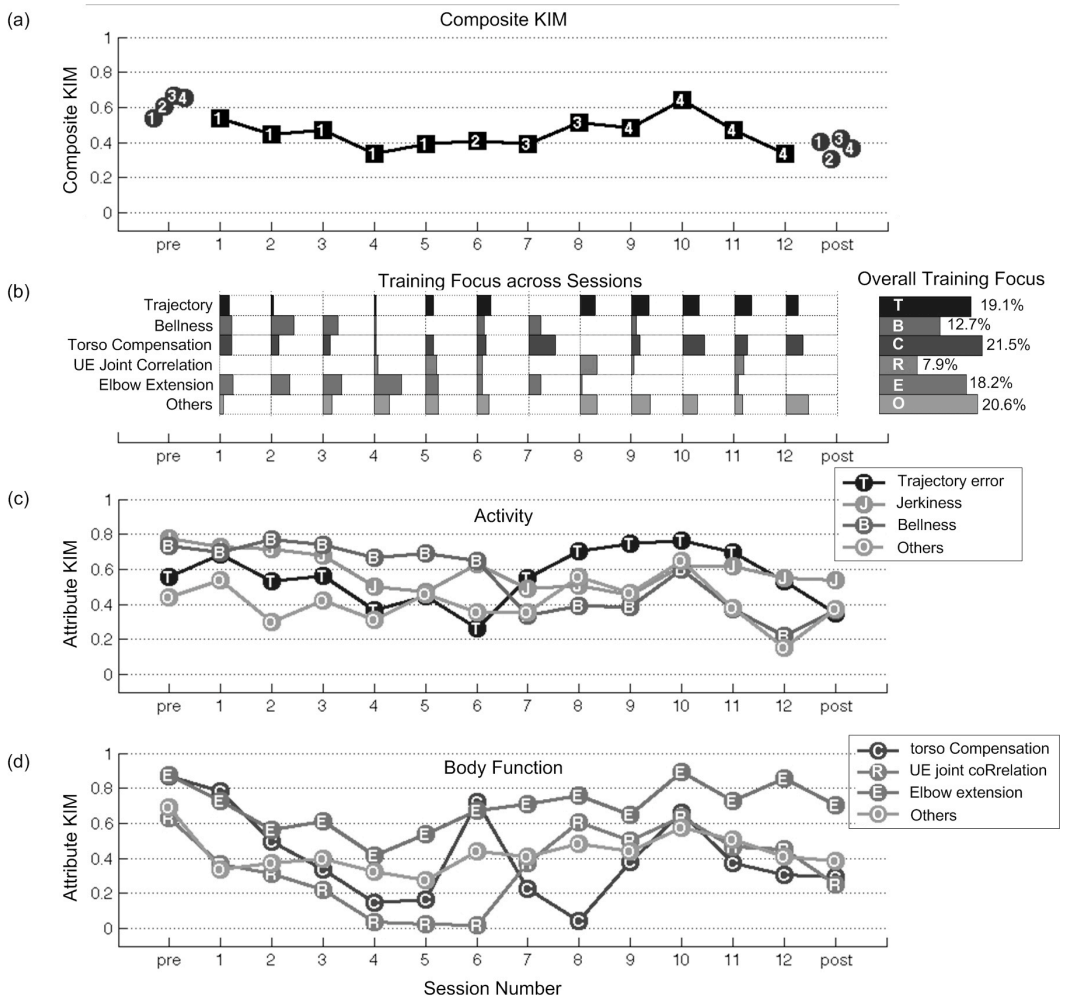

Figure 18. Participant 2's case study results: (a) composite KIM measures (numbers shown in the composite KIM graph indicate which number target was evaluated at the beginning of that session. All four targets were evaluated during the pre- and posttests and these are all shown as the blue circles in the graph), (b) attribute focus throughout therapy, (c) activity level attribute KIMs, (d) body function level attribute KIMs throughout therapy, including the pre- and post-test evaluations. All measurements were made during the initial set of 10 reaches (before training started, no audio or visual feedback).

Participant 2's training protocol and results throughout training

Participant 2 spent a majority of his training working on body function level parameters, such as elbow extension and torso and shoulder compensation, and the activity level parameters of trajectory

error and velocity profile bellness (percentages of each training focus is shown in Figure 18b). Figure 18 also shows the interconnected nature of training: the important body function of elbow extension is trained within the context of a strongly related activity parameter (velocity profile) for this participant. This participant demonstrated a trend toward improvement in his composite KIM throughout the therapy (Figure 18a). Composite KIM improved for all targets from pretest to posttest. The three activity level parameters (Trajectory error, Jerkiness, and Velocity bellness) that were focused on most during training, along with a combined measure of the remaining activity parameters, improved throughout the therapy (Figure 18c). The three body level parameters (Torso compensation, Upper extremity joint correlation and Elbow extension) that were focused on most during the training, along with a combined measure of the remaining body function parameters, also improved throughout the therapy (Figure 18d).

Participant 2's kinematic and clinical scale pre- and post-test results

Participant 2 improved in many kinematic parameters, resulting in an overall impairment reduction, as seen in Figure 19. This participant reduced his composite KIM by 40% and reduced his category KIMs by at least 40% in 5 out of 7 categories. Table 5 also shows pre- and post-training raw values and KIM values for five kinematic attributes on which the training was focused. Participant 2 also had positive changes in a majority of his clinical scale results (Figure 20). His MAL amount of use increased from an average score of 0.8 to 1.36 and his quality of use

increased from an average score of 0.88 to 1.12. His SIS improved from a 76.7% recovery to an 83.1% recovery. The Wolf Motor Function test (WMFT), which is rated and timed by a clinician, showed improvements in the average functional activity score (from 2.6 to 3.1) and the task completion time (from 409.3 seconds to 380.5 seconds). The Fugl-Meyer had a small decrease or no change in most sections, except motor function, which improved from a score of 37 to 41 (out of 66).

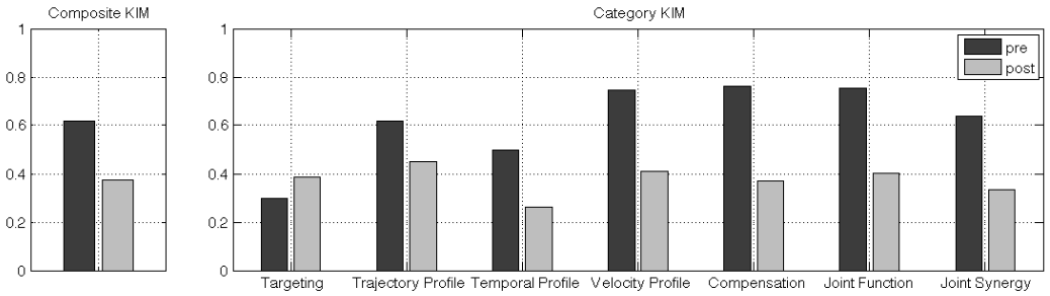

Figure 19. Left: participant 2's overall kinematic impairment measure (KIM) improves from the pre- to post-test; right: change in each KIM category from the pre- to post-test.

Table 5. Average pre- and post-AMRR therapy raw values and KIM values for 5 attributes that were heavily focused on during the training of Participant 2 (Number of Phases refers to the number of distinct sections in the velocity profile due to hesitations while reaching and % AAR is the percentage of range of motion achieved compared to Active Assisted Reaching).

	Horizontal Trajectory Error		Number of Phases		Elbow Extension		Upper Extremity Joint Correlation		Torso Flexion	
	cm	KIM	Raw value	KIM	% AAR	KIM	Raw value	KIM	Degrees	KIM
Pre	4.6	0.72	6.6	0.79	42.0%	0.87	0.81	0.57	12.6	0.87
Post	3.1	0.44	2.3	0.29	60.0%	0.70	0.90	0.19	4.6	0.28

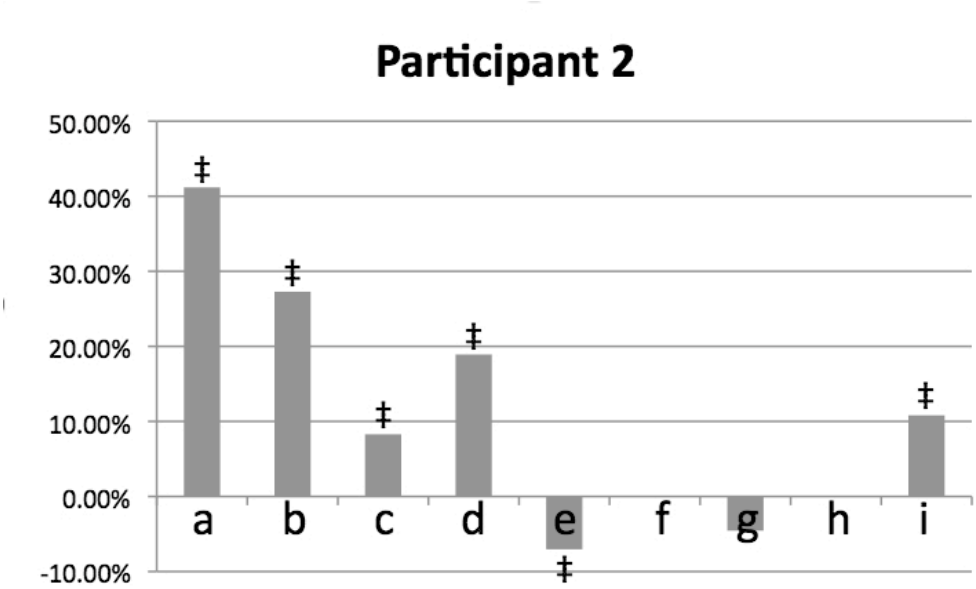

Figure 20. Participant 2's percent change from the pre-test to the post-test for four different clinical scales. (a – Motor Activity Log Amount of Use, b – Motor Activity Log Quality of Motion, c – Stroke Impact Scale, d – Wolf Motor Function Test Functional Activity Score, e – Wolf Motor Function Test task completion time, f – Fugl-Meyer Joint Range of Motion score, g – Fugl-Meyer Joint Pain score, h – Fugl-Meyer Sensation/Proprioception Score, i – Fugl-Meyer Motor Function score; ‡ indicates a change associated with improvement)

Participant 2's kinematic and clinical scale results discussion

Participant 2 initially presented with *moderate to severe* impairment, mainly attributed to reduced distal joint use, excessive compensatory use of his torso and shoulder and ataxia. After 12 hour-long AMRR therapy sessions, he showed a substantial improvement in most kinematic parameters on which his rehabilitation was focused. While his improvements were not consistent throughout the therapy, with many attributes varying in KIM values from session to session, most of the attributes trended towards overall improvement. Inconsistencies could be due to target and feedback adaptations during the training or to personal

learning patterns. When the target was raised off the table (Targets 3 and 4), this participant showed a poorer trajectory KIM, most likely due to increased error in his vertical trajectory. However, the therapist adjusted the system to focus on this problem, and trajectory error returned to levels comparable to those observed during gravity-eliminated training. The upper extremity joint correlation was also affected when the targets were placed in off the table locations, which required a more complex joint coordination, but showed an overall improvement of over 50% during the post-test. The category KIM results from the pre- and post-test evaluation sessions also show that this participant had improvements over a majority of the categories, even categories that include kinematic attributes that were never the focus of training. The composite KIMs (shown for each target in Figure 18a) improved during the month-long therapy sessions for all targets and in all category KIMs except the targeting category. This finding suggests that the system promotes integrated generalizable learning, caused by the integrative nature of the feedback. Also, focused training of a movement component at one target corresponds to the improvement the trained component, as well as related components, at multiple target locations.

Although Participant 2 saw substantial progress in many aspects (including the velocity profile, compensation and joint function categories), he still had residual moderate impairments in many of the category KIMs at the post-test (Figure 19). He achieved improved movement patterns

through better distal joint function and decreased compensation but the targeting aspect of his movement may have been negatively influenced y the development of these new patterns. Because the AMRR system tracks and displays such detailed kinematic data, this information can be used to assess whether additional therapy is needed and upon which aspects of the movement consequent therapy should focus. For example, additional training sessions may have addressed the targeting category KIM more effectively.

Participant 2 showed improvements in several clinical scales including an almost 20% improvement on his average FAS of the WMFT and over 5% decrease on his total task completion time (results shown in Figure 20). The completion time improvement is relatively low because this participant was unable to perform two of the complex tasks of the WMFT during both the pre- and post-test, due to the severity of impairment. The AMRR is not yet designed to train fine motor control, which is the basis for completing many of the complex tasks. Removing the tasks Participant 2 was unable to perform would have resulted in a 17% decrease in total task completion time.

Participant 2's self-reported scales (MAL and SIS) showed that the MAL amount of use improved by over 40%, the quality of use improved by almost 30% and his SIS recovery score increased by about 8%. Although his scores on both sections of the MAL were relatively low, the detailed scale results show that he reported now performing two tasks that he

could not do in the pre-test. Additionally, he increased his ratings on many other tasks by one point. Anecdotal evidence from this participant indicates that he was very self-motivated and would often practice therapy tasks at his home, which may have contributed to the improvements recorded in his health related quality of life measures.

Impact of the two case studies

The AMRR system provides a useful tool for therapists in structuring therapy based on kinematic parameters and enhancing therapy outcomes through engaging, interactive audio and visual feedback. The two case studies presented here show that the AMRR system allows the therapist to adapt the training in real-time based on the participant's progress. The AMRR system provides a platform for integrated therapy, meaning that even while one or two attributes may be the focus of each set of therapy, the other attributes relating to the movement are being trained as well, as measured by the KIM improvements for both participants. The AMRR system also enables the participants to transfer the improvement from the trained reach and grasp task to functional tasks and arm movements related to functional tasks, such as those measured in the Wolf Motor Function Test (WMFT). Compared to the pre-test, both participants improved their functional scores and time to task completion, as measured by the WMFT, substantially.

However, the AMRR system had a less obvious positive impact on the self-reported evaluations. Because the MAL and SIS are quality of life self-

reports, these mixed results indicate that each participant may need more individualized dialogue and encouragement, and tools for intuitive self-monitoring of their progress to ensure that their daily activities and internal sense of quality of life is also being positively impacted by the therapy. Participants who are not self-motivated may also need a clear demonstration of their progress and improvements and possibly direction on how to use strategies learned in the clinic in activities of daily living. Incorporation of these features into the AMRR system is an area of future research.

The evaluation and feedback frameworks established within the clinic-based system are now being applied to the development of a low cost home-based system that participants can use at their convenience with regular consultations and therapy adaptations made by a trained therapist. This home-based system has the potential to provide a low-cost way to extend training and can help empower the stroke survivor to become the driving force behind his or her recovery. A key challenge in creating a home-based system is developing an effective and efficient automated adaptation of the feedback based on real-time analysis of participant performance. Current research involves modeling the therapist's decision-making process (e.g. determining the training foci of each session and adapting which feedback streams are necessary and how sensitive each stream should be to error) based on clinical data from the current study.

Group comparison results

This section will present the full statistical analysis of the two groups. These results highlight the consistent changes in many parameters of movement quality seen in the AMRR group that are absent from the Control group's results. These results also hold over an untrained task that employs different cognitive strategies. Clinical scale results are also shown, highlighting that while the two groups make improvements in function (as measured by the WMFT and the motor function section of the FMA), the Control group has significantly better improvements in both the motor function and passive arm measurement sections of the FMA.

Four participants (2 from the AMRR group and 2 before group assignment) withdrew from the study for unrelated medical reasons or because of unreliable transportation. The resulting two groups that completed treatment were not significantly different in age, time post-stroke or baseline Fugl-Meyer (all p-values > 0.05, data shown in Table 3).

Clinical scale results

Median values and 1st and 3rd quartiles (shown in parentheses) for the Wolf Motor Function Test (WMFT), Fugl-Meyer Assessment (FMA), Motor Activity Log (MAL) and Stroke Impact Scale (SIS) are shown in Table 6 with significant P-values bolded. Both the AMRR group and Control group significantly improved their WMFT FAS score. Neither group had a significant change in their median time to completion of the WMFT tasks. Both groups increased their FMA Motor Function scores

significantly, but only the Control group significantly increased the scores in the Range of Motion / Pain / Sensation sections. Neither group had a significant increase in the MAL for either the Amount of Use or Quality of Movement sections. The Control group significantly improved their Stroke Impact Scale score from a reported 64.41% recovery to a 76.48% recovery. Between group analysis of the FMA scores shows that the Control group's increase was significantly greater than that of the AMRR group in both sections. No other between group analyses of the clinical scores was significantly different.

Table 6. Clinical scale data for the AMRR and Control groups (median values and (1st, 3rd) quartiles) measured pre- and post-treatment. Within group comparisons are shown immediately after the group data and between group comparisons shown in the last column. Significant p-values are bolded.

	AMRR pre	AMRR post	p-value	Control pre	Control post	p-value	ΔControl vs. ΔAMRR p-value
Wolf Motor Function Test							
Functional Ability Score (/5)	3.42 (2.98, 3.75)	4.00 (3.39, 4.16)	< **.001**	3.64 (3.36, 3.86)	4.11 (3.86, 4.50)	**.0020**	.70
Median time (s)	2.21 (1.91, 3.89)	2.25 (1.85, 3.71)	.16	2.42 (1.82, 2.76)	1.97 (1.43, 2.51)	.32	.92
Fugl-Meyer Assessment							
ROM, Pain, Sensation (/60)	52.00 (47.75, 56.25)	54.00 (47.25, 55.00)	.83	53.00 (52.00, 54.00)	57.50 (55.00, 59.00)	**.0039**	**.0027**
Motor Function (/66)	51.00 (45.25, 52.00)	53.00 (45.25, 54.50)	**.0039**	52.00 (44.00, 54.00)	57.50 (53.00, 60.00)	**.0039**	**.0085**
Motor Activity Log							
Amount of Use (/5)	2.28 (1.51, 3.58)	2.48 (2.00, 3.96)	.084	2.16 (1.24, 2.6)	3.00 (1.8, 4.04)	.11	.92
Quality of Movement (/5)	2.40 (1.20, 3.15)	2.44 (1.75, 3.52)	.11	1.82 (1.12, 2.32)	2.82 (1.40, 3.88)	.13	.46
Stroke Impact Scale							
Score (/100%)	70.34 (63.56, 80.51)	71.61(62.08, 84.64)	.53	64.41 (56.78, 72.88)	76.48 (66.10, 78.81)	**.020**	.085

Kinematic results – trained task (cone reaches)

The median values (filled circle) and 1st (bar below the median) and 3rd (bar above the median) quartiles for the composite KIMs, histograms of the percent change of the composite KIMs of all participants, and category KIMs for each group for both groups are shown in Figure 21a, 21b and 21c, respectively. The AMRR group showed a significant reduction ($p <$

.001) in composite KIM (indicative of an improvement in overall movement quality), whereas the Control group's improvement was not statistically significant ($p = .065$). The distributions of the percent change in composite KIM were mean improvements of 50.76% (±13.59%) and 15.69% (±54.47%) for the AMRR and Control groups, respectively. The two distributions were significantly different ($p = .023$). The AMRR group showed a significant reduction in KIM for 6 of 7 kinematic categories ($p < .001$ for Velocity, Compensation, Joint Function and Joint Correlation categories and $p < .005$ for Trajectory and Temporal Profile categories). Targeting was unchanged. The Control group showed a significant reduction in only Joint Correlation KIM ($p < .01$).

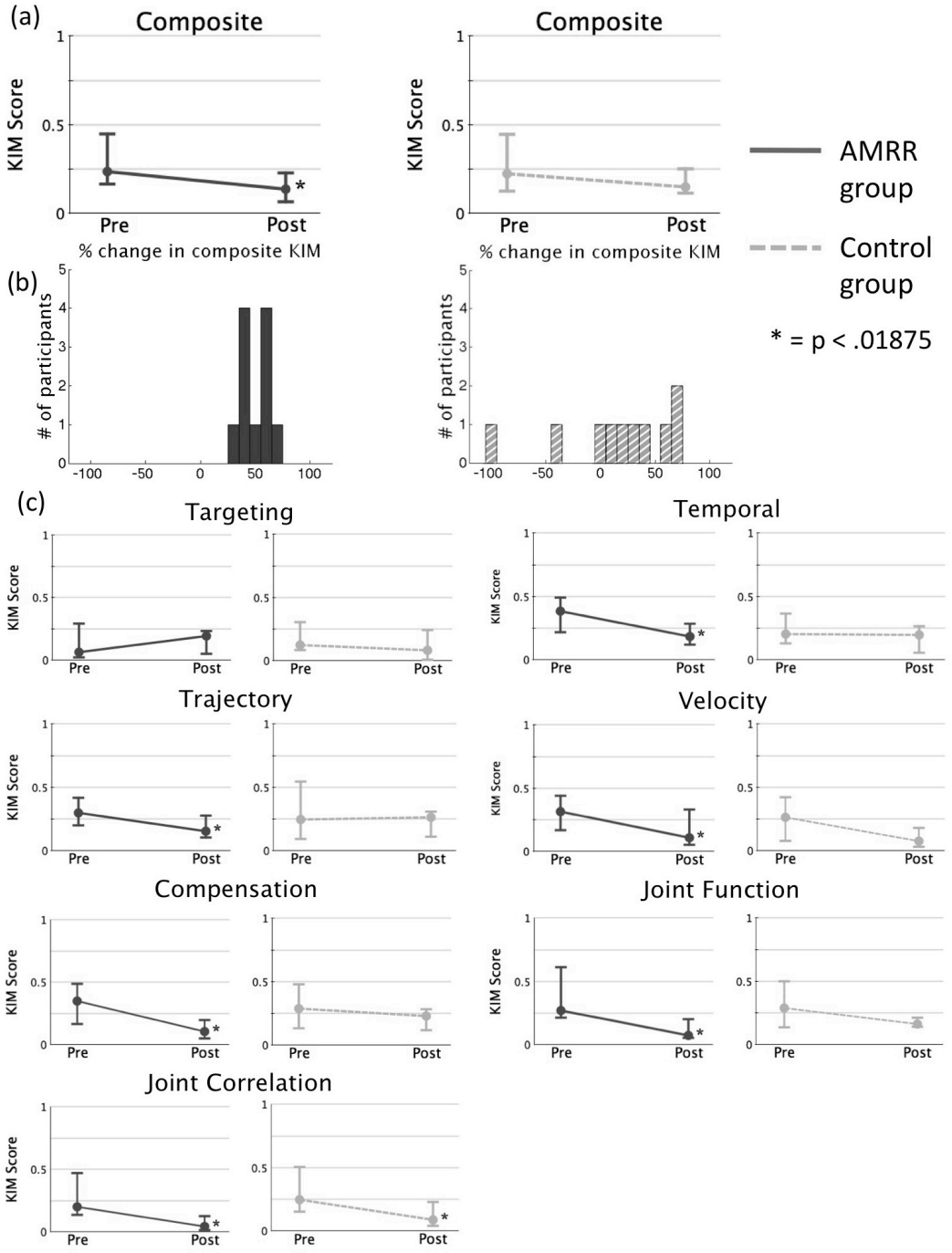

Figure 21. Kinematic Impairment Measure (KIM) scores for the trained cone reach task performed during the pre- and post-intervention evaluation. The composite KIM values (Figure 21a) and category KIM values (Figure 21c) for the AMRR group (solid dark line) and for the Control group (light dashed line) are shown as median values (filled dot) and the 1st and 3rd quartiles (upper and lower horizontal bar). Figure 21b shows histograms for the participants' percent changes in composite KIM

score following treatment. The AMRR group's distribution is shown with dark, solid bars and the Control group is shown with light, striped bars.

Kinematic results – untrained task (button box reaches)

The kinematic results from the button box reaches were analyzed similarly to the cone reaches and are shown in Figure 22. The AMRR group improved in Trajectory ($p<.001$), Torso Compensation and Joint Correlation (both with $p<.005$). The Control group significantly improved in only Trajectory ($p = 0.027$).

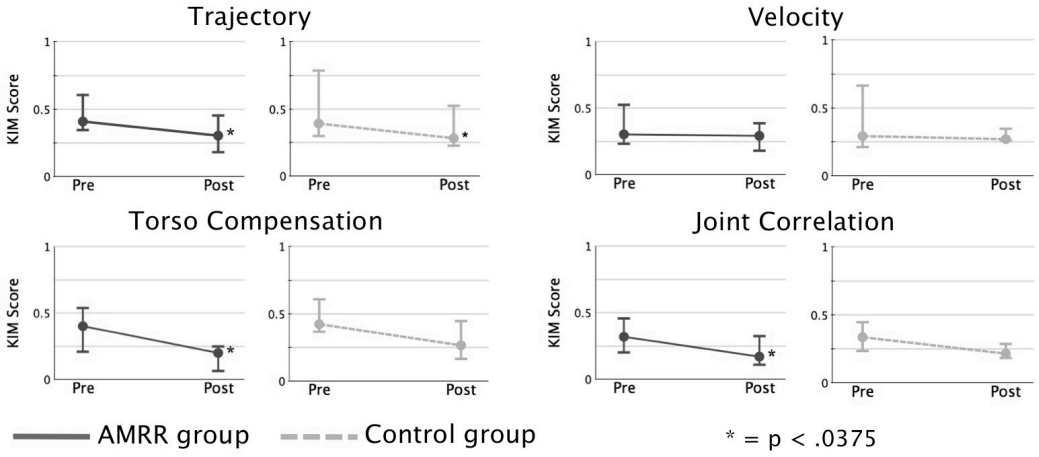

Figure 22. Kinematic Impairment Measure (KIM) scores for the untrained button reach task performed during the pre- and post-intervention evaluation. The category KIM values for the AMRR group (solid dark line) and for the Control group (light dashed line) are shown as median values (filled dot) and the 1st and 3rd quartiles (upper and lower horizontal bar).

Discussion of control group study results

This study examined kinematic and clinical outcomes of an adaptive mixed reality rehabilitation (AMRR) system compared to traditional reaching therapy. AMRR participants showed statistically significant improvements in 6 of 7 kinematic categories (excluding Targeting) that are representative of upper limb impairments seen after

stroke. The Targeting category uses end-point error during the grasping phase as a metric of accuracy, adapted from previous studies.[11,65] However, those studies investigated a reach-to-touch or reach-to-point task to a small target, while studies that explored reach-to-grasp movements did not use end-point error as a measure of grasp accuracy.[66,67] A successful grasp of the cone object required consistent hand placement, resulting in both groups having low initial Targeting KIMs and very little room for improvement. The simplified motion capture setup also removed all markers from the fingers, allowing different finger postures to accompany the same location and orientation of the hand. This lack of resolution may have also contributed towards the ambiguity in the Targeting measurements. Future analyses will look more closely at the sensors that are activated during the cone grasping to determine if the hand is in the correct position during grasp.

The composite KIM (weighted average of category KIMs) results show that AMRR therapy can induce highly consistent improvements in movement quality, even though each participant received a unique training regimen. Previous studies have questioned how factors such as gender,[68] age,[69] lesion location,[70] impairment severity[71,72] and time post-stroke[8,67] affect motor recovery; however, the low variance among participants' change in KIM scores after treatment suggests that AMRR therapy would be effective for participants with different demographic and clinical characteristics. Further data must be acquired to definitively state that the

positive outcomes related to AMRR therapy are sufficiently robust to apply to participants with variable attributes.

The two participants from the Control group with composite KIMs that got worse (negative change) were the first two participants run in the study and the two participants with the highest improvements in composite KIM (positive changes at over 70%) were the 3rd to last and last participant run in the study. This indicates that the therapist was also changing her approach to addressing movement quality during the traditional therapy. She may have also become more aware and attuned to finer points of kinematics and how the kinematic movements aligned to the severity of the impairment from her exposure of the KIM results and feedback responses during the AMRR therapy. One therapist performed both types of therapies as to not introduce the potential confound that the therapist skill was influencing the results. However, it was not anticipated that the kinematics training she received during the administration of AMRR therapy would affect her administration of the Control therapy. Although the sample size is too small to make definitive statements as to whether the ordering of the group significantly affected the composite KIM results, the results do establish an issue for future research. Even if AMRR therapy is not available at every clinic, training therapists (using a system such as AMRR) to be more attentive to addressing issues of movement quality may have a positive effect in all types of therapy.

Kinematic improvements were also seen in the untrained button reaching task, indicating that motor strategies learned during AMRR therapy were applied to a movement condition in which the participant can anticipate neither the initiation nor the specific direction of movement, both of which require different motor and cognitive abilities than were trained.[73,74] Traditional therapy did little to induce favorable changes in overall kinematic-based impairment measures, among the trained task (Figure 21) or in the untrained task (Figure 22). A possible explanation for this failure to impact KIM scores is that traditional therapy often focuses on regaining function and less on reducing compensatory movements or recovering pre-morbid movement patterns. Even if a therapist wished to provide information on certain motor elements, assessing and providing feedback on multiple movement aspects in synchrony with the movement would be impossible. Although the exact relationship between increased movement quality and improved long-term recovery is still unknown, many researchers and clinicians speculate that addressing issues of movement quality and compensation is essential to sustaining and enhancing functional gains made during therapy.[55,75,76]

Both the AMRR group and the Control group demonstrated similar statistically significant improvements in the Wolf Motor Function Test, likely because both groups received the same dosage of therapy and both focused on repetitive training of varying tasks and target locations. Both groups also had significant increases in the motor function portion of the

Fugl-Meyer Assessment, with the Control group demonstrating a larger change in that section. The Control group also improved more in sections rating sensation, pain and passive joint function. Control therapy participants had more flexibility in the target locations of their reaches to utilize a greater combination and magnitude of arm joint movements and may have also received manual therapy to the arm (such as range of motion exercises, active-assisted reaches or stretching). During the AMRR intervention, reaches were restricted to four designated locations in order to accurately calculate the KIM and provide feedback, thus minimizing alternative directions of movement or therapist manual guidance. Future AMRR systems could include an increased number of target locations or could be used in conjunction with traditional therapy methods to address sensory compromise within the arm.

The Control group also had a preferentially greater improvement in SIS score. Because the AMRR group was challenged to continuously improve their kinematics, the focus may have inadvertently shifted from how much they had progressed to how much more they could improve, resulting in lower perceptions of health related quality of life. The AMRR system would likely benefit from a graphical interface that reflects therapy progress and provides motivation to continue making improvements. Neither group had significant increases in either section of the Motor Activity Log, possibly because the MAL reporting time (2 weeks prior to evaluation visit) overlapped too much with the intervention time (4 weeks

prior to evaluation visit). Alternatively, this result could reinforce current evidence that arm performance during laboratory measurements is not necessarily predictive of use and functionality at home.[77-80] In order to help participants better transfer the skills learned in the clinic towards everyday activities of daily living, the AMRR system is being transitioned to a home-based therapy system[81] that will continue to reinforce the recovery of pre-morbid movement patterns as well as offering a wider variety of functional tasks to practice.

Limitations

Although the AMRR system appears to be a promising tool to deliver therapy focused on function and movement quality, the study presented had some limitations. This study used the same therapist to administer both therapy types, so the group results would not be skewed by the skills of the therapist. Future studies will include several therapists trained to administer both types of therapy and have them randomly assigned to participants. Further study is also needed on a larger, randomized sample, which will allow for a better generalization of the results and correlation analysis between the participants' clinical profiles and their responses to therapy. The study also recruited an older population, as well as people with lesions at any location resulting in right-side hemiparesis or multiple strokes. These liberal criteria may have confounded kinematic or clinical improvements due to pre-existing joint, neurological, or movement impairments. The study also lacked a follow-up

evaluation so although short-term movement quality improvements were made in the AMRR group, the extent to which changes persisted after treatment ended is unknown. Lastly, although the KIM scores have been positively correlated with validated clinical scores[20], the relationship between movement quality and long-term recovery is still under investigation, making it difficult to truly determine how much improvement in movement quality is needed to become relevant to a person's recovery after stroke.

Conclusions to the control group study

The AMRR system provides a unique method of monitoring and addressing movement quality by providing integrated and adaptive feedback based on high-resolution motion capture during a therapy task. The AMRR therapy generated improvements in validated clinical scales and in kinematic measures during trained and untrained tasks. While Control therapy of matched dosage resulted in greater gains in the Fugl-Meyer Assessment, it failed to produce significant improvements in most of the kinematic parameters in any task. AMRR therapy appears to be an effective way to improve both function and movement quality, in an effort to enhance and sustain overall recovery.

Chapter 4

CREATING A MODULAR PHYSICAL SENSING ENVIRONMENT AND TOOL-KIT FOR USE IN A LONG-TERM, HOME-BASED AMRR SYSTEM

While the results from the above studies indicate that AMRR therapy can provide beneficial therapy in a clinical setting, supervised by a therapist and researchers, this type of interaction is not feasible for long-term therapy. Many stroke survivors lack the financial resources to continue to work with a therapist and may also find it extremely difficult to find reliable transportation to visit a clinic frequently. Improvements in function and movement quality were seen after AMRR therapy; however, there was no significant increase in the participants' self-reported amount of use or quality of movement of the affected arm during their daily lives. The evaluation of long-term motor learning was also unavailable, so participants may lose the learned strategies once the reinforcement of regular therapy is no longer present. In order to best enhance the recovery of a person following stroke, a long-term plan to receive easy-to-use, fairly inexpensive beneficial therapy must be in place. Our group is working towards the development of a home-based therapy system that uses the theories and design principles from the clinic-based system, with scaled down the complexity and cost to make it appropriate to be installed in any home. The feedback and adaptation will also be uniquely created to fit the environment and communicate the intent of the therapy to the patient without the need for a therapist or researcher to be constantly present.

An initial version of the home system was constructed and installed in two patients' homes and an improved version is currently under development. Research on the current home-based AMRR system will be conducted at several research sites to test: the ability of multiple therapists to administer AMRR therapy; how well the therapy concepts transfer from the clinic to the home; the ability of people with stroke to setup and use the system reliably; and the validity of the feedback and physical environment comprising the therapy to improve function and movement quality during reaching tasks.

Review of other types of in home therapy

Because people who have had a stroke may lack the accessibility, mobility or resources to continually attend therapy sessions, especially after insurance no longer covers the sessions, a long-term plan to receive therapy at home at a low-cost is crucial to achieving full recovery. However, when performing therapeutic tasks at home, with no therapist present, it may be more difficult to self-correct issues of movement quality or function and to stay motivated to complete the full range of exercises prescribed. Many research groups are attempting to bridge modern technologies with home health care to create home-based or telerehabilitation therapy systems.

Most home based upper-extremity therapy systems fall into three basic categories – traditional therapy tasks assigned to be performed at home, with either in person or video conference check-ins by a therapist;

custom or off the shelf video games or other technological devices used by the stroke survivor for a prescribed amount of time; or compulsory use of the impaired limb during every day activities, as in constraint induced movement therapy. Unfortunately, very few studies included large, randomized groups to show how effective home-based therapy systems were in comparison to no intervention or to usual care, especially in terms of long-term recovery. However, many systems were demonstrated to be safe and feasible for home-based therapy.

The simplest way to transition therapy from the clinic to home is to assign the stroke survivor various therapeutic tasks to perform at home. Specialty exercise programs have been developed to maximize functional recovery,[82] which have been shown to improve lower-extremity function when performed at home. However, these exercises were not completed by the participants unsupervised, but were specifically directed by a therapist who physically visited the stroke survivor at home. Although this type of arrangement would be ideal for stroke survivors of limited mobility, it is still resource intensive. Other research has done[83] to examine if home visits where the therapist encourages the stroke survivor to engage themselves in continuous exercises at home, as opposed to providing direct therapy, were feasible and preferred by the stroke survivor and caregivers. Home visits were effective and accepted by the participants, but were not shown to be better than regular outpatient therapy.

Other attempts have been made to enhance the traditional physical therapy exercises performed at home with novel or commercial technologies. Effectiveness of using the Wii gaming system (a video game system that uses a motion-based controller) has been tested[84] compared to usual care. This study, however, only showed an decrease in time to perform tasks in the Wolf Motor Function Test, which shows no evidence that the participants were performing functional tasks better, just that they were performing them more quickly. Although video games can help increase reaction and movement times, as those aspects are crucial to game play, there is little evidence that they lead to better long-term recovery.

The last widely used method of home-based intervention is constraint induced movement therapy (CIMT). During CIMT, the more functional hand is encased in a mitt or restrained, making it difficult to use. This forces the stroke survivor to engage with their environment using the more impaired hand. Forced use can increase dexterity of the arm,[54] decrease the time to perform functional tasks,[55] and improve self-reported measures of arm use,[54,55] probably because the person had previous not used the impaired arm much during activities of daily living. However, immobilizing an entire upper extremity is not practical for long-term therapy and reduces the ability to perform other functions that may require both hands. CIMT also does not address the movement quality aspect of recovery, just the increased use of the impaired limb.

Any type of therapy that can safely and successfully used at home will offer more benefit to stroke survivors than doing no therapy at all. However, certain aspects can be assembled from the existing home therapies to determine what is important when designing such a system. Traditional therapy exercises generally use task-driven repetitive exercises that mimic activities of daily living, the completion of which is the end goal of most therapy. Technology-driven interventions use exciting gaming and narrative structures to motivate the stroke survivor to use their impaired arm to complete the tasks and sensing technologies to track how the arm or hand are moving during the game. Constraint induced movement therapies force the use of the impaired limb, compelling the stroke survivor to practice movements with their arm that they may have not otherwise done.

Adaptive mixed reality rehabilitation (AMRR) has proven to be effective in providing repetitive task therapy to the impaired arm in the context of a media-rich feedback environment in the clinic attempting to aggregate the characteristics that have proven effective in stroke therapy. As the system is transitioned to the home, all of these aspects must be maintained and adapted to the new unsupervised environment. The system must be easy to use by someone with impairments to one side of their body, but complex enough to provide effective therapy that can be tailored to a diverse population stroke survivors and remain effective throughout the progression of recovery. And as the recovery progresses,

both function and movement quality should improve as a result, ideally both within the context of the therapy system and during activities of daily living.

During the development of the home-based AMRR systems, my work has focused on creating sensing environments that can track hand position and function. With the first version of the home system that was piloted with two stroke survivors, this involved creating stationary cone objects used as targets to the grasp and contributing to the development of the Wii-mote based motion capture system. In the current version of the home system, my work has included creating a tool-kit of tangible objects that have embedded sensors and require different hand postures and forces during manipulation. The objects sense hand function unobtrusively and can provide feedback to the stroke survivor about aspects of the movement. All of the objects can also be interchanged within the workspace to create environments tailored to the type of therapy required by the individual participant.

Home system pilot study

A study with the initial version of the at-home system followed the pilot study of the AMRR system (see Chapter 2). This system is comprised of a tabletop overlay, that can be used on top of any flat surface such as a dining room table, that had three permanent target cone positions and a rest position based on each participant's reaching ability. A low-cost motion capture setup monitored end point (wrist) trajectory during the

reach and low-cost sensors track reaction and reaching times, as well as relative grasping force. A microcontroller and small computer collected information from the sensors and motion capture cameras and provided simple cues to the participants about the start and end of the movement. This system was tested with two participants with the expectation that it was an easy to use and minimally intrusive assessment tool that could provide informative data during and after upper extremity rehabilitation interventions for under $1000.

This home system was a purely assessment tool to track reaching kinematics over time and to track the retention of motor learning from the participants' improvements during AMRR therapy in the lab. The system used lighted targets to initiate a reach to grasp to three force-sensitive cones. Consistent reaching distance was maintained by monitoring the rest position with a sensor. A low-cost, custom-built motion capture system using two Wii Remotes captured the trajectory of the wrist over the movement. A small, hidden computer collected data for tracking patient's progress over time. The system was a low cost way to track reaching trajectory, reaching time, reaction time and relative grasp force that requires minimal setup and was constructed from easily available off the shelf components and software.

Physical Setup

This system is portable, fits over any table and is easily modified to meet any patient's reaching abilities. The form factor mimics the table

used in the clinical and laboratory versions of the system has a grid of holes to secure the targets at locations best suited for individual reaching abilities (Figure 23). The armrest on the unaffected side has a hinge that opens for easy exit and the entire surface is overlaid with softly textured beige plastic (Sintra) covering the grid and provide a smooth reaching surface. The targets are based on the cones used during the clinical version of the AMRR system and were rapid prototyped in ABS plastic.

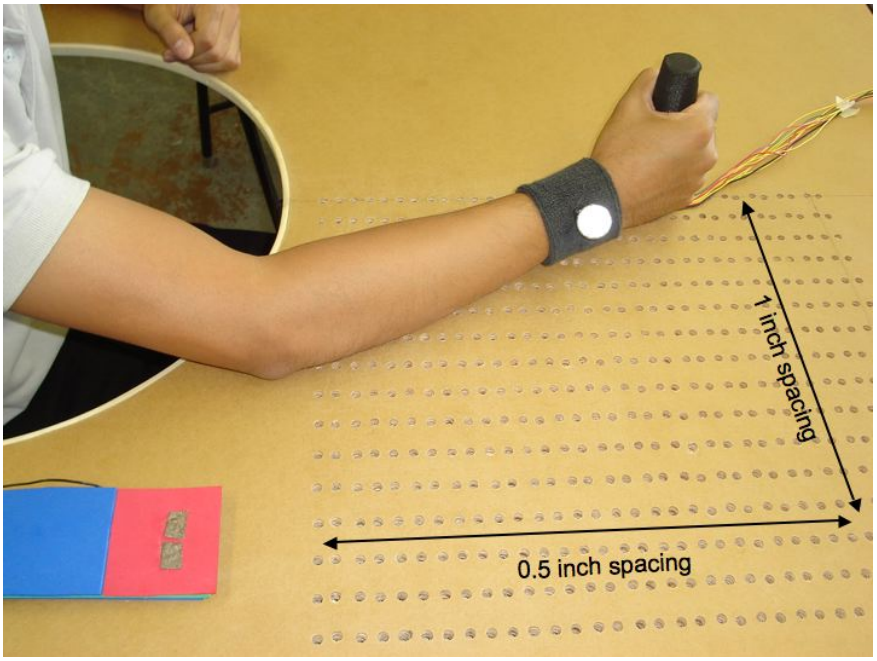

Figure 23. Physical setup of the underlay of the first home system. The black cone can be placed in any of the holes to accommodate different reaching distances, the hand's spatial location is tracked by the marker on the wrist, and wrist and elbow position at rest is tracked by the blue and red pad at bottom left.

Electronic Design

A Wiring (http://wiring.org.co/) microcontroller board controls the home system's inputs and outputs, monitors when the target has been grasped, when the hand is in the correct rest position, and controls the

lighted stimulus presentation. The data is transmitted to a small Mac Mini computer (http://www.apple.com) computer via USB-serial connection. High intensity red and green LEDs embedded in the top of each cone provide visual stimulus to elicit a reach. All electronics components are readily available off the shelf.

Each cone target was covered in sixteen 0.5” circular force-sensing resistors (FSR) to detect successful grasps (http://www.arduino.cc). Each FSR was part of a voltage divider circuit with a 2.2 kΩ resistor, which provides the largest range of voltages for forces normally seen in grasping. The FSRs were attached to the cone using the factory provided adhesive. The outputs from the force sensors for each cone were 8 to 1 multiplexed into two analog inputs on the microcontroller.

A bright red foam pad marks a consistent rest position, where the subject's wrist will be between target reaches. The foam pad has two conductive cloth contacts on its surface, which comprise a switch. The subject wears a wristband (Figure 24) with a piece of conductive cloth sewn onto it, which closes the rest position switch when in contact. A sound plays if the hand is not resting in the correct position and the target stimulus will not light until the hand returns to the correct position. To ensure proper relaxation of the arm between reaches, a second embedded switch monitors if the forearm is applying pressure to the rest pad while the wrist is in the correct position.

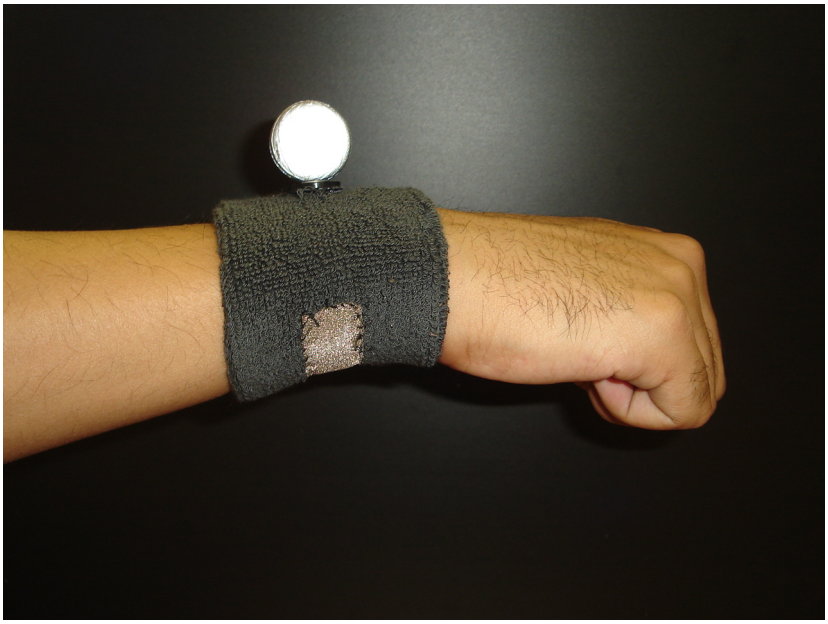

Figure 24. Wristband with reflective motion capture marker and conductive cloth used for rest position contact switch.

The audio feedback was provided using the Mac Mini computer and its built-in speakers. A Max/MSP (http://www.cycling74.com) patch communicated with the microcontroller using the serial protocol and received flags from the microcontroller to trigger sounds for audio feedback. The patch also logged and time stamped the reaction and reaching time data. The Max/MSP patch then communicated with custom motion capture software to begin recording from the IR cameras. IR camera data was logged using a custom program. The system architecture is presented in Figure 25.

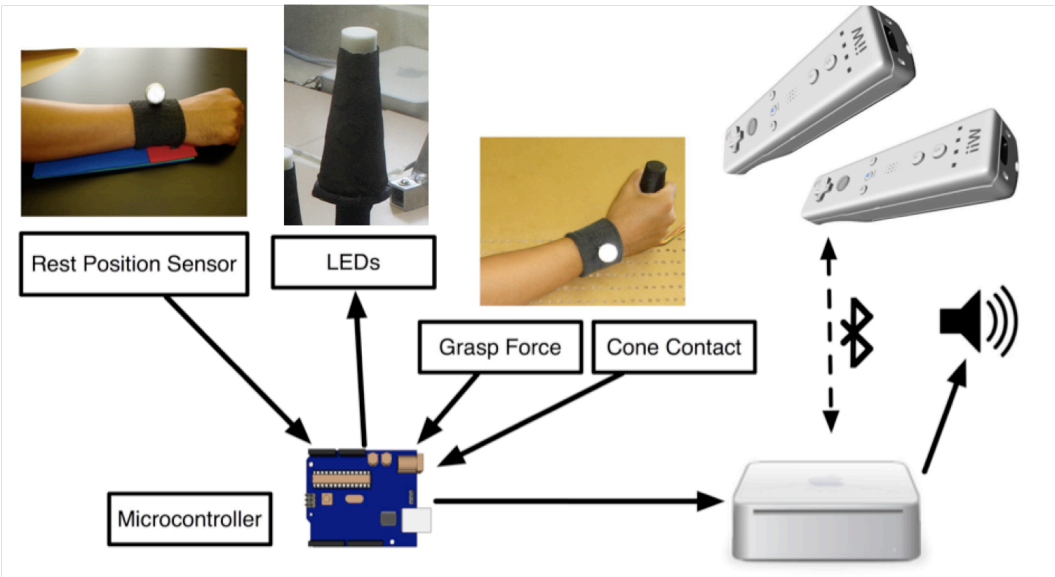

Figure 25. System architecture for hardware interactions of the first version of the home system.

Motion Capture

End point trajectory measurements are important to assessing stroke patients' reaching patterns, in terms of efficiency and smoothness of the trajectory and end point velocity. These measurements may be made using costly and cumbersome motion capture systems, but for this first home system version, an inexpensive camera setup using controllers for the Nintendo Wii gaming system (http://www.nintendo.com) was developed. The remote control for the Wii gaming system (the Wii Remote) contains an embedded infrared camera with 1024x768 resolution and an approximately 40° x 30° field of view for only $39.99. The controller uses Bluetooth to connect with the Wii game console and was easily interfaced with the Mac Mini computer's Bluetooth protocol. Open source software was used to connect to and record data from the Wii Remote. The Wii infrared (IR) camera is a proprietary system-on-a-chip from PixArt

(http://www.pixart.com.tw) that is able track 4 infrared sources at 100 Hz and returns their planar coordinates and intensity. A wristband with a single marker (Figure 24) was tracked by the two Wii Remotes and the data was used to reconstruct three-dimensional trajectory and velocity measurements using the open-source DarwiinRemote code (http://sourceforge.net/projects/darwiin-remote). To avoid relying on AA batteries powering the Wii Remotes, the power terminals of the Wii Remotes were connected to a 3V regulator.

Since the passive reflective marker required a source of infrared light to reflect, an array of TSAL6400 (http://www.vishay.com) infrared light emitting diodes (LEDs) was designed and mounted on the Wii Remote. The array dimensions (8 LEDs by 6 LEDs) maximize the number of LEDs that can be powered on two arrays from a single12V, 1500mA power supply. The LEDs have an optimal combination of intensity (40 mW/sr) and angle of half intensity (25 degrees). The remote and array is presented in Figure 26.

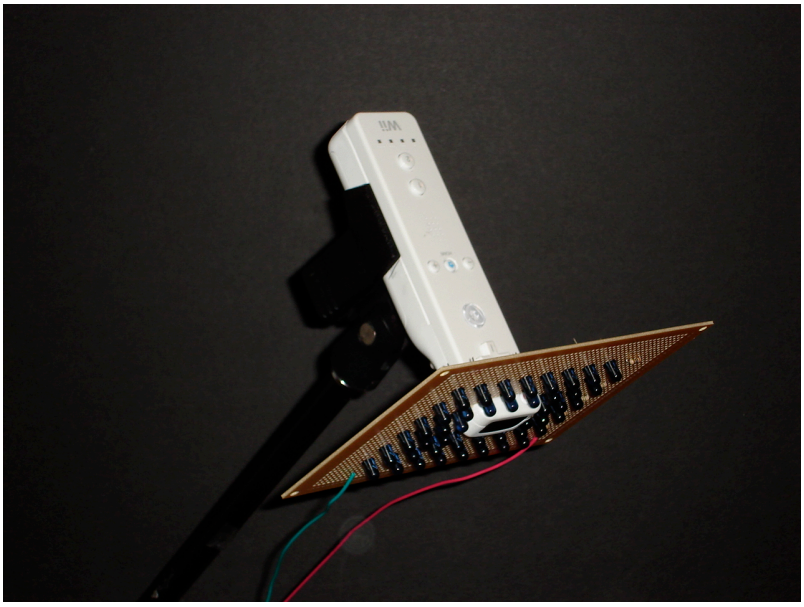

Figure 26. Wii Remote with attached IR LED array. Two such setups were used to recreate the 3D position of the reflective marker on the wrist.

To convert the standard camera coordinates returned by the two Wii Remotes (Wiimotes) into global coordinates, a camera calibration was performed using a trapezoidal frame. The intensity values returned by the cameras were not used due to their low 4-bit resolution. By capturing the location of four markers using a trapezoidal calibration frame at various locations in space, a transformation to the global coordinate system can be created based on Zhang's method.[85]

Data collection

The system was installed in the homes of stroke patients that have taken part in the pilot study for testing AMRR therapy to determine the feasibility and usefulness of the home based system. The participants were asked to use the assessment system three times a week for eight reaches to each cone at a specified time of day to monitor their reaching

abilities for one month. The game begins when a subject presses the start button. A sound plays to indicate that their hand should move to the rest position. Once on the rest position, one of the cones is selected as the target for that reach and a red LED on that cone lights up for a pseudorandomized rest period between 3.5 to 5 seconds. This provides an adequate period of relaxation between reaches for the subject and allows the subject knowledge of what cone he will be reaching to. The required duration on the rest position is variable and pseudorandom so that the subject performs discrete reaches and does not form a "rhythm" since there are different neural bases for rhythmic and discrete arm movements.[86] Varied rest times also reduce the subject's tendency to anticipate the movement before the stimulus appears.

After this rest period, a green LED turns on to indicate that the subject may initiate a reach. Sudden feedback near a grasp can affect a grasp or cause a jerk, thus, no feedback is given for a successful grasp other than the physical feedback from contacting the cone. If the subject is unable to reach the cone within 6 seconds, the light turns off to prevent frustration and proceeds to the next rest period and light after the subject returns to rest. If the subject anticipates the stimulus and comes off the rest position while the red light is on, the timer resets and the subject has to return to the rest position for another 3.5 to 5 seconds before the next light turns on. These timing values are based on the START assessment device data.[61] Wrist trajectory, relative grasp force, reaction time, and

movement time were recorded and stored locally on the password-protected computer.

System Validation

Patient acceptance. Figure 27 shows the home system installed in a stroke survivor's home. Both participants that used the home system were patients who had previously completed the pilot study (Subject 2 and Subject 3 – Chapter 2) and were familiar with the type of task. Since the home system is less complicated than the rehabilitation training that they have already participated in, both subjects were easily able to complete the month-long home assessment period. Initial reactions from both subjects were positive and both played the game at least 3 times a week. Both subjects reported some improvement in daily functional ability during their weekly status questionnaires. One subject reported an increase in writing with her right hand during her month of playing the home system game. The other subject played the game almost every day that it was at his house and his only complaint was that he wished the game was more challenging and had some sort of feedback to tell him how he was doing. Both of those issues will be addressed in the subsequent versions of the home system.

Figure 27. A stroke survivor using the home system in his home.

Motion capture. The motion capture data after 3-D reconstruction was cross-validated with a 12 camera Eagle RealTime motion capture system and EvaRT software from Motion Analysis (http://www.motionanalysis.com) as reference. Data was smoothed using a five-point moving average window in Matlab (http://www.mathworks.com). Mean squared error was calculated for each direction for displacement and velocity. The mean squared error was greater for displacement than for velocity. However, for this system, since the reach completion is detected by the touch sensor, the motion capture can be used to study velocity and acceleration with some degree of accuracy. Data from the trajectory (top) and velocity (bottom) for the x-direction is shown in Figure 28.

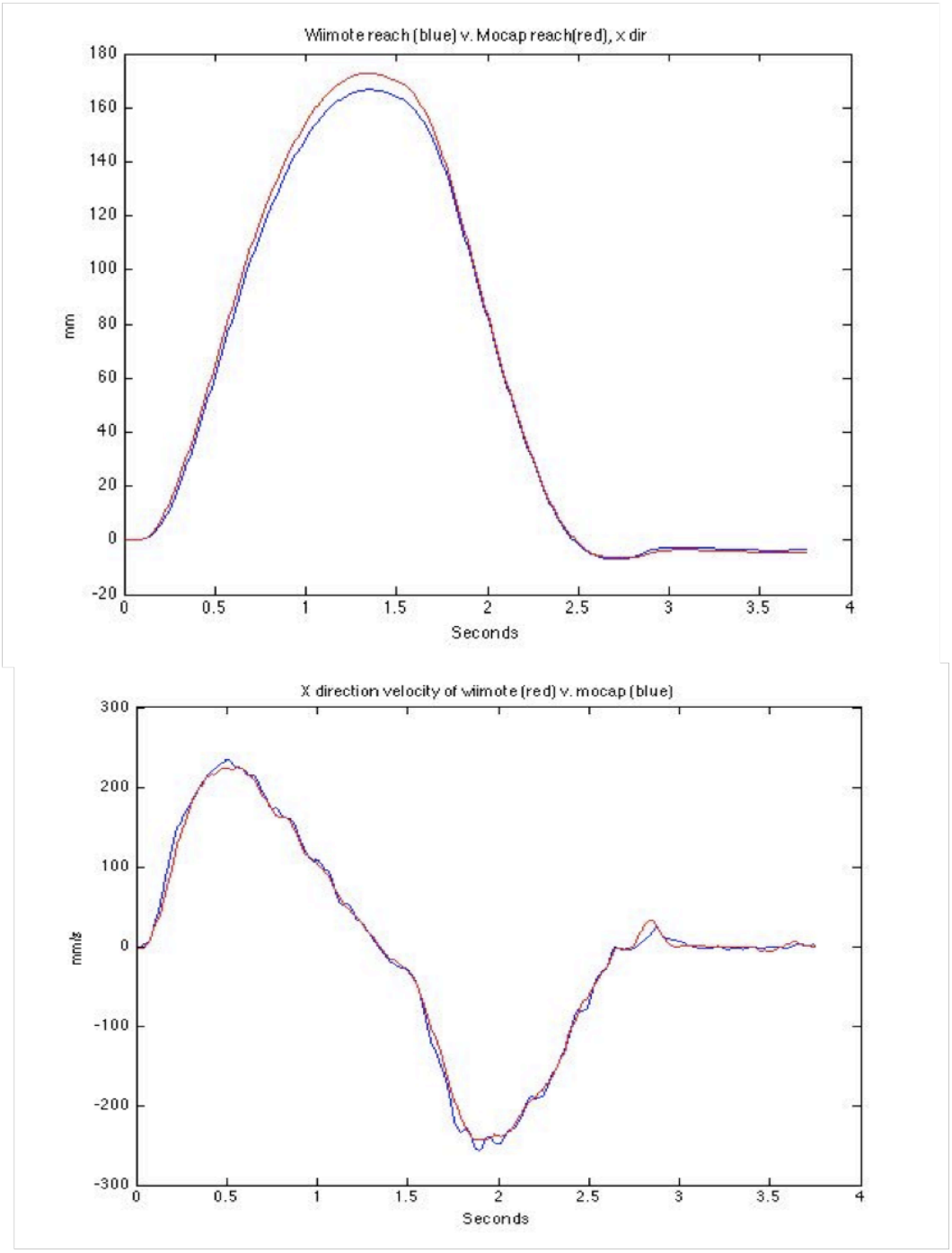

Figure 28. Example Wiimote data (blue line) versus Motion Analysis camera data (red line) for displacement and velocity in the x-direction.

Data storage. To test the robustness of the data storage software and avoid memory leaks, the system was left recording motion capture data for several days. There were no software errors during this duration.

Discussion of issues present in the original design

The installation and data collection from the first version of the home system revealed a number of design issues that need to be reconsidered. This system used a Bluetooth protocol to send the data from the motion capture cameras to the computer, which caused a number of issues. The Bluetooth needs to be specifically paired to the computer that it is communicating with to effectively send the data. The pairing of the Wiimote camera to the computer requires interaction with both the computer and Wiimote. The cameras can become unpaired during an interruption of the power supply to the cameras or computer or simply due to software glitches. During the period over which the home system was in one subject's home, the cameras became unpaired twice, which required a researcher to drive to the subject's home to simply re-pair the Wiimotes to the computer. The data collection software was also written in such a way that the data coming from the Wiimotes was continuously collected as it streamed from the cameras (not prompted for collection at a specific sampling rate), causing a discontinuous and inconsistent sampling of data between both cameras, and was not synchronized with the data coming from the tangible objects (cones). Both cameras need to produce data at the exact same time to create an

accurate three-dimensional picture of the arm's movement and the seemingly random loss of data caused the 3D reconstruction of the reaches to become impossible. The kinematic data was subsequently unable to be analyzed. However, it was clear that the tangible objects and rest position sensors did work and collected data throughout the entire month-long installations.

This version of the system also did not offer any evaluation or feedback on the reaching performance to the participant. The lack of evaluation left the participants to wonder if they were making any progress and if there was any point to continuing to use the system. Because there was no real time evaluation of the performance, there was also no feedback given. The participants had no way to assess and improve their performance without feedback. The lack of feedback also made performing the reaches extremely boring. There was no motivational factor to ensure the participant would continue to use the system. The physical set up also stayed consistent throughout the month of use, making the therapy very monotonous. The lack of other physical targets also meant the task difficulty was constant and did not allow any reduction or increase in movement complexity during the month. The study with these two participants suggests that the basic design of the home system is viable; however, aspects need to be improved to make the system a viable therapy option such as: developing hardware and software that is reliable and robust; assessing the movement kinematics in real-time; using the

kinematics to provide useful feedback during the reaching and as a summary after sets of reaches; introducing a wider variety of physical objects that can be adjusted throughout therapy to train a wide variety of functionally based tasks.

Current version of the home system

The current version of the home system advances the system from a purely assessment device to a longer-term full assessment and training system. This system incorporates additional and more complex tasks and instructive audio feedback and visual feedback on the movement. The audio and visual feedback will expand to become a long-term engaging narrative that the participant will interact with over the course of months. The amount of real-time feedback given to the participant will be reduced, compared to the clinical system, as a way to help them to create strategies that tend to rely less on external feedback and become able to self-assess the movement. The amount of real time feedback is also limited by the kinematic parameters that are being measured, which at present are aspects of the wrist and torso movement. The new system will also feature different tangible objects that can assess hand function during a variety of tasks. The objects can easily be moved around or interchanged in the reaching space by the participant. The participant's visual attention during the reach is on the physical environment, instead of an immersive screen or display as in the clinical system, which creates a stronger tie to reality. However, the participant will still be receiving real-

time information about their reach through the audio feedback and visually through the tangible objects. A picture of the current prototype of the home system is shown in Figure 29. The therapy will also be regulated with a semi-automated adaptation of the difficulty and nature of the physical task and the kinematic foci of each session (i.e. the sensitivity and activation of each feedback stream). The next sections will describe the overall structure of the new home-based AMRR system, but will focus on my work on the tangible object design.

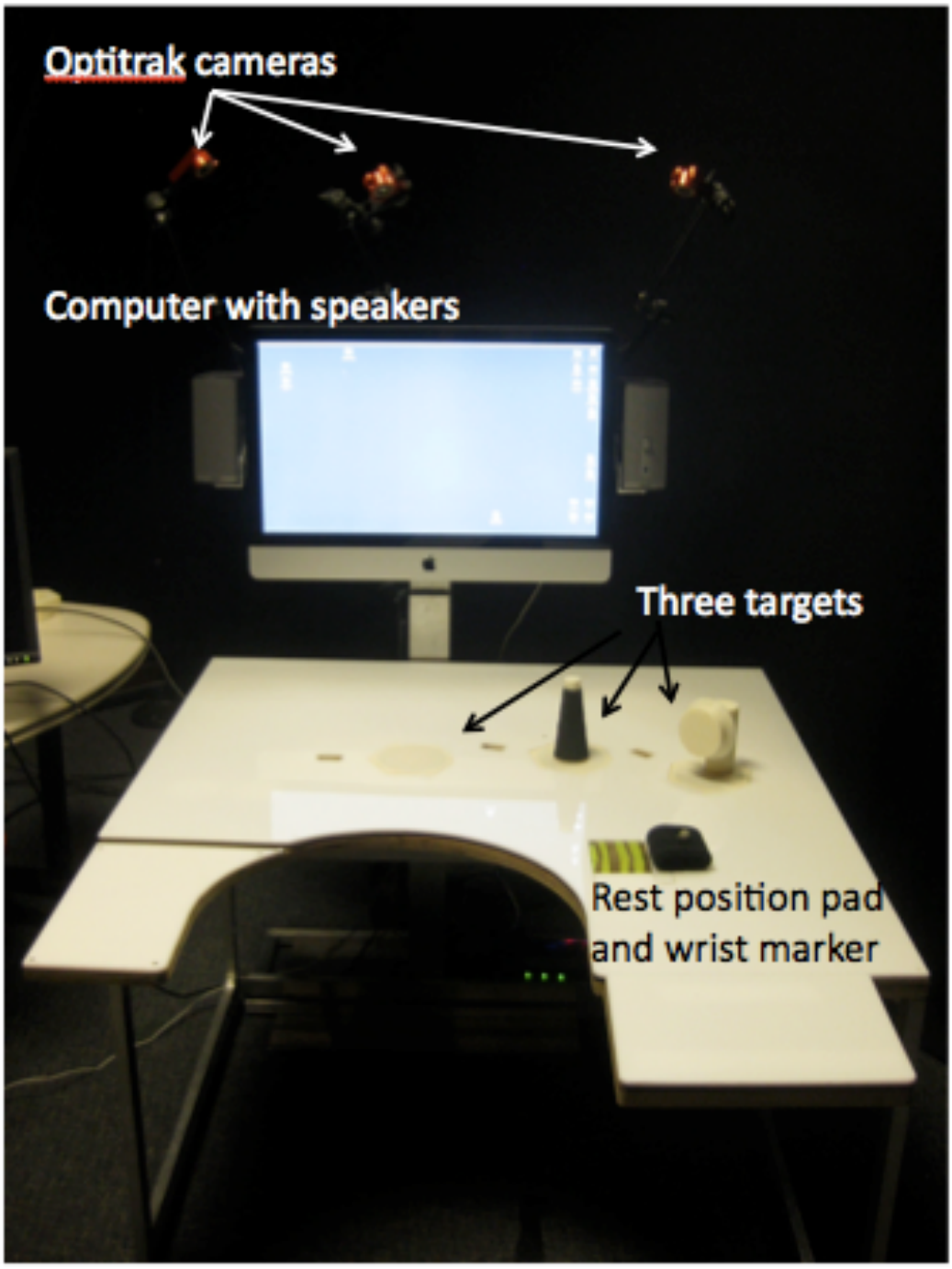

Figure 29. Current home AMRR system: Custom table with three embedded tangible object targets and rest position; three Optitrak cameras to track the wrist marker position; and a computer with speakers to analyze the data and present the audio and visual feedback.

Measuring hand interactions

Measuring the posture and kinetics of the hand during rehabilitation can be extremely useful in training fine motor control movements. However, methods for recording joint angles of or force exerted by the fingers can be restrictive to natural movement and extremely time-consuming to set up. Wearable gloves or exoskeletons have been developed to directly record hand movements using bend of sensors at each of the finger segments. CyberGlove (http://www.cyberglovesystems.com/), a company that produces commercially-available force, angle and touch sensing gloves, uses sensors that have high resolution and accuracy and can transmit the data wirelessly for unencumbered use. Unfortunately, such gloves have proved to be somewhat unsuitable for stroke patients to use, although some groups have used them in rehabilitation systems.[11,87,88] The gloves are stiff due to the underlying sensing structures and can restrict normal ranges of motion in the fingers. They are also designed to fit snugly and may be difficult for someone with weakness or ataxia to independently put on easily and correctly, making them problematic for unsupervised therapy.

Another method that is widely used in a laboratory setting is tracking individual finger segments using IR or other motion capture systems.[89-92] This method is extremely accurate and can provide high-resolution data about the finger joint angles and kinematics. However, the systems used to track such small, close together markers are prohibitively

expensive for home-based rehabilitation systems and require a great deal of time and knowledge to apply the markers correctly and consistently. The markers also need to be placed on each segment of the fingers, some of which are inaccessible on a patient with flexed hand posture. The lack of control a stroke patient has over the movement and flexion of their hand may also contribute to markers being scraped off or shifted during movements.

Many of the issues presented with tracking the posture and movements of the hand can be overcome in a supervised laboratory or clinical setting. The ultimate goal for the AMRR system, however, is to translate to long-term, unsupervised training in the home. This means that any hand sensing must be done in a way that is extremely easy for the patient to set up, but can still consistently track interaction in an accurate way and measure information relevant to the activities of the hand that are being trained. The systems must also balance cost with accuracy. The solution for these issues is to combine a low-level motion capture of parts of the hand with smart sensing objects. The ultimate aim is to be able to detect enough hand functioning to provide feedback on the action. The development of the objects and the first stage of developing a hand function analysis paradigm are presented here.

Measuring hand – environment interactions using tangible objects

Research has been done to measure grasping forces and tangible interaction both in stroke patients and able-bodied control subjects. Some

groups have used expensive load cells to create grasping objects that measure forces of the hand and fingers. Some of these objects require that the grasp orientation of the hand to produce force along a common axis,[93] or the full force may not be read. Other groups have used sensors[94] or gloves on the hand to measure forces.[11,87,88] While these systems can be an accurate way to measure tangible interactions, the sensors may register false readings to due deformation (not force) and the gloves can be bulky and restrictive to a normal movement. Because no currently available hardware met the needs of the system, custom-built instruments were designed, allowing us more control over the cost and parameters of each object. Custom building allowed full control over the shape, size and weight of each object, to ensure that different types of interactions could be sensed. The objects also use sensor sets that are tailored to measure the hand function being trained. The objects also all have the same base shape and size, to allow the objects to be interchanged at the same locations. The following sections show how the interchangeability was designed and then detail each of the objects types. The types of visual feedback presented in the objects and on the screen are also explained in context of each task.

Design of interchangeable tangible objects and table for use in home-based therapy

The physical location of the targets each participant reaches to during home-based AMRR therapy will be set at the beginning of therapy

based on their individual abilities and will be consistent throughout the training. As in the first home system version, the underlying layer of the table will be allow the targets to be positioned at the correct distance from the subject. However, the new version will now use sockets at each of the target locations, into which tangible objects may be placed. These sockets are bolted to a recessed chamber in the table and provide a way for the objects to be latched into place, and will also have a mechanism for the objects to be easily exchanged. The sockets electronically interface with the objects to provide power to the inner electronics and transmit data to and from the objects. Each socket (and correspondingly the object bases) is hexagonal in shape. This shape was chosen to approximate a circle but to allow flat sides to accommodate the latching structure and provide a secure fit into the socket. Figure 30 shows a prototype of the socket.

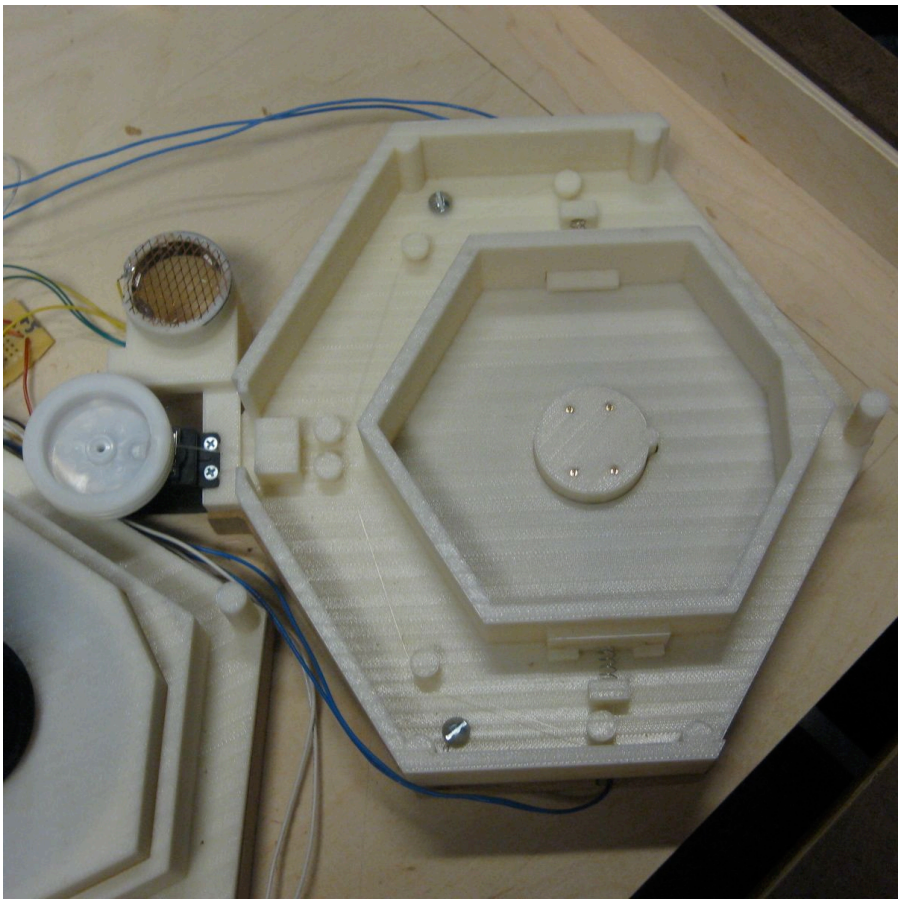

Figure 30. Prototype of the socket that will hold the tangible objects in the home-based system table. The latches secure the object in place and the motor withdraws the latches when the touch-sensitive switch is activated.

The socket secures the object with two small slanted pieces on either side of the hexagon. These latches are released through a motor/pulley mechanism that is controlled by a touch sensitive button. A visual interface on the system's screen guides the participant through interchanging the objects before the start of each therapy session. The touch sensitive button also has embedded LEDs that diffuse through the table as a lighted circle. The user simply has to touch the lighted circle through the table and the pulley will rotate enough to pull lengths of monofilaments attached to each of the slanted latches. A spring loaded

circular piece at the bottom of the socket both provides a secure electrical connection between the socket and object and pushes the object out of the way of the latches when the person has touched the release button to interchange objects. A close ups of the socket's slanted latches and circular spring-loaded connection piece are shown in Figure 31. Figure 32 shows one latch mechanism. The monofilament pulls the latch to release the object and the spring pushes the latch in when the object is being inserted. All pieces were 3d modeled in Rhino3d (http://www.rhino3d.com/) and rapid prototyped in ABS plastic or machined from MDF board.

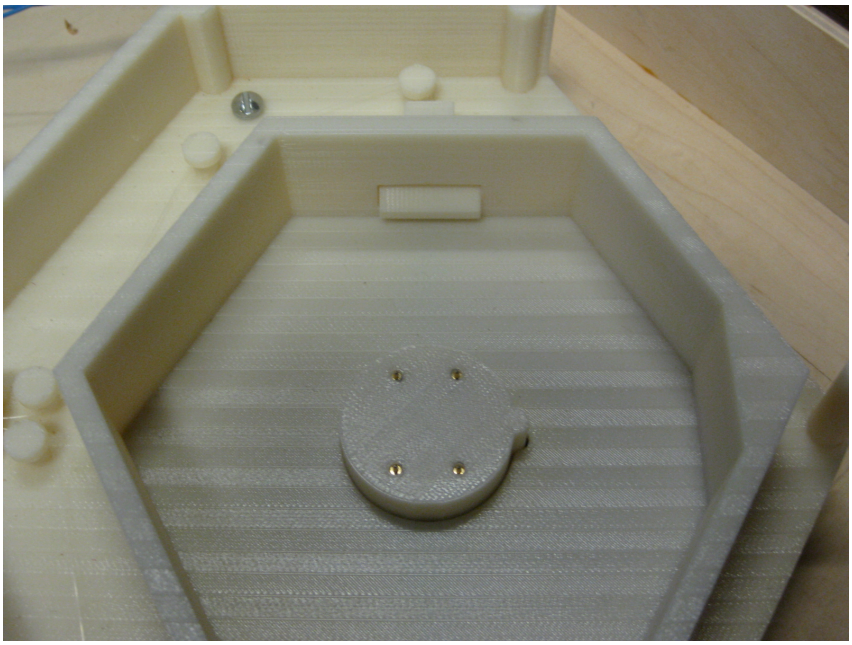

Figure 31. A close up of the latch that holds the object in the socket. The circular piece in the middle acts to push the object out of the socket when it is being removed and will be the site of the electrical connections between the socket and object.

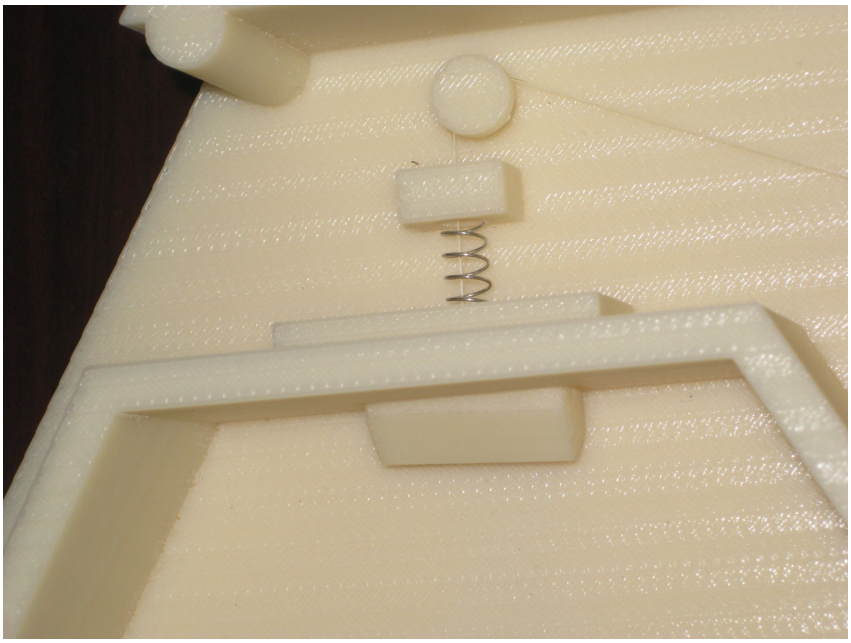

Figure 32. Close up of one of the latches. The latches are retracted by the monofilament when the release button is pressed and are pushed into the object to hold it into the socket by the spring.

Each of the objects also provides feedback to the user about their movement through the base of the object. The feedback area is lit from underneath by high-power LEDs that provide a color-coded cue to the participant about the error in their trajectory. The feedback area is an embedded circle inside the hexagon. Visual feedback is presented within this shape gives the impression of an overall, continuous color, without obvious sides or anything that could be misconstrued as information about location or spatiality of the error.

Tasks being trained in the AMRR Home System

The objects were designed to accommodate therapy for people with impairments ranging from moderately severe (unable to perform complex movements due to difficulty in controlling the arm in space,

increased weakness in the arm and high reduced ranges of motion in the arm and hand) to mild (able to perform movements, including grasping, but with weakness or reduced speed or control). Tasks were derived from both the clinical AMRR therapy system (reach to a virtual target tasks – no physical manipulation required; reach to touch a button tasks – hand must touch a flat surface perpendicular to the table; reach to grasp tasks – hand must grasp a cone) and were newly developed for the home system (reach to grasp a cylinder – hand must grasp a cylinder and reach to grasp and transport a cylinder – hand must grasp a cylinder and move it to a different location on the table). Although each task uses a different shaped object, the feedback was consistently presented to allow strategies learned during any task to be genralizable to a different task. The main focus is train the motor components comprising the task, regardless of the end goal, in a way that can be used as a strategy during a variety of movements.

Reaching movement for virtual, touch and grasp tasks

The virtual, reach to touch and reach to grasp tasks all follow the same basic movement pattern, and thus provide the participant with similar feedback. These reaches can be done sets of 10 with summary visual feedback presented after each reach, or in sets of 5 with summary visual feedback presented after each set of 5. The different levels of feedback allow the therapist to taper off the amount of real time feedback and for the participant to begin to have a higher-level understanding of the

movement over the course of multiple reaches. When real-time feedback is being used, the object presents a set of lighted feedback to communicate different states of the reach and aspects of movement. Figure 33 shows a pictorial representation of a reach in the context of the home system environment.

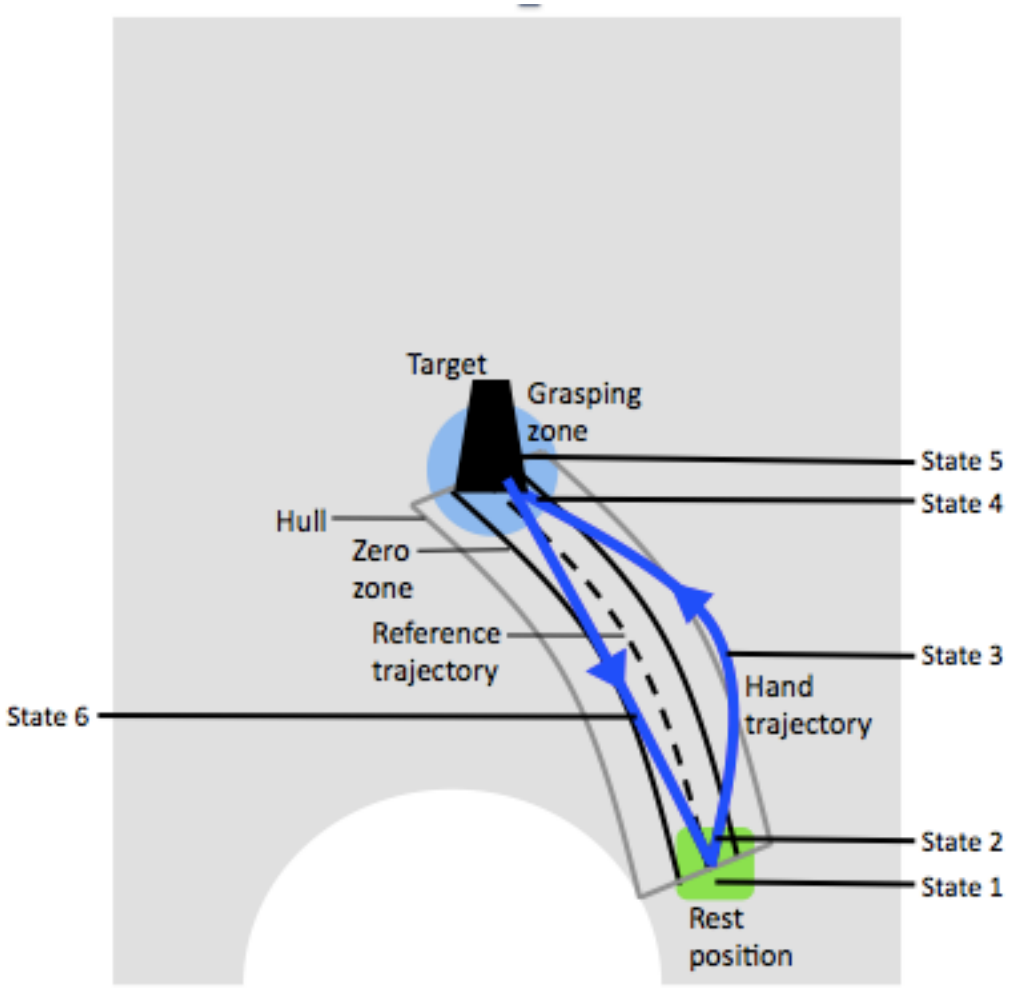

Figure 33. Table (grey square) view of an example reach from the rest position to a target.

The participant starts each reach with his hand on the rest position pad (State 1). State 1 is used to provide the participant with a break from

the task and requires no attention to the physical environment and all objects in the space are unlit. When a sufficient rest period has passed, the computer selects the target that the participant should reach to and turns on a green light within the main feedback space of the object, located in base, as an indication to ‘go.’ This light remains green as long as no trajectory error is detected. Each object has a reference trajectory associated with it for each location, as calculated from an average of a cohort of unimpaired movement data. This reference trajectory is shown in Figure 33 as the black dotted line between the rest position and target. The sensitivity of the trajectory feedback is determined by two spatial boundaries. The ‘zero zone,’ shown as the black lines surrounding the reference trajectory, is the area in which the movement is considered to have no error, and consequently no negative feedback. If the movement is within the hull, but outside of the ‘zero zone,’ a category 1 error is detected and yellow light feedback is provided to the participant. If the movement is outside of the hull (State 3), a category 2 error is detected and corresponding red feedback is given through the base of the tangible object. The design has to effectively communicate the information about the trajectory while not overloading the stroke survivor cognitively or distracting them from the movement. The error colors are distinctly different from the object color and the go cue and can be easily seen through peripheral vision during the reach, which allows them to continue to focus on the task instead of shifting their visual attention to understand

the information. The colored feedback is created by RBG LEDs embedded under the objects' surfaces, which is composed of white, semi-translucent ABS plastic.

The size of the hull is based on the sensitivity assigned by either the therapist or the adaptation protocol (based on previous input from the therapist). For all reaches, left and right sided errors are not uniquely displayed. This allows for the participant to be aware that some part of their trajectory is outside of the acceptable range, but does not burden them with real-time, detailed information about how the trajectory varies from the ideal model. The additional spatial information can either be extracted by the patient's own visual and proprioceptive feedback or through the summary on-screen visual feedback presented after the reach.

As the subject approaches the target, and enters the 'grasping zone,' the trajectory feedback stops responding to new errors in trajectory and remains fixed at the last category of error recorded (State 4). This allows the participant to focus on the manipulation portion of the reach without having to process additional feedback. When the task is successfully completed, a green light (separate from the trajectory feedback) turns on (State 5). This light is positioned in a place where it is easily visible to the participant during normal manipulation of the object and can be used to indicate quality of manipulation (dim green light represents the task was completed but with quality problems and a bright

green light represents the task was completed within the parameters set by the therapist. If the task is not completed after a certain period of time, all lights are turned off and the participant is instructed to return to rest). As the participant returns to rest, all feedback is turned off (State 6) and has a short rest between reaches. The reaching cycle repeats itself as dictated by the therapy protocol.

Reach to touch a virtual point task. The virtual object requires a simple reach to touch (on the plane of the table) task. The participant must make contact with the center of the object to complete the task and they may do the entire task without lifting their hand from the table. This task requires the least complex joint movements and does not require a specific configuration of the hand during touch. This object is completely flat with a touch-sensitive center. The touch sensor electrode is comprised of aluminum mesh that is connected to a capacitive touch sensor IC (Atmel AT42QT1011-TSHR), chosen for its automatic calibration, drift compensation, and ease of use. Currently the sensitivity is set to require at least two fingers touching the object to constitute a touch, (i.e. the IC sends out a 5V signal when the capacitance has changed consistent with at least two fingers being in contact with the plastic top of the object) but this sensitivity can be adjusted through changes in the electronic circuit components. The electronics and feedback LEDs of the object is controlled by an embedded Arduino Pro Mini microcontroller (http://www.arduino.cc/), which transmits sensor and receives state data to

and from the system computer. Task start and trajectory feedback is shown the main circular area of the object and task completion feedback is shown in a thin ring around the feedback area, which allows the participant to see the feedback regardless of their hand position at the end of the reach. Figure 34 shows the virtual object highlighting each of the 6 states as described above.

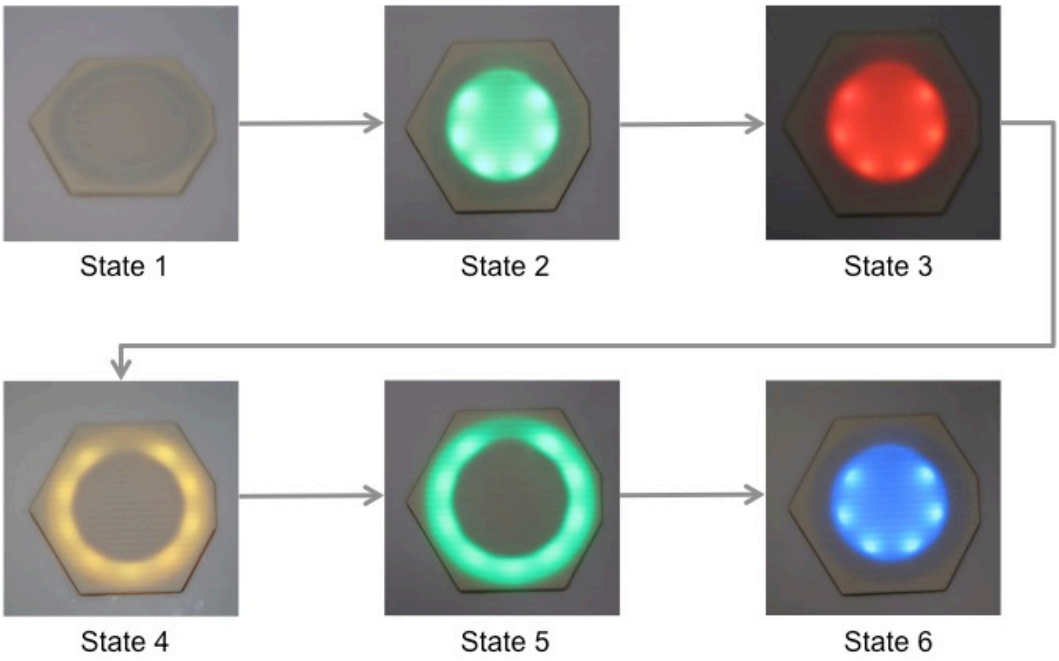

Figure 34. Six states shown for the virtual object - Rest (State 1), Go/no trajectory error (State 2), Category 2 error (State 3), Entering the grasping (touching) zone (State 4), Task completion (State 5), Return to rest (State 6). The spatial arrangement of these states during the reach can be seen in Figure 33.

Reach to touch a button task. The button object requires a reach to touch to a surface above and perpendicular to the plane of the table. This object is raised, flat, 3” circular object with a touch-sensitive front. The touch sensor and accompanying electronics are exactly the same those of the virtual object described above. The participant must make contact with the

sensor to complete the task and they must at least raise part of their hand from the table to complete the task, making this task slightly more complex than the virtual task, but the hand may still be in a variety of postures to activate the sensor. If deemed necessary by the therapist, the sensor data can be combined with the hand position during the task to train targeting accuracy during touch. The large area in the base provides feedback on the trajectory and the task completion feedback is shown in an angled ring around the button, which allows the participant to see the feedback regardless of their hand position at the end of the reach. Figure 35 shows the button object in each of the 6 states described above.

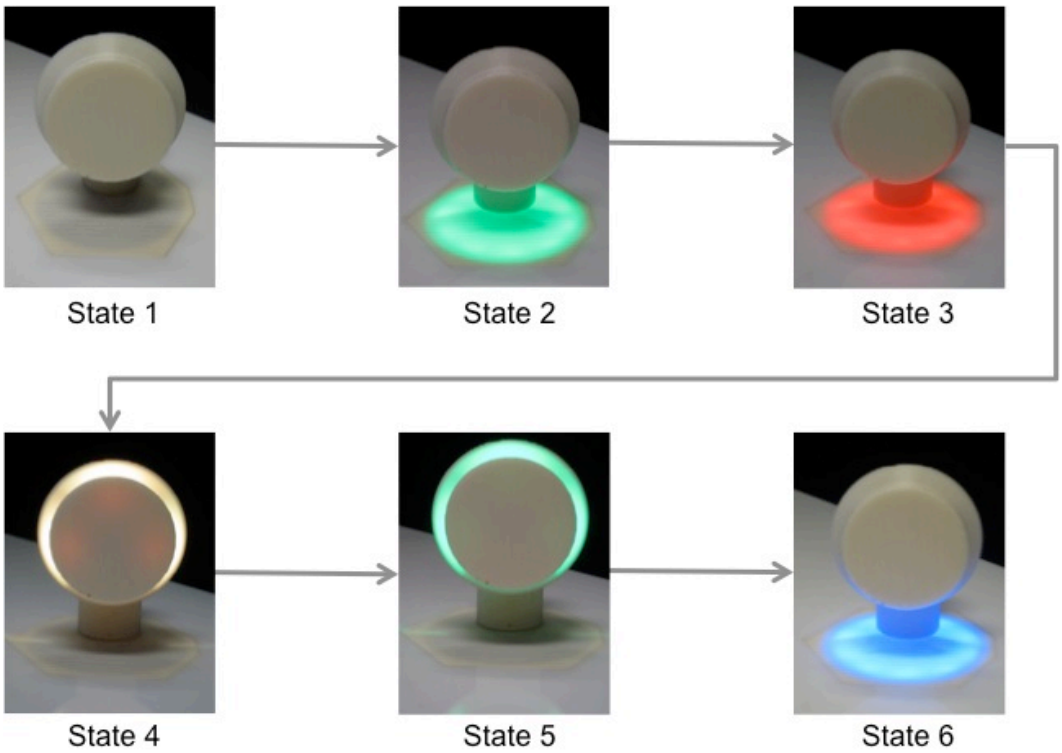

Figure 35. Six states shown for the button object - Rest (State 1), Go/no trajectory error (State 2), Category 2 error (State 3), Entering the grasping (touching) zone (State 4), Task completion (State 5), Return to rest (State

6). The spatial arrangement of these states during the reach can be seen in Figure 33.

Reach to grasp a cone task. The cone target is based on a shape widely used in traditional rehabilitation therapy that encourages hand supination and grasping, which makes this task more complex than the previous two touch tasks. The shape of the cone allows for a number of aperture sizes. Users who cannot extend their fingers fully can grasp the smaller top, while users who have a greater range of finger extension can grasp anywhere on the cone. The shape also allows users with a smaller range of motion in their fingers to use the shape to extend their fingers by sliding down the length of the cone while grasping. The cone is covered in 16 force-sensitive resistors each in part of a voltage divider with a 2.2kOhm resistor (chosen to maximize sensitivity and range). The participant must exert the magnitude and spatial layout as determined by the therapist and system algorithm (described in section *Classifying hand function*). FSRs were chosen due to their low cost, ease of use and physical flexibility. The FSR sensors (via a 16-1 multiplexer) are read by an Arduino Pro Mini, which also controls the feedback LEDs and data communication. The large area in the base provides feedback on the trajectory and the task completion feedback is at the very top of the cone, which allows the participant to see the feedback when they have correctly grasped the cone. Figure 36 shows the cone object in each of the 6 states described above.

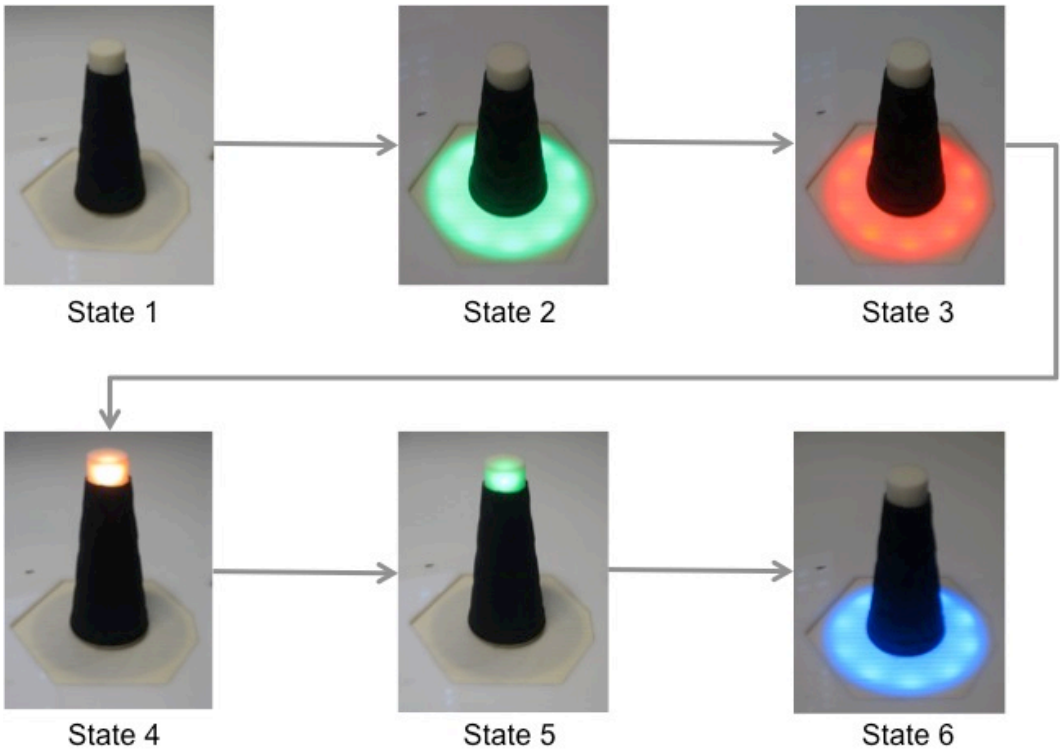

Figure 36. Six states shown for the cone object - Rest (State 1), Go/no trajectory error (State 2), Category 2 error (State 3), Entering the grasping zone (State 4), Task completion (State 5), Return to rest (State 6). The spatial arrangement of these states during the reach can be seen in Figure 33.

Reach to grasp a cylinder task. The cylinder target also encourages hand supination and grasping, but it is a consistent diameter and requires the hand to fully achieve a certain aperture prior to grasp. The size of the cylinder is representative of a can or drinking glass that would be picked up during activities of daily living. The cylinder is covered in 32 force-sensitive resistors. The grasp analysis and feedback are analogous to that of the cone but are described in more detail below (section *Reach to grasp and transport task* and section *Classifying hand use)*. The large area in the base provides feedback on the trajectory and the task completion feedback is at the very top of the cylinder, which allows the participant to

see the feedback when they have correctly grasped the cone. The cylinder can be grasped on the table or 6 inches off the table to provide anti-gravity reach training. Figure 37 shows a picture of the cylinder object.

Figure 37. Picture of the cylinder object. This object can be used to do reach and grasp tasks or reach to grasp and transport tasks.

Reach to grasp and transport task. Although the reach to touch and grasp tasks provide a variety of hand positions and actions for the stroke survivor to practice, in reality most interactions humans have with their physical environments are not with stationary objects. Most objects generally can be picked up, transported, moved, or manipulated in a way that is much more complex than a simple grasp or touch. And the consequences of not having the strength, coordination or other ability to complete the manipulation are that the object may tip over, fall or have another undesirable outcome. The successful negotiation of these objects is how stroke survivors can relearn the activities of daily living that they may not currently be able complete and an effective stroke rehabilitation system must incorporate this type of task.

Previously, all physical objects used in the AMRR system have been securely fastened to the table. Because the challenges faced by the stroke survivor in using their affected hand may have discouraged them from use or negatively affected their outlook on their rehabilitation, the system was designed to avoid any negative consequences for the participant as a result of not successfully completing the task. When the objects were securely attached to the table (both in the hospital system and initial versions of the home-based systems), the participant felt free to explore their movement and coordination abilities without risking damaging the object or knocking it down. This gives them a greater confidence in their movements. However, as the participants gains new strategies and confidence in their movements during training and can accurately and consistently reach the stationary objects and perform a grasp, there must be a next stage of training, especially in a home-based system that is intended for multiple months of use.

The next step in training will use an object that facilitates multi-stage movements (e.g. grasping, lifting, transporting and placing/releasing an object). Although the task will be different, the feedback should remain consistent to encourage use of generalizable strategies, so the transportable object is the cylinder object that was previously described. Creating an object that can be moved unencumbered required a rethinking of the power and data transfer protocols used in the stable objects. The electronics related to sensing and task completion feedback are now

controlled through a separate Arduino Pro Mini that is embedded in the cylinder object. Power to the electronics is provided through a rechargeable 9-Volt battery and the data is transmitted through an X-Bee wireless module. The transportable cylinder is set into a base (consistent with the bases of the stable objects) that houses the trajectory feedback LEDs and a separate Arduino Pro Mini. The receptacle also has an embedded electromagnet that lines up to a steel disc in the bottom of the transportable cone when the cone is placed correctly in the receptacle. The electromagnet is used to keep the cone securely in place while the participant grasps the cone. The electromagnet can be activated at all times to provide a stable object during reach to grasp a cylinder task or turned periodically on and off during the transport task. Figure 38 shows the receptacle for on table reaches (left) and off table reaches (right).

Figure 38. On and off table receptacles for the transportable Cylinder object, showing the electromagnet that bonds the object to the receptacle, providing a stable target

The transportable cylinder is part of a more advanced task in the home system that requires multi-stage planning and execution. This task moves the participant from doing repetitive task reaches to a stable target to a more realistic, functionally relevant task. Because of this, the real-time feedback provided to the participant is greatly reduced. The participant no longer receives trajectory feedback from the base of the object and solely relies on the feedback for location information and state changes (completing a successful grasp in order to lift and transport the object. Similar to the stable grasp task, the transport task has a rest period between tasks where no lights are present (State 1). The receptacle with the cylinder in it then lights up green to signal the task has started (State 2) and stays green throughout the reach, regardless of the trajectory performance. State 3 and 4 are exactly the same as the stable cylinder, with the top of the cylinder lighting up green when the grasp is successfully completed. State 5 is the stage of lifting and transporting the cone from one receptacle to the 2nd target location (which lights up green to indicate that is the location of the end goal of the task). Once the cone has been correctly placed in the receptacle, all lights are turned off to indicate the person should return their hand to the rest position. The task can then be performed in reverse (Target location 2 to target location 1). The spatial arrangement of the states for this task is shown in Figure 39. The top of the cylinder is also outfitted with 3 reflective markers (to create a rigid body). This will allow us to track the movement and orientation of

the cylinder throughout the transport. The cylinder motion capture data, combined with the wrist motion capture data will provide information about the relationship between the position of the hand and the cylinder, which will also provide information as to if the object was dropped. The cylinder may be transported between two receptacles that are on the plane of the table or between one receptacle on the plane of the table and one that is 6 inches off the table.

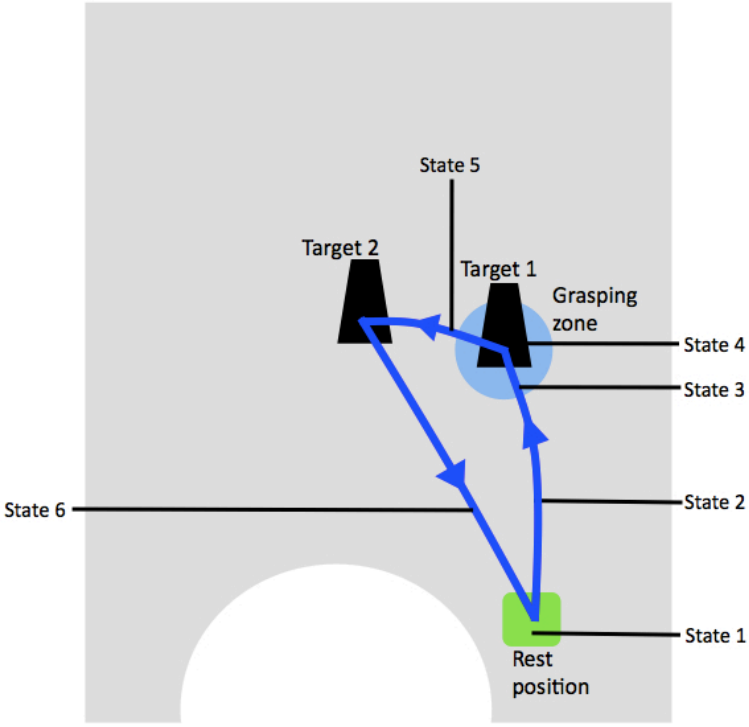

Figure 39. Table (grey square) view of an example reach and transport from the rest position to grasping the cone at Target 1 and transporting it to Target 2.

Software modularity for interfacing with custom hardware

The objects were designed to work as a larger software system and my contribution was in creating a modular program that could work within

the structure of the overall home system software architecture or could be easily modified to work independently. The main goals of the software were to collect data via serial communication from the objects' microcontrollers, synchronize the data received from the microcontrollers to the data received from the motion capture system, to evaluate the hand function in context of the task required by the specific object being used and to pass messages from the computer software to the object hardware. All code was written in Objective C through Cocoa for use on Mac OSX systems. Specific issues that were addressed were: determining ideal sampling and baud rates for the objects based on hardware limitations and communication protocols (i.e. wired USB connection vs. wireless XBEE connection); using the preprogrammed motion capture data sampling and time stamping verification to ensure the two data streams were being collected concurrently; integrating the object toolkit data collection and analysis software into the larger modular software of the home system; and creating classification schemes for evaluating hand function during manipulation of different objects.

Classifying hand function based on object interaction

During interpretation of the control group study, it was discovered that while targeting was an important measure during reach to point or touch tasks, it became less important to measure during reach to grasp tasks. Since the home system uses both types of tasks, the evaluations will be subsequently be adapted to better reflect the aspects of movement

quality important to the specific task being performed. During the reach to touch tasks (as in with the virtual object and the button object), the evaluation will involve measuring both if the hand activated the sensor by coming in contact with the object and where the hand was during the activation, as measured by the motion capture data from the wrist. This measure of targeting will reflect how well the participant was able to create a movement strategy to accurate get to the target. As the person becomes more accurate and stable in their reach, the error at the manipulation phase of the reach should be reduced.

During reach to grasp tasks, targeting became less of an issue, presumably because participants had a target that they were actually holding on to. The sensor layout on the cone and transportable cylinder objects allow for a reading of relative forces exerted on the object in multiple locations. This sensor data can be used to measure the amount of force and the orientation of the force exerted to determine if a grasp was successfully applied to the object. This analysis is especially important when determining the quality of a grasp before transport. The grasp needs to be stable, with an equal and opposite amount of force applied by the thumb and at least one finger, before the object can be lifted. The transportable cylinder also uses motion capture markers embedded into the top of it to track the stability and efficiency of the path taken during the transport.

All of the evaluations are made in the context to unimpaired subject data to provide a reference of impairment, similar to the KIM evaluations. This evaluation is then used to provide feedback to the participant in hopes of training a more accurate and efficient reach and object manipulation. The objects all have a lighted section that is specifically used for manipulation feedback. This light can be bright green – indicating the evaluation fell within therapist specified limits in all aspects (i.e. both in sensor activation and end point error), dim green – indicating the evaluation fell within the limits for one aspect (i.e. touched the object, but with a large end point error), or no light – indicating the evaluation was not met for either aspects. This type of feedback give the participant a rough idea of how well they are doing but expects them to self-evaluate to determine the cause of the specific feedback they are receiving.

One of the main features of the hand evaluation is that it is extracted solely from external sensing solutions, both a smarter motion capture system and the sensors on the objects, instead of requiring additional sensing or equipment put on the hand. The ultimate aim of this analysis will be to provide therapists with an informative measure of hand function without introducing additional burden on the clinical staff or participant during the therapy. This information can be used as a measure of therapy effectiveness and also to drive task adaptation, as the reaching KIM is currently used.

Future work - Validity and reliability testing with a person with stroke

While I have designed the tangible object tool-kit with knowledge of the limitations faced by stroke survivors during home-based therapy, the system has not yet been fully user tested. This next step is crucial to finalizing the designs and ensuring a smooth and easy workspace set up by someone with stroke or by their caregiver. A pilot study with stroke survivors could be used to answer the following questions.

Usability. The physical environment was designed to be able to be interchanged using a one-handed approach. However, some stroke survivors have impairments to both sides of their body and it needs to be determined if the objects require too much dexterity to interchange. All possible scenarios for incorrect object placement need to be explored and safeguards and alerts should be put in place. The participant will also be lead through setting up the physical environment through screen based prompts and it is yet to be shown that these prompts lead to correct set up with minimal frustration or error.

Reliability of software and hardware performance and task evaluation

The system, as a whole, has not yet been used in someone's house for an extended period of time. Further study is needed to ensure that the software and hardware can run for an extended period without crashing or malfunctioning. The sensors also need to be evaluated for the ability to detect and evaluate the performance of stroke survivors of many different types of impairments and to integrate those varying performances into the evaluation algorithm. Along those same lines, while the objects

were designed to provide tasks of different degrees of complexity and function, it needs to be shown that the objects can provide challenging therapy to a wide range of stroke survivors over the long-term, without the therapy becoming too easy or too repetitive.

Feedback comprehension

The objects are embedded with trajectory feedback in their bases and task completion feedback in the site of the manipulation. Although unimpaired subjects easily understand this feedback, it needs to be shown that people with stroke can connect the trajectory of their arm to the feedback seen in the base of the object. This feedback should also be intuitively linked to the summary, screen-based feedback of the trajectory after the reach. Successful knowledge of inaccuracy both during and after the reach will maximize the ability of the stroke survivor to correct their movement. The same logic needs to be applied to task completion, so the participant can distinguish between the dimmed and bright green lights and correct the hand manipulation accordingly.

Conclusions

My work on creating a modular toolkit of tangible sensing objects represents a key contribution to more fully integrating virtual reality environments with physical tasks to provide a optimally enriched mixed reality environment for stroke rehabilitation. The toolkit provides a way for stroke survivors to perform a variety of tasks at a variety of locations within the comfort of their own home. These tasks are also integrated into a

larger system that tracks and provides feedback on multiple aspects of movement quality and function. Although this dissertation only describes my development of the objects, the built-in modularity and ease of reproducibility by exploiting digital rapid prototyping techniques will allow my work to be carried on to explore the remaining unanswered questions or to be used in other rehabilitation environments.

Chapter 5

CONCLUSIONS AND FUTURE WORK

Administering effective therapy to people who have had a stroke remains a huge challenge in health care. Although stroke is the leading cause of disabilities in the US and upper extremity impairments can greatly reduce a person's quality of life and ability to perform activities of daily living, the best approach for achieving recovery is still poorly understood. The advent of new motion sensing systems, computational models of movement and greater understanding on how to best achieve motor learning has led to an increased interest by the rehabilitation community in using novel, technology driven therapy interventions. The AMRR system is one such intervention that has been shown to effectively improve measures of movement quality and function during a control group study and also shows promise as a home-based therapy system.

Conclusions

This dissertation describes the work I have done to formalize the administration of adaptive mixed reality rehabilitation (AMRR) based on the results of a small pilot study. The complexity of analyzing the pilot data demonstrated a need for metrics of movement quality that could be easily and accurately combined across subjects. During the pilot study, the therapist increasingly chose to employ physical objects to provide a target to the reach, which led me to begin development on a larger suite of objects that are suitable for use in the clinic and during home based

therapy. The pilot study results demonstrated positive outcomes on a per participant level, but a larger study to compare changes in movement quality and function made by stroke survivors who had received AMRR therapy or tradition upper extremity therapy was needed. During this control group study, I took the lead in developing the assessment metrics and in overseeing the evaluation visits. I also developed the data analysis and statistical comparison procedures to successfully evaluate the validity of the hypothesis that administering abstract audio and visual feedback about kinematic elements of the therapy task would be more effective in improving movement quality than traditional therapy. The data showed evidence that AMRR therapy could increase function and movement quality after 4 weeks of therapy, however the data failed to show an increase in participant-perceived usage or movement quality of the upper extremity during activities of daily living. This result reinforced the need for a home-based system that could provide effective mixed reality therapy at a low-cost and at increased comfort and convenience to the participant. As part of the development of the home-based system, I designed a collection of physical objects that provide targets for multiple kinds of therapy task and an integrated hardware and software structure that provides feedback on kinematic performance during the reach and senses and evaluates hand function during manipulation of the object.

Therapists and researchers are beginning to embrace quality of movement alongside functional ability as important components of the

recovery process after stroke; however, how to measure movement quality in a nuanced, objective, and repeatable way has not become standardized. This dissertation outlines a first attempt to use kinematic data to evaluate movement quality in the context of a pilot study using mixed reality rehabilitation. Although a detailed analysis of kinematic attributes was extremely helpful in pinpointing areas of impairments and tracking the participants' progress throughout therapy, the data could not be easily combined to provide aggregate descriptions of impairment. The raw data values also provided no context to the researchers or therapists about where that data fell in the spectrum of impaired and unimpaired movement, like most other clinical scales are able to do. Raw kinematic values were informative to researchers who were already familiar with their significance, but were too complex for most people to quickly understand or utilize during therapy.

The development of the Kinematic Impairment Measure attempted to address the issue of presenting kinematic data in a standard straightforward way that could be used by people with only a basic understanding of the algorithm used in the calculations. My work on the KIM was contributing towards the theoretical basis underlying its development and to evaluate its use in the control group study. During that study, I facilitated the therapist's understanding of the KIM and advised her on how to use the values in tracking the participants' progress as well as in making real-time adaptations to the therapy. The data analysis I

performed for the control group study also demonstrated the KIM could be used to successfully describe the detailed impairments of individuals, as well as the overall characteristics of groups of stroke survivors. The measure proved useful in combining multiple parameters prior to statistical analyses, even if the parameters had very different raw value scales. The use of the KIM as a measure of movement quality in a control group study represents the first example of a standardized kinematic-based evaluation for stroke and demonstrates the value these types of measures afford to studies of stroke rehabilitation.

The control group study, carried out in partnership with Banner Baywood Medical Center, provided the data I have used to demonstrate that AMRR therapy can be successfully administered in the clinic and can promote gains in both movement quality and function in trained and untrained tasks among a diverse group of stroke survivors. The study was a collaborative effort between many researchers and clinicians and the main focus of my work was in the study design, evaluation metrics and data analysis and interpretation. Originally, the therapist was asked to use a guideline of measured milestones and therapy progressions to administer AMRR therapy in an attempt to provide equivalent dosage and intensity of therapy to all participants receiving AMRR therapy. However, as I observed the therapist performing her work, it became clear that the impairments of stroke survivors are not best addressed with a regulated schedule of therapy. The therapist had to be free to change the feedback

parameters that were not achieving desired outcomes and to tailor the tasks and therapy foci to meet the specific therapy needs of the individual in real time. The case studies presented in this dissertation show that two participants, stroke survivors who entered therapy with extremely different initial impairments and received AMRR therapy that addressed their needs through adaptive manipulation of the tasks and feedback, both saw remarkable improvements in movement quality measured by the KIM. Function, as measured by the Wolf Motor Function Test, was also increased in both participants. Allowing the therapist to be flexible in her application of certain therapy features lead to an experiment where the intervention group received therapy that was equal in dosage among all participants, yet varied based on the needs of the individual. The results shown here demonstrate that a rigorous scientific evaluation of the AMRR system is possible, even if each participant did not receive the exact same therapy. Stroke survivors require highly adaptive and personalized therapy to advance their recovery most effectively and this study has shown that this is possible, even within a controlled experiment.

Participants in the traditional therapy group also received individualized therapy guided by the therapist but without the added audio and visual feedback driven by kinematic performance. The evaluation measures that were used to determine outcomes in both groups during the pre- and post-evaluation visits were carefully selected to elucidate improvements in multiple areas, from multiple perspectives and included

kinematic assessments, therapist rated clinical scales and participant answered questionnaires. The AMRR group demonstrated improvements in their kinematic measures for both the trained task (reach to grasp a cone) and an untrained task (reach to touch a lighted button). This indicates that the motor learning that occurred during AMRR therapy was able to generalize to performing tasks that were similar (both involved reaching) but had different physical or cognitive requirements (the buttons were located in a space that required larger joint movements and the location of the target button was unknown until directly prior to the movement). Providing participants with genralizable opportunities for motor learning is extremely important to ensuring that they can utilize the strategies in a variety of everyday situations. The group who received traditional reaching therapy did not have significant improvements in measures of movement quality during the trained or untrained tasks.

The clinical scale results demonstrated that the AMRR and Control groups similarly improved their ability to perform the tasks comprising the Wolf Motor Function Test, indicating an increase in overall function. However, while the AMRR and Control groups both increase their scores on the Fugl-Meyer Assessment scale, the Control group had a significantly larger increase. Although the AMRR therapy was highly adaptable in terms of what feedback could be used and which of the three types of targets could be used, it was limited in terms of the target locations and because of the lack of fine manipulation used in interacting with the

objects. This may have contributed to the lesser increase in the FMA since the FMA uses measures of range of motion and many different types of grasps and movements in the evaluation. Traditional therapy had a wider range of physical tasks and objects available to the therapist, allowing her to provide therapy targeted towards hand function and range of motion better than she could in the AMRR environment.

After evaluating the participant-answered questionnaires, especially the MAL, it was also clear that participants were not necessarily transferring the strategies they had learned during therapy to activities of daily living or that they were either unaware that they were doing so or unable to accurately gauge how much and how well they were using their arm throughout the day. The clinical AMRR system focuses on movement quality related to the arm and torso, but lacks a way to provide detailed feedback on the hand function. And although the targets could be raised off of the table to provide a reach against gravity, there were no instances of tasks that required the participant to lift an object or work on any strength training. In daily life, most activities of daily living involve exerting force on a tangible object in specific way to produce a desired translation or rotation of the object. Because these movements were not practiced during AMRR therapy, the participants may not have felt comfortable performing those types of tasks at home. Further versions of AMRR therapy need to take this limitation of the clinical system into account to make sure the therapy tasks more closely mimic useful activities of daily

living and require the use of corresponding muscles to connect to the kinematic feedback being received. However, incorporating additional, more complex tasks to the system will require long-term training that may not be feasible in an inpatient or outpatient clinic.

Therefore, the next step in the AMRR rehabilitation project was to transition the principles of the clinical system to a low cost and easy to use system for home rehabilitation. Acknowledging that the AMRR therapy could be enhanced by additional tasks and by better connecting the therapy to every day life, I focused my efforts on creating a toolkit of physical objects that could be used in the home AMRR system. The first version of the home system featured three stationary cone objects. These objects also did not offer any feedback or interaction beyond a lighted go cue. Participants reported that this set up was very boring and did not provide much motivation to continue the therapy. I integrated the participants' feedback into my new designs to create a system of objects that can be easily interchanged by the participant and provide a variety of tasks that relate to everyday activities. This tool kit allows for feedback to be given in the physical space to start better transferring strategies outside the therapy environment, yet could also be easily modified to work with a variety of mixed reality environments. The entire tool kit was designed to be modular and all the physical aspects were created from digital files, allowing other users to easily change or reproduce the designs. The toolkit also contains an integrated hardware / software solution that allows for the

objects to sense and evaluate hand function and receive messages from the system to provide feedback based on evaluations of the reach. The object toolkit will be used in an upcoming study to determine the participant usability, effectiveness of the hand function evaluation algorithms and ensure that both function and movement quality can be successfully improved using the home-based mixed reality rehabilitation system.

Future work

The work I have done with the AMRR system was focused towards proving that AMRR could be successfully administered in a clinical setting and would contribute to increases in function and movement quality among a small convenience sample of stroke survivors. While this objective was accomplished, the AMRR system needs further validation and development before it could become widely used at a clinical level. Successful use of AMRR depends on the administering therapist correctly utilizing the KIM evaluations and collaborating with researchers to select the optimal feedback streams and sensitivities and therapy environments to induce the desired improvements. The control group study only used one therapist to administer the therapy. Future work must expand the study of AMRR therapy to different locations to ensure that the AMRR system is easy to use and understand by therapists with a variety of backgrounds and training. Careful evaluations of the data must

also be performed to determine if and how the administering therapist influences the study outcomes.

Additional work also needs to be done on the physical object toolkit to provide the best possible therapy. Currently, grasp is only detected by opposing forces being applied to the object, with very crude thresholds for vertical force application and force magnitude having been garnered from unimpaired subjects. This classification is useful in giving the participant a general idea if the grasp is adequate or not, but does not provide any amount of detail on what parts of the grasp (such as which fingers are not applying enough force, specific placement of the fingers vs. the object's center of gravity, or insufficient pre-grasp aperture of the fingers) need to be addressed. Similarly to the KIM calculations for the arm movement, additional data can be collected from a number of participants with varying hand impairments to create a more detailed evaluation for the hand.

The current version of the home system also only utilizes a limited joint space (all targets are directly in front of the participant and require the hand to approach from the front to complete the proper manipulation). Additional objects could be created that require more complex sets of joint movement or that require more fine manipulation by the fingers. Since the objects were designed to be modular and the feedback is generalized across all tasks, the expansion of the toolkit should be straightforward. As the manipulations become more complex, following the logic of grasp

classification above, more data would need to be collected from unimpaired and impaired subjects to provide the hand function evaluations that provide useful information about the task being performed.

If impairments of hand function are being adequately addressed through a variety of tasks and feedback during AMRR therapy, the strategies learned during therapy should begin to better transfer to activities of daily living. Full recovery after stroke can be characterized by normal usage of the affected body structures with the same frequency and using the same motor strategies as before the stroke. Participants should be encouraged, motivated and empowered to use the skills learned during therapy in their everyday lives to better enhance their recovery. The best way to track hand and arm usage and provide the participant with the proper information and feedback is a very important issue to tackle in the future.

Finally, while the AMRR system is based on a strong foundation of motor learning, media theory, and physical rehabilitation principles, it has only been proven effective in a small group proof of principle study. A full randomized control trial is needed to confirm that AMRR provides an added benefit to therapy following a stroke beyond what is normally gained through usual care. A large clinical trial will also include stroke survivors with different lesion locations, times post stroke and impairment profiles, allowing correlations and relationships to be drawn between clinical and demographic parameters and the effectiveness of certain

therapy and feedback types. This would be a huge step towards establishing engaging, effective, semi-automated adaptive therapy that can improve both the function and movement quality of people following stroke.

Once the system has been thoroughly investigated through a larger study to determine the best clinical practices for administering mixed reality rehabilitation in the home and in the clinic, more practical matters will have to be considered. Specifically, the commercial viability of producing a system to be used unsupervised in the home will need to be analyzed, as well as demonstrating that the system has the potential to augment overall recovery enough to justify the cost. Additional work can also be done to incorporate this system into currently installed technologies in the home, such as a television or computer, to reduce overall costs and ensure the system is affordable to all who would like to use it.

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APPENDIX A

IRB APPROVAL DOCUMENTS

ASU IRB approval letter for pilot study (Chapter 1)

ASU ARIZONA STATE UNIVERSITY
RESEARCH AND ECONOMIC AFFAIRS

Office of Research Integrity and Assurance

To:	Jiping He ECA
From:	Carol Johnston, Chair Biosci IRB
Date:	07/24/2009
Committee Action:	**Renewal**
Renewal Date:	07/24/2009
Review Type:	Expedited F7
IRB Protocol #:	0609001145
Study Title:	Developing an Interactive and Immersive Multi-media Biofeedback System
Expiration Date:	07/23/2010

The above-referenced protocol was given renewed approval following Expedited Review by the Institutional Review Board.

It is the Principal Investigator's responsibility to obtain review and continued approval of ongoing research before the expiration noted above. Please allow sufficient time for reapproval. Research activity of any sort may not continue beyond the expiration date without committee approval. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the approval of this protocol on the expiration date. Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please notify the Committee of the study termination.

This approval by the Biosci IRB does not replace or supersede any departmental or oversight committee review that may be required by institutional policy.

Adverse Reactions: If any untoward incidents or severe reactions should develop as a result of this study, you are required to notify the Biosci IRB immediately. If necessary a member of the IRB will be assigned to look into the matter. If the problem is serious, approval may be withdrawn pending IRB review.

Amendments: If you wish to change any aspect of this study, such as the procedures, the consent forms, or the investigators, please communicate your requested changes to the Biosci IRB. The new procedure is not to be initiated until the IRB approval has been given.

ASU IRB approval letter for control group study (Chapter 2)

ASU ARIZONA STATE UNIVERSITY
RESEARCH AND ECONOMIC AFFAIRS

Office of Research Integrity and Assurance

To:	Thanassis Rikakis BKYD
From:	Carol Johnston, Chair Biosci IRB
Date:	01/06/2009
Committee Action:	**Expedited Approval - Limited**
Approval Date:	01/06/2009
Review Type:	Expedited F3
IRB Protocol #:	0812003572
Study Title:	Mixed Reality Rehabilitation for Stroke Patients
Expiration Date:	01/05/2010

The above-referenced protocol was granted limited approved following expedited review by the Institutional Review Board.

This approval is limited, pending receipt of the Banner Baywood Medical Center IRB approval. No human subjects enrollment can occur until the Arizona State University IRB has recieved and reviewed the Banner Baywood IRB approval.

TIt is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date. You may not continue any research activity beyond the expiration date without approval by the Institutional Review Board.

Adverse Reactions: If any untoward incidents or severe reactions should develop as a result of this study, you are required to notify the Biosci IRB immediately. If necessary a member of the IRB will be assigned to look into the matter. If the problem is serious, approval may be withdrawn pending IRB review.

Amendments: If you wish to change any aspect of this study, such as the procedures, the consent forms, or the investigators, please communicate your requested changes to the Biosci IRB. The new procedure is not to be initiated until the IRB approval has been given.

Please retain a copy of this letter with your approved protocol.

Banner Health IRB approval letter for control group study (Chapter 2)

Banner Health®

January 20, 2009

Paul Blake, M.D.
Attn: Barbara Lambeth, Paul Blake, M.D.
Rhodes Rehabilitation Institute
Banner Baywood Medical Center
6644 E. Baywood
Mesa, AZ 85206

RE: **Project # 08-09-0001**
Mixed Reality Rehabilitation for Stroke Patients
iRIS Reference # 007385
IRB Expedited Approval – New Protocol, Informed Consent and Authorization to Use or Disclose PHI in Research

Dear Dr. Blake:

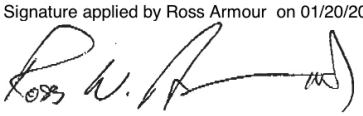
This letter serves to notify you that the above referenced Protocol, Informed Consent, and Authorization to Use or Disclose PHI in Research received expedited review and approval by Ross Armour, MD, Chair of the Banner Health Institutional Review Board (Western Region Panel) on January 20, 2009 for conduction at Banner Baywood Medical Center. This expedited review was performed in accordance with 21CFR56.110 (b) and 45CFR46.110(b). This study has received approval for one year. The FDA requires that all studies be reviewed at least annually. The final approved, stamped Informed Consent is available electronically. You must use photocopies of this Informed Consent exclusively. A copy of the signed Informed Consent document must be placed in the patient's medical records.

The Board's approval to conduct your study will expire on 1/19/2010. The IRB requests that you submit a Continuing Review report one month prior to the January 2010 IRB meeting. This allows time for processing and review prior to the IRB expiration date of the study. A Closing report is required upon completion of the project. The occurrence of adverse reactions/events must be reported to the Board in writing within 3 days of the occurrence. Any changes in the study protocol, unusual events, results of the study or any additional information relative to the study must be submitted to the Board. In the event the study results are published, please send a copy to the Banner Health Research Administration so it may be included in the file. A copy of this letter will be placed in the study file.

The Board appreciates your participation in research. If you have any questions, please contact Michelle Faber, CIM, IRB Coordinator, at 970-346-3722.

Sincerely,

Signature applied by Ross Armour on 01/20/2009 11:31:55 AM GMT-07:00



Ross Armour, MD