An Adaptive Mixed Reality Training System for Stroke Rehabilitation

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***Abstract*—This paper presents a novel mixed reality rehabilitation system used to help improve the reaching movements of people who have hemiparesis from stroke. The system provides real-time, multimodal, customizable, and adaptive feedback generated from the movement patterns of the subject's affected arm and torso during reaching to grasp. The feedback is provided via innovative visual and musical forms that present a stimulating, enriched environment in which to train the subjects and promote multimodal sensory-motor integration. A pilot study was conducted to test the system function, adaptation protocol and its feasibility for stroke rehabilitation. Three chronic stroke survivors underwent training using our system for six 75-min sessions over two weeks. After this relatively short time, all three subjects showed significant improvements in the movement parameters that were targeted during training. Improvements included faster and smoother reaches, increased joint coordination and reduced compensatory use of the torso and shoulder. The system was accepted by the subjects and shows promise as a useful tool for physical and occupational therapists to enhance stroke rehabilitation.**

***Index Terms*—Mixed reality, motion analysis, reach and grasp, stroke rehabilitation, upper extremity.**

I. Introduction

STROKE is the leading cause of chronic adult disability in the United States. Improving the motor abilities, including physiological recovery, body function recovery, and activity recovery, of stroke survivors generally requires a long therapy process and research efforts are currently devoted to finding the most effective forms of therapy. Studies have shown functional improvements (measured by standard clinical scales) and induced neural plasticity in people who are a year or more post-stroke when appropriate therapy, based on motor learning principles, is administered [1], [2]. Improvements in certain kinematic or functional parameters of the upper extremity have been achieved through a number of different methods: repetitive movement therapy, constraint induced therapy and robotic assisted therapy [3]–[5], and virtual reality therapy [6]. Research has shown that effective stroke rehabilitation therapy focuses on helping the patient regain the ability to successfully complete functional tasks while relearning pre-morbid movement patterns. This therapy may minimize the use of compensatory strategies and increase the range-of-motion of distal joints [7]–[9], although subjects experience discomfort as they are asked to reverse their learned non-use and/or compensatory strategies [9]. Therapy can be made more engaging and effective when enhanced by external feedback, to augment information gained from intrinsic sensory organs that may have deteriorated. The feedback can offer guidance, motivation, and encouragement, all integral parts of motor learning, and adaptive feedback can reduce boredom and monotony, which can depress motor learning [10]. Interactive environments, which can provide this kind of feedback, encourage sensorimotor integration, promote motor learning, and help stroke survivors to gain confidence in the use of the affected limb [11], [12].

Digital feedback systems are able to tailor the feedback to focus on certain movement parameters [13] and monitor which types of feedback will elicit a positive performance response from the patient. The feedback can be connected to observable parameters of physical action (i.e., hand trajectory) or less obvious parameters (i.e., joint coordination). This information can be presented as true feedback about the current movement or used to aid in feed-forward planning of the next movement. Feedback can be presented in audio, visual, or tangible forms, or as an integration of those media. The ideal interactive environment should combine all types of feedback relevant to a specific function, and present them to the participant in a meaningful and intuitive way [7], [11], [14]. The task and feedback should encourage active physical and cognitive participation with the end goal of the patient learning generalizable movement strategies [11]. The task and feedback must also be adaptable to the subject's individual abilities, allowing the patient to be challenged without causing frustration [6], [15]. These principles would be best used within a stimulating environment, as animal studies have shown that enriched environments can lead to increased neurogenesis and motor learning [16], [17].

Mixed (combined virtual and physical) reality environments can provide complex, adaptive scenes for interactive practice and feedback that engage the user physically and mentally [7]. When used with advanced motion capture, these environments can measure detailed kinematic parameters used to assess improvements in arm movement patterns and provide very accurate feedback on the movement [6], [18], [19]. Patient

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Fig. 1. Photograph taken during one of the training sessions. The therapist (right) monitors and instructs the subject (left) during the entire interactive session.

interactions with such an environment have been shown to improve cognitive and physical function, increase self-esteem, and lead to feelings of greater self-efficacy and empowerment [14], [15]. Feedback systems also provide the patient with the ability to implicitly learn the movements and self-correct. Implicit learning has been shown to be more effective in promoting motor learning than explicit instructions in individuals with strokes that occurred in the supplementary motor cortex and basal ganglia regions [20]. This paper presents a novel mixed reality system that aims to extend the benefits of mediated rehabilitation through the use of interactive arts principles, real-time motion analysis, a mixed (physical and virtual) training environment and computational adaptation of system parameters. A picture of a stroke survivor and the therapist using the system is shown in Fig. 1. This paper will also present kinematic and clinical assessment results from a pilot study of three chronic stroke survivors who were trained on the system for two weeks.

II. Mixed Reality Rehabilitation System

Our mixed reality rehabilitation system aims to increase subject engagement, empowerment, and learning by taking advantage of the parallels between a successful artistic experience and a successful rehabilitation experience. A successful artistic experience transfers the subjects from the frustration of everyday reality to an alternative reality, where they are empowered to overcome cognitive, physical, and psychological limitations and use their experience to tackle their problems in a new way [21], [22]. Often this alternative reality is achieved through the use of abstract artistic metaphors that increase the scope and reach of the artistic experience and allow the message to be communicated through the handling of artistic form

People with movement disabilities may be empowered by experiencing their movement in an artistic context that is not related to the frustrations they face everyday. Our system introduces this new context by mapping movements during a traditional therapy task (reaching to grasp/touch a target) to feedback linked to the composition of an interactive artwork. Initially, the subject can primarily focus on developing movement strategies that will complete the virtual composition, with the focus gradually shifting to the physical task as therapy progresses. The feedback communicates measures of performance and improvement directions for many kinematic aspects of the therapy task and the abstract nature of the composition encourages generalizable learning

Online adaptation of therapy is crucial to meet the unique needs and abilities of each subject and to adjust the focus of the rehabilitation based on progress and performance variability between and within sessions. Kinematic data is used to drive the feedback, as well as for assessing the movement and adapting the parameters linked to the feedback presentation and the physical environment that determines the type of task. The sequence and intensity of tasks can also be varied per subject. We have developed customized computational algorithms and tools to assist the therapist in making the decisions related to adjusting the feedback and task to better address each subject's rehabilitation needs. This section will present a description of the adaptive mixed reality rehabilitation system, including the motion capture setup, the kinematic features derived from the motion capture data, how the features are used to create audio and visual feedback, and how this feedback relates to interactive arts principles and rehabilitation theory.

A. Experimental Setup

Kinematic features are derived from hand, arm, shoulder, and trunk movements recorded with a 10-camera 3-D infrared passive motion capture system from the Motion Analysis Corporation. Reflective markers are placed on the torso, and right shoulder, upper arm, elbow, wrist, and hand. Marker movement data is collected at 100 Hz and low pass filtered to suppress noise. The subject is seated at a height- and position-adjustable table in front of a large display screen that provides visual feedback and two speakers that provide audio feedback.

B. Training Task

During training, subjects perform a reaching task, either by reaching to a target, reaching to touch a target or reaching to grasp a target. Reaching movements start from a consistent rest position. The target can be a physical object or virtual (no physical object). This results in the following four different training environments: 1) virtual (no physical target, interactive audio and visual feedback); 2) mixed two (a physical target is added but the subject still experiences audio and visual feedback); 3) mixed one (the physical target is present, along with audio feedback only); 4) physical (no audio or visual feedback). The controlled interplay of these environments helps connect learning in virtual space to tasks in physical space. The physical target can be a non-moveable 5-in-tall cone in which 25 force-sensing resistors are embedded or a 3-in-diameter touch-sensitive plastic button. Data from these sensors is synchronized with the motion capture data and used to differentiate the reach and grasp/touch stages of the movement.

Subjects are trained to reach towards four target locations that are placed according to each subject's reaching ability (each target is places at a standard percentage of the subject's active assisted reach). The targets are: supported ipsilateral (SI)

TABLE I
STRUCTURE OF THE TRAINING PROTOCOL AND FEEDBACK MAPPINGS

	Task	Kinematic Focus	Feedback	Assessment Attribute Focus
Simple activity - virtual or push button target	1A	Gross targeting	Picture fills the frame	End point accuracy
		Task completion sound	End point consistency	
	1B	Reaching duration	Length of musical phrase	Time to target
	1C	Trajectory accuracy	Sway of image particles	Trajectory error
			Music detunes	Trajectory consistency
	1D	Reaching speed	Speed of musical notes	Speed of movement
			Peak speed of the rhythmic sequence of the music	Velocity peak value / consistency
			Rise and fall of rhythmic sequence	Velocity profile shape
	1E	Integrated reach and push	All feedback	All assessments + Velocity bellness
Body function recovery - virtual or push button target	2A	Trunk compensation (all axes)	Unpleasant crackling sound	Torso rotation around all axes
	2B	Shoulder compensation	Unpleasant scraping sound	Shoulder displacement forward and upward
	2C	Elbow extension	Swelling of string instruments	Elbow joint range of motion
	2D	Shoulder and elbow joint synchrony	Sequence of rhythmic and string swelling peaks	Cross-correlation
	2E	Finger extension	Sensory and proprioceptive	Finger configuration at target
Complex activity with body function recovery - cone target	3A	Fine targeting	As 1A above, with increased sensitivity	End point accuracy
	3B	Forearm supination	Image rotates with forearm	Supination range of motion
	3C	Trajectory	As 1C above, with increased sensitivity	Trajectory accuracy
	3D	Shoulder, elbow and forearm joint synchrony	Sequence of audio/visual feedback	Cross-correlation
	3E	Integrated reach and grasp	All feedback	All assessments + Velocity bellness

—target is on the table and on the subject's right side, supported midline (SM)—target is on the table and at the subject's midline, against gravity ipsilateral (AGI) —target is 6-in above the table and on the subject's right side, and against gravity midline (AGM)— target is 6-in above the table and at the subject's midline.

C. Major Kinematic Parameters

The assessment of each reach includes measures of goal completion, speed, trajectory, accuracy, velocity profile, range of joint angles, joint coordination and compensatory shoulder and torso movements. Average values and consistency across reaches are calculated for all these parameters to assess quality of movement. Table I shows the major kinematic parameters, the assessment focus of each parameter and the interactive feedback that is mapped to each parameter, which is described in the following sections.

1) End Point Parameters: The hand position during reaching is calculated in terms of a local coordinate system that is defined by: z', a vector between the rest position and the target (parallel to the table), and two vectors perpindicular to z', x' (parallel to the table) and y' (perpendicular to the table). The hand position, measured over time, is used to calculate: target acquisition accuracy, trajectory efficiency (measured by length and shape), peak velocity, reach duration, jerkiness, and velocity profile (bellness) of the reach. These parameters represent improvements in activity level recovery, as they relate directly to task completion. The bellness is a measure of how well the velocity profile matches the ideal bell curve, which indicates a smooth, continuous reach with no hesitation or adjustments when approaching the target. These adjustments, designated by a change in sign of the velocity profile slope, segment the reach into phases [19]. The bellness is measured by 1) the number of phases, or local minima, between the first phase and the target acquisition and 2) the normalized adjust area, a ratio between the area under the velocity curve following the first phase and the area under the velocity curve after the peak. A lower normalized adjust area and lower number of phases will indicate a smoother, more direct reach to the target. Jerkiness is calculated by finding the third derivative of the hand marker in all directions over the whole reach and then taking the square root of the sum of their squares and finding the integral of that square root over the duration of the reach.

2) Joint Angle Parameters: Joint angles are measured by the range of movement of individual joints and the coordination of these joints, measured by their correlation during the reach.

3) Compensatory Strategy Parameters: Stroke survivors may increase the use of their shoulder and torso to compensate for deficiencies in the range-of-motion of their distal joints [23]. Our system measures both types of compensation as a way to assess the subject's body function during the reach. Shoulder upward (elevation) compensation is measured by the angular relationship of the projection of the shoulder marker on the torso plane (determined by the three markers on the back) and shoulder forward (protraction) compensation is measured by the distance from the shoulder marker to the torso plane. Torso forward compensation (torso flexion) and torso twist compensation (rotation around the midline) are measured in degrees by two rotation angles of the torso plane. All compensation measures are computed as the difference between the raw subject measurement and reference measurements derived from reaching tasks performed by six unimpaired subjects and are matched as a function of normalized distance from the hand to the target. This approach allows the system to differentiate and react to compensatory strategies that exceed those used by unimpaired subjects, which often results in compensation measures that are smaller in magnitude than reported elsewhere.

D. Online Assessment and Interactive Feedback

Motion capture data and kinematic parameters are archived and visualized during the therapy to assess the subject's performance during the current or past training sessions. Real-time visual and audio feedback engines map selected motion parameters into features of a multimodal, abstract, interactive arts environment. The resulting multimodal environment aims to both encourage the subject to perform the required training task and to offer the subject an intuitive way to self-assess their movement performance, understand the cause of error and develop an improvement strategy.

1) Visual Feedback: The visual sense is well suited to relaying spatial cues [24] and communicating explicit narratives of multimedia compositions [25]. Our system uses visual feedback to inform the subject of task completion, target acquisition accuracy, movement trajectory, and hand orientation. At the start of each reach, a picture appears on the center of the screen and then breaks into hundreds of particles that scatter across the screen. The picture can be any image chosen by the subject to help promote excitement and desire to complete the task. The scattering of the picture into particles moving away from the center of the screen (seemingly towards the subject), creates the intuitive need for the subject to react and balance the scattering motion coming towards their body [26]. The particles coalesce as the subject's hand moves towards the target and the picture reassembles fully when the target is reached. If the subject deviates from the set trajectory sensitivity tolerance zone (hull), in either the x' or y' directions, the particles move in the direction of the deviation. The particles move back towards the center as the subject corrects the deviation. The particles have turbulence, a random though contained movement, throughout the reach. The movement of particles during the reach from an unorganized distribution over a large area towards a focal point creates a sense of gravity that helps carry the arm of the subject towards the goal [27]. If the reach task includes supination of the wrist, the subject's forearm rotation controls the rotation of the image. If the wrist is not supinated to the proper degree when the subject reaches the target, the picture will be askew and may be used as a condition for task completion.

2) Audio Feedback: Auditory feedback in the form of structured music is a powerful tool for movement training, particularly of timing aspects, because music helps the brain connect body, space, and action in a highly intuitive manner [28], [29]. Multimodal compositions like film rely on music to communicate implicit messages and emotional states [25], [30]. The feedback uses musical rhythm and harmony to drive the timing of the reach over space and musical affect to promote completion of the task using full joint range-of-motion and reduced compensation.

The velocity of the subject's hand controls the rhythm of the music, such that a higher velocity results in a higher density of sounds per beat (a faster rhythm). The subject is encouraged to perform their movement with smooth acceleration and deceleration in order to hear a gradual rise and fall in rhythmic sequence rather than abrupt changes in the pace of the music. Likewise, a familiar harmony, common to many popular songs, is controlled by the normalized distance of the hand to the target along the z' axis, which motivates the subject to complete the reaching task to hear the complete musical phrase [30], [31]. Association of the rise and fall in the rhythm with the corresponding harmonies of the musical phrase helps the listener to connect the spatial and temporal aspects of their movement. The volume and duration of the notes of a background musical line performed by string instruments reflects the extension of the subject's elbow. As the foreground melody (controlled by hand velocity) reaches its peak and begins to drop, rich string sounds in the background begin to swell (controlled by elbow extension). By linking these auditory cues, the subject is coaxed to fully extend the elbow,

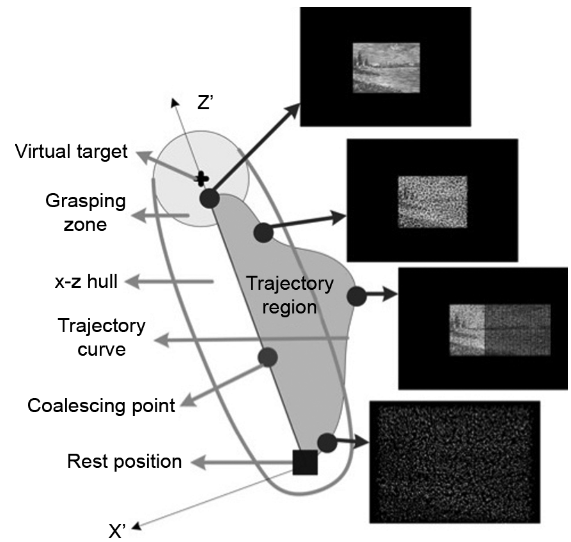

Fig. 2. Illustrative example of a reach. When the hand moves out of the x-z hull, the image is perturbed in the direction of the movement. When the hand reaches the coalescing point, the image is identifiable and when the hand reaches the grasping zone (an area around the virtual target indicating reach success), the image is frozen into place.

coordinated in space and time with their endpoint trajectory and velocity [32].

Auditory cues are also provided to discourage certain undesired movements. If the subject elevates (shrugging) or protracts their shoulder past a predetermined threshold during the reach, a metal scraping sound is produced. Excessive leaning forward or trunk rotation triggers a wood crackling sound. These sounds are readily perceived as jarring and distinctive, thus reminding and encouraging the subject to adjust their shoulder and trunk to the desired position in order to avoid interruption of the pleasant music.

The human brain is known to have a strong memory for musical constructs [31], [33]. Thus, the subject begins to connect successful reaches with the structure of the musical phrases heard. The memory of the successful musical phrase is then used to plan future successful movements. The majority of this type of music-assisted movement learning happens subconsciously, similar to the intuitive learning happening during dance [28]. The subject explicitly focuses on successfully completing the visual task (reconstructing the image) while the music implicitly trains the timing structure [34].

3) Feedback Sensitivity: The sensitivity of each mapping of a movement parameter to feedback is controlled through a variable tolerance zone called a hull. The shape and size of these hulls determine how large an error is needed to elicit corrective feedback. For example, in Fig. 2, the grey oval shows an example x'-z' trajectory hull. When the trajectory of the hand moves outside that region (at the far right black marker) the system recognizes error and provides spatial location visual feedback. The sizes of the hull and the target zone (the targeting accuracy required to signal task completion) are adaptable. This allows the therapist to vary the difficulty of the task to reward the subject's efforts during early training and gradually increase the challenge.

4) Ensuring Feedback Understanding: All feedback streams were previously tested on unimpaired subjects and results show that those subjects, when reaching in a virtual space with accompanying feedback, performed similarly to physical reaching [35]. In these trials, all learning was implicit with the subjects exploring the feedback to learn the correspondence. While we encourage our stroke survivors to also figure out how their movements relate to the feedback, the therapist and system controller are always available to prompt understanding and provide explicit explanations if necessary. The adaptive nature of our system's feedback also allows for any feedback to be turned off or the sensitivity to be decreased if a certain stream is producing frustration in a certain subject.

E. Adaptive Therapy Sequence

The training generally starts at the target location with the simplest joint space (SI) and gradually moves to the target with the most complex joint synergies (AGM). The training for each target is realized through a sequence of numbered training steps, which are broken into a sequence of lettered training tasks. Each training task focuses on improving a specific movement parameter while maintaining or further advancing gains made in earlier tasks. Each task has an associated set of system parameters (e.g., the size of the trajectory hull) and training environment (virtual, mixed I, mixed II, or physical), although these can be changed as directed by the therapist. As the training steps and training tasks progress, the complexity of the feedback and the self-assessment increases. Each training step, each of which can be used at all target locations, is summarized below and is shown in greater detail in Table I.

Step 1: (Tasks 1A-1E) focuses on the recovery of a simple reaching activity. The first element to performing this task is the subject being able to move their hand to a large target area (4–6 cm radius) in space. Following this, the system can focus on training reaching speed and duration, reaching time consistency, trajectory efficiency, and performing the entire task by reaching out to touch a target while retaining movement characteristics gained in the previous tasks. At the end of this step the subject should be able to reach the target zone accurately, with an efficient trajectory and improved velocity profile.

Step 2: (Tasks 2A-2E) focuses on recovery of body function, including multijoint coordination of the arm and reduction of torso and shoulder compensation, which may assist in activity recovery [41]. At the end of this step, the subject should show improved target acquisition ability and trajectory efficiency as well as improved shoulder and elbow joint synergy and a reduction of trunk rotation or shoulder elevation or protraction.

Step 3: (Tasks 3A-3E) focuses on integrating the previous two steps into a more complex movement of reaching to grasping. The subject works on improving endpoint accuracy by reaching a smaller and more complex target with a more efficient trajectory. This step uses the cone target whose affordance compels the subject to supinate their forearm when approaching it. The target zone can be gradually reduced so that task completion requires a full grasp of the cone. Lastly, this step focuses on the subject using their shoulder, elbow and forearm rotation. At the end of this step, the subject should be able to use all the previously learned skills together to successfully and smoothly reach and grasp the cone.

The system recommends a progression from one step to the next based on performance thresholds and retention of goal completion, activity recovery and body function recovery [36] related to the task being trained, as evaluated by improvements in multiple kinematic parameters. These adaptation suggestions are based on our unique deficit-training-improvement (DTI) correlation framework, whose principles can be generalized for use with any rehabilitation program. This framework is based on the correlations between the subject's initial movement deficit (D), the training implemented through our system (T), and the improvement in the subject's movement (I). Deficit and Improvement are calculated from kinematic parameters and Training is a computational summary of which training tasks and their associated parameters have been implemented. The DTI correlation tells us about the effect of the therapy by showing the subject's progress (DI), and the correlation between the improvement and training (TI). With this framework, we can evaluate and compare the different training procedures implemented through our mixed reality system. A detailed explanation of the adaptation process and computational tools can be found in [42]. The therapist can utilize the DTI calculations and suggestions, and the visualizations of the kinematic data, when deciding how to adapt the feedback or task.

III. Feasibility Pilot Study of the System

Small pilot studies have been conducted with unimpaired subjects and stroke survivors to test key elements and concepts of this system [35], [38]. The present study assesses if a formalized implementation of the adaptive mixed reality training is feasible and beneficial to stroke rehabilitation. One major objective was to assess whether adaptation decisions could be made across subjects in an organized, principled, and reproducible manner. Another objective was to evaluate whether this type of training promotes functional recovery, both at the activity and body function levels, and whether there is a correlation between the improved movement parameters post-training and the parameters targeted by the adaptive training. The study protocol has been reviewed and approved by the Institutional Review Board at Arizona State University. A medical monitor was present at all sessions of the study to ensure the safety of the subject.

A. Subject Selection

We limited our subject pool to stroke survivors presenting clinical symptoms consistent with left-sided motor area lesions resulting in right-sided hemiparesis. Subjects were categorized as having mild or mild-to-moderate impairments by an experienced rehabilitation doctor. Specifically, the subjects 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°–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. Four subjects were recruited from direct referrals from medical care providers or through previous research studies. One subject was excluded because he had nearly normal arm kinematics and had little potential benefit from the study. The three subjects that participated in the study had the following characteristics at the start of training: Subject 1 was a 77 year old male, 14 months post-stroke; Subject 2 was a 76 year old male, 20 months post-stroke; and Subject 3 was a 71 year old female, 32 months post-stroke. All subjects 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 subject'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 subject with limited hearing will very rarely be trained using two concurrent audio feedback streams.

B. Study Procedures

Each subject 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 subject 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 subjects to rate their hemiparetic arm on the amount of use and quality of use 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 subjects 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]. For a standardized measure of arm function, subjects performed the upper extremity portion of the 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]. Subjects also performed eight reach and grasp movements, with no feedback, using the pressure 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 subject was asked to briefly rest after each reach (2–3 s) to discourage mechanical rhythmic movement and aid in the segmentation of the data. Subjects rested for 2–3 min between targets. The WMFT and reach and grasp movements were performed while recording motion capture data, as described in Section II, and were conducted by the same therapist who performed the therapy.

Each training visit lasted 90 min, including 20–30 min of setup, and consisted of approximately 120 reaches (12 sets of 10 reaches). Each subject'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 subject'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 subject's movement to be fundamental to their rehabilitation.

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

C. Data Analysis

Clinical scale scores and reaching kinematic data were obtained from each subject at the pre- and post-training sessions. All kinematic parameters given in Table I were tracked and assessed for each subject. 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: $\alpha = 0.05$ and $\alpha = 0.00156$, which corrects for the multiple comparisons of eight parameters at four different targets. Because of the individual nature of each subject's impairments and therapy protocol, statistical comparisons of kinematics are made individually for each subject and are not combined across subjects. Clinical scale results are presented qualitatively with no statistical comparisons.

IV. Results

A. Clinical Scale Results

The MAL (scoring range 0–5, with five representing movement frequency or quality at pre-stroke levels) scores for subjects 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 0.52 points, respectively after training. The third subject had a slight worsening in the amount of movement of $-.56$ points and slight increase in the quality of movement of 0.28 points after training. The SIS scores (normalized score of 0–100 with 100 representing full recovery) of all subjects show an average increase of 5.7 points in their

TABLE II
MOTOR ACTIVITY LOG AVERAGE AOU AND QOM, THE STROKE IMPACT SCALE NORMALIZED SCORES AND THE WOLF MOTOR FUNCTION TEST AVERAGE 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

scores after training. The Wolf Motor Function Test did not show any consistent trends among the three subjects. Subjects 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 Subject 1 decreased slightly. The total time to complete the tasks was slightly longer for both Subject 1 and 3 during the post-test while Subject 2 reduced his time by more than half during the post-test. Average scores, across the rated daily activities, for each subject's amount and quality portions of the MAL, normalized SIS scores (Subject 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 subject in Table II.

B. 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 subject's individual training protocol. Despite the short training period of two weeks, all three subjects 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 subject are shown in Fig. 3.

Subject 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 Fig. 3(a).

Target AGI was not included in any analyses for Subject 2 due to missing data during the post-training evaluation. Subject 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 subject also significantly reduced the average reach duration at all targets. Subject 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 Fig. 3(b).

Subject 3 made the most improvements in body function, both joint range-of-motion and correlation and shoulder and torso compensation. Subject 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 Fig. 3(c).

V. DISCUSSION

The kinematic results show that all three subjects improved their reaching movements after training with the interactive mixed reality system, especially the targeted parameters. Due to the limited training period of only two weeks, however, we did not expect the clinical assessments to show significant functional changes. One possible explanation is that the finer changes in movement that are detected by kinematic analysis are not reliably detected by the clinical tests [6], [36].

After training, two subjects 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 subject'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 [43]. 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 subject, 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 subjects' 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. Subject 2 decreased his time to completion by over 100 s 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 s. 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 [11], [18].

Each subject showed significant improvements in their reaching kinematics in merely six sessions, specifically for movement parameters on which their training was focused. This indicates that our 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 may have improved some parameters of the subjects' end effector behavior (velocity, trajectory, etc.), each subject'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 [32], [34]. This suggests subjects 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

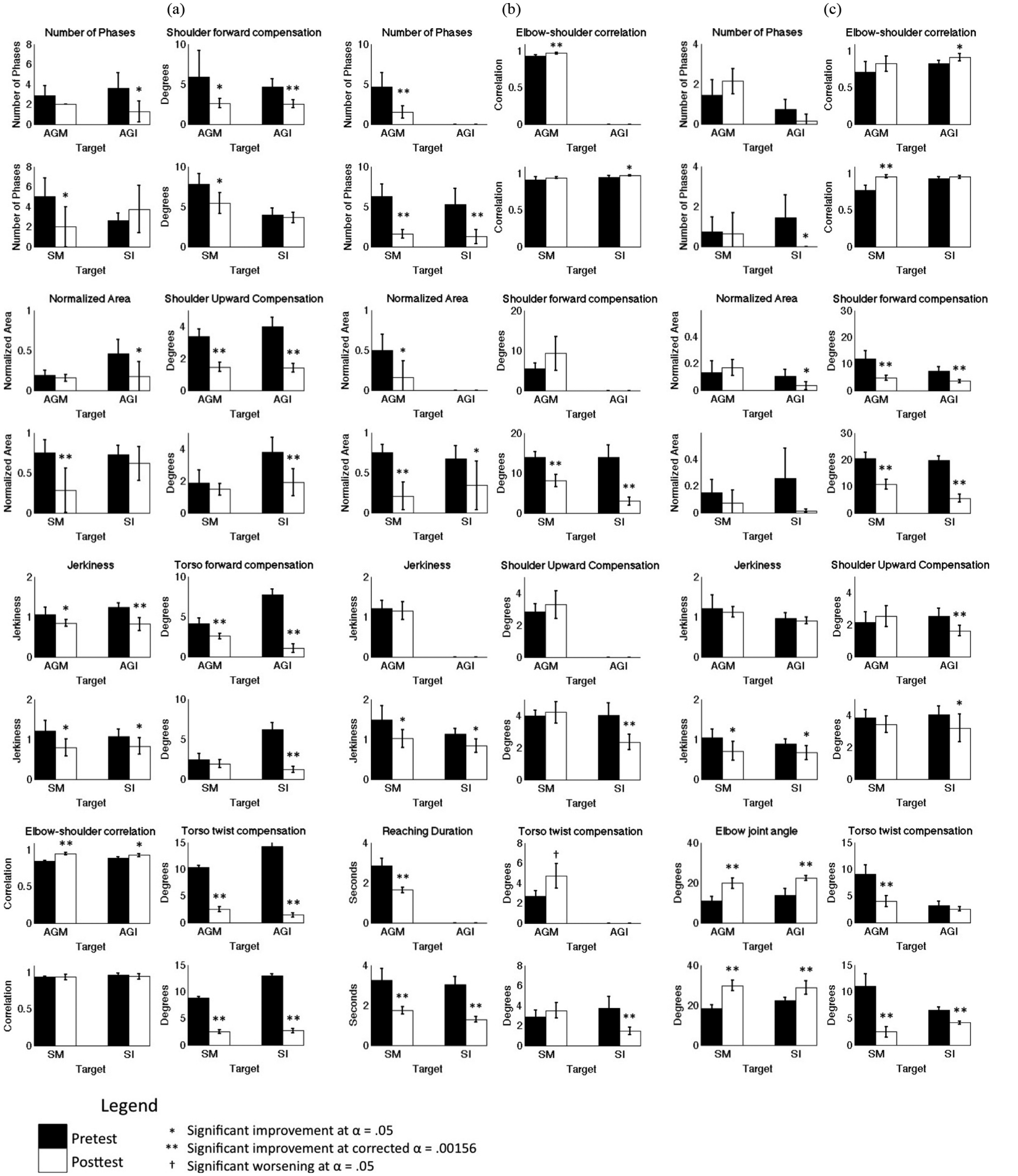

Fig. 3. Comparison of kinematic parameters during reaching from pre- and post-training evaluations for (a) Subject 1, (b) Subject 2, and (c) Subject 3. AGM: reaching to a target 6-in in the air aligned with the trunk midline. AGI: reaching to a target 6-in in the air on the ipsilateral side. SM: reaching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

to concurrent system developments. For example, because we used our evolving experience with the study to finalize the implementation of mixed training, the intensity and quality of mixed training increased as we moved from Subject 1 to Subjects 2 and 3. Finally, because we chose subjects with only mild and mild-to-moderate impairments, each subject was already performing adequately in some parameters prior to training which left little room for improvement in those areas.

We have now formalized an approach to adaptive training where the overall training structure can be repeated across subjects but specific parameters of the training can be customized to each subject using quantitative data. The results suggest the feedback is intuitively and effectively communicating measures of performance and direction for improvement to the subjects. We were successful in integrating mixed (physical-virtual) environments into the training to promote motor learning bridging the virtual and physical worlds. Movement improvements made during training in the virtual and mixed environments successfully transferred to their post-training physical reaching tests. Subjects improved at four different targets locations (supported and against gravity to locations ipsilateral to the affected side and at the midline) pointing to the potential of the system for promoting generalizable learning.

Other studies [3]–[5] 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 subject to move in a certain way or restrain their body such that they must use the affected limb. Conversely, our approach allows the subject to be free to move as they wish, while providing mediated incentives to the subject to move in a more efficient way and mediated deterrents from using compensatory or inefficient movements. This allows the subject to actively, yet often subconsciously, construct his or her own strategies, reducing dependencies on external constraints. Our system also helps subjects progressively integrate strategies learned for each kinematic parameter to form a complete movement strategy. Finally, the system effectively trains the subject 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 subjects during the pilot study suggests that the mixed reality system is suited for therapeutic application in the clinic.

This study has also led to improvements in the system infrastructure. The setup for each visit took 20–30 min per subject, which became tiresome for both the subject and research team. This setup time was prohibitive to running multiple subjects in one day or running subjects for an extended training period. A revised setup uses predefined rigid body motion capture markers, which are more easily identified by the motion capture software with less calibration. While this change does prevent us from gathering data from smaller joints, such as the fingers, we are working on creating smart sensing objects to detect tangible interaction without the data provided by detailed hand motion capture. We have also developed more advanced control software 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.

VI. Conclusion and Current Work

The presented study has successfully shown a proof of principle that adaptive mixed reality rehabilitation system can provide customized reaching and grasping training for chronic stroke survivors and elicit improvements in important movement parameters. This system can help therapists to structure therapy based on kinematic performance and to target specific aspects a functional task, with the help of interactive audio and visual feedback.

The outcomes of the presented pilot study lay the foundation for a current clinical study at the Rhodes Rehabilitation Institute at Banner Baywood Medical Center. This study is being conducted with a stable system, using a larger group of subjects and will include a matched control group who will receive traditional repetitive task training of equal intensity. Our expectation is that mediated rehabilitation will yield better clinical scale results, improve movement kinematics in a faster time, help the subjects create generalizable movement strategies and be as well received by subjects as traditional therapy. Subject data from this study will further inform the system's adaptation and training protocols. The data will also be used to draw correlations between feedback and performance to determine how subjects utilize each feedback stream. Work is also being done to create low-cost portable systems, based on the fixed clinical system, for use in the home.

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