Editor's Introduction: *There is considerable current interest and activity in using robotic technology combined with video "gaming" and virtual reality technology as a method to measure and improve upper limb motor control in patients with stroke and other disabling neurological conditions. Although a few of these devices and programs are becoming commercially available, most of these interventions are currently under development and investigation at a few centers. Innovation is an important driver of these developments. This paper by Chen and colleagues at Arizona State University, Rhodes Rehabilitation Institute, and Emory, offers a description of a novel adaptive mixed reality rehabilitation system, which uses integrated information on motor performance derived from a combination of multiple feedback sources and methods. The paper also reports on the application of this technology to two people who were disabled by stroke and its value in improving reaching and grasping. It reinforces the role of using an interactive environment as a means of providing guidance, support, and motivation to enhance movement among people with stroke-related motor control deficits.*

A Novel Adaptive Mixed Reality System for Stroke Rehabilitation: Principles, Proof of Concept, and Preliminary Application in 2 Patients

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This article presents the principles of an adaptive mixed reality rehabilitation (AMRR) system, as well as the training process and results from 2 stroke survivors who received AMRR therapy, to illustrate how the system can be used in the clinic. The AMRR system integrates traditional rehabilitation practices with state-of-the-art computational and motion capture technologies to create an engaging environment to train reaching movements. The system provides real-time, intuitive, and integrated audio and visual feedback (based on detailed kinematic data) representative of goal accomplishment, activity performance, and body function during a reaching task. The AMRR system also provides a quantitative kinematic evaluation that measures the deviation of the stroke survivor's movement from an idealized, unimpaired movement. The therapist, using the quantitative measure and knowledge and observations, can adapt the feedback and physical environment of the AMRR system throughout therapy to address each participant's individual impairments and progress. 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 2 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. **Key words:** *adaptive therapy, computational motion capture, kinematic analysis, mixed reality rehabilitation, multimedia feedback, reach and grasp, upper extremity*

Recent research in stroke rehabilitation has focused on the development of novel systems that enhance therapy through interactive computer-generated (digital) audio and visual feedback environments. Systems that use only digital feedback and aim to immerse

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the user in the resulting virtual environment are referred to as *virtual reality training environments*, whereas systems that provide combined training in virtual and physical environments are referred to as *mixed reality training environments*. Both types of interactive environments can be used to provide meaningful and intuitive external feedback on a stroke survivor's movement, which may augment information provided from intrinsic sensory organs whose function may have been compromised by stroke, while encouraging sensory-motor integration.[1-3] The feedback also offers guidance, motivation, and encouragement and may help the stroke survivor to improve the quality of movement and gain confidence in the use of the affected limb.[1,4] Use of digital feedback environments can also recontextualize the training task and dissociate the therapy from possible negative feelings associated with daily physical performance of the task. Therapeutic interactions with such environments by stroke survivors have been shown to improve cognitive and physical function, increase self-esteem, and lead to feelings of greater self-efficacy and empowerment.[3,5] The therapy task and feedback should jointly encourage active physical and cognitive engagement by the stroke survivors, thus promoting learning of generalizable movement strategies.[1] The task and feedback must also be adaptable to the individual's ability and progress, allowing for each person to be challenged physically and cognitively without becoming frustrated.[5,6]

High-resolution motion capture (technologies that can record movements at high frequencies and with millimeter precision) can be used within a digital interactive environment to provide the most accurate feedback and to compute evaluations of the movement based on kinematic parameters.[6,7] Research groups that have applied motion capture–driven interactive therapy to stroke rehabilitation have demonstrated improvements in kinematic and functional performance of the upper extremity.[6,8] However, the feedback provided by most existing systems does not communicate multiple aspects of the movement simultaneously and in an integrated manner, thus limiting the possibilities for self-assessment and the development of generalizable motor plans. Furthermore, most systems lack real-time kinematic evaluation of the movement. This type of evaluation can be extremely useful to the clinician when adapting an interactive system during therapy and in quantifying the overall effects of the therapy. Computational kinematic evaluation may offer useful supplementary data to existing clinical scales by providing reliable, repeatable, and quantitative measures of movement. This type of analysis yields a continuous measure of most aspects of movement (eg, hand velocity or joint angles),[7,9] and recent rehabilitation studies have used kinematic measures to evaluate recovery in detail.[6,9]

Our lab has developed an adaptive mixed reality rehabilitation (AMMR) system to train reaching and grasping movements in stroke survivors. The AMRR system integrates traditional rehabilitation and motor learning theories with high-resolution motion capture and sensing technologies, smart physical objects, and interactive computer graphics and sound. A mixed reality therapy environment was developed to connect virtual learning to physical reality, thus better facilitating the transfer of strategies from therapy to activities of daily living.[10] The AMRR system uses kinematic measurements, derived from motion capture data, to generate multiple streams of customizable audio and visual feedback on the movement and as a standardized measure of impairment. The kinematic measures are also used to help the therapist assess the contribution of individual movement components to overall impairment. Here, we present a summary of the system principles and the training process and results from 2 stroke survivors who underwent 1 month of therapy using the AMRR system at a local rehabilitation clinic. Both participants demonstrated substantial improvement in kinematic and clinical scales measurements. Given the differing impairment levels of the 2 participants, the data offer proof of principle that the AMRR system has the potential to considerably foster progressive recovery of stroke survivors with a variety of impairments. These 2 clinical experiences are contrasted to show the importance of constructing individualized adaptable therapy plans based on each participant's unique movement impairments, progress, and outlook on recovery.

Adaptive Mixed Reality Rehabilitation

The AMRR system was developed for stroke survivors with a primary intent of training reaching and grasping task-specific behaviors. The system provides a customizable way to map functional features of movement to real-time interactive feedback, allowing for scenarios appropriate for stroke survivors of varying impairment and throughout different stages of recovery. The AMRR system architecture is illustrated in **Figure 1**. Human-to-human interactions are shown with a thick arrow, and interactions involving the system are shown with a thin arrow. The participant's movement is simplified into an action representation composed of key kinematic features, derived from motion capture data, of a reaching and grasping movement.[11] Here, motion capture data refers to the three-dimensional positions of 11 reflective sensors, placed on the participant's torso, right hand, and right arm, which are tracked by optical cameras during the movements. The kinematic features are used to generate the digital feedback, which facilitates self-assessment of the movement by the user and ideally leads to improvements in task performance. The clinician running the therapy uses visualization of the computational assessment, his or her personal observation of the participant's movement and interaction with the feedback, and his or her expert knowledge as the basis for adapting the feedback, the tasks, and the physical environment throughout the therapy sessions. The clinician also provides verbal and physical input to the participant, supplementing or clarifying information received from the feedback.

As seen in **Figure 1**, key components of the AMRR system for reach and grasp training include (1) kinematic feature extraction from the movement based on a simplified action representation, (2) computational assessment of the movement, (3) interactive feedback for participant self-assessment, and (4) clinician

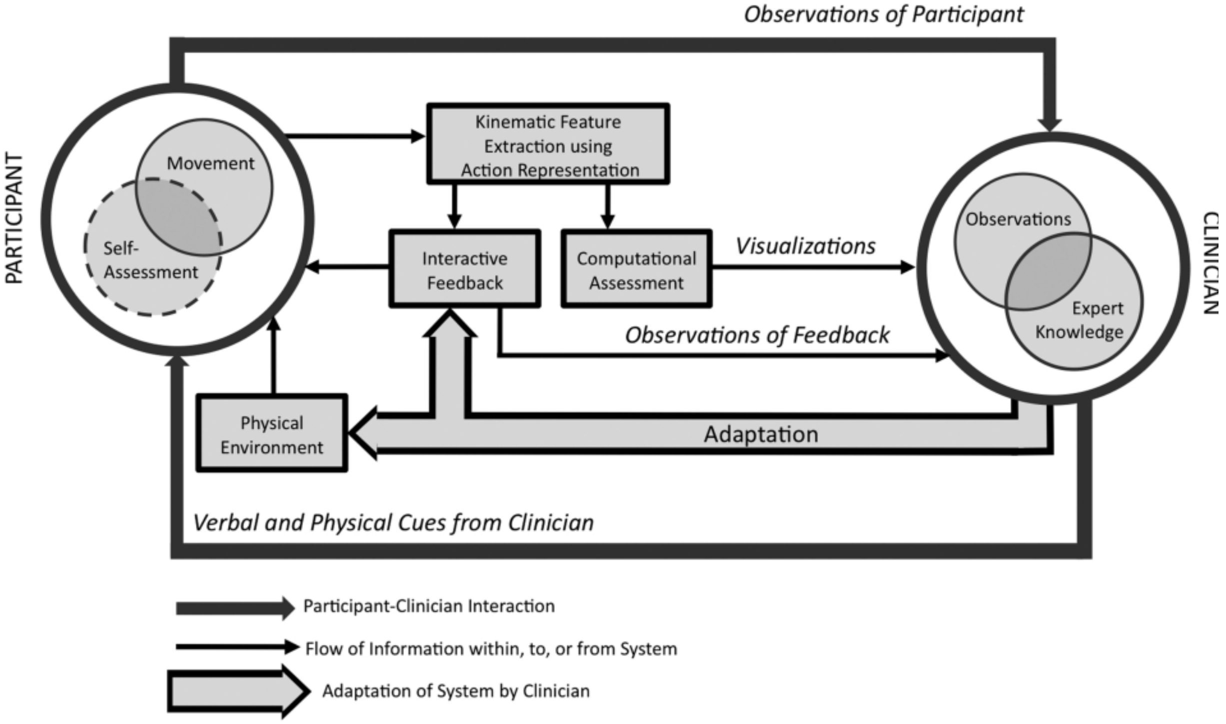

Figure 1. Adaptive mixed reality rehabilitation (AMRR) system architecture diagram showing how the participant's movement is simplified and measured as kinematic features, how those features are used to drive feedback and assessment, and how the clinician integrates all parts of the therapy to guide the participant and adapt the system.

adaptation of therapy and interaction with patient based on observations and knowledge. We discuss each of these below.

Kinematic feature extraction from the movement based on simplified action representation

A simplified action representation is necessary to reduce the reach and grasp movement to 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.[11] Kinematic attributes were selected to represent key movement components used within clinical practice and presented in literature on stroke rehabilitation.[7,9,12,13] These attributes are organized into 7 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[14] category comprising measures of shoulder and torso compensatory movements, and "temporal profile" is an activity level category comprising measures of hand speed and reaching duration. The categories and their relationships are shown in **Figure 2**. Activity level categories are depicted closer to the action goal based on their increased importance in completing the action, as compared with body function level categories. This visualization presents an illustrative summary of category relationships, with overlap among categories showing the *potential* generalized correlation among categories and their kinematic

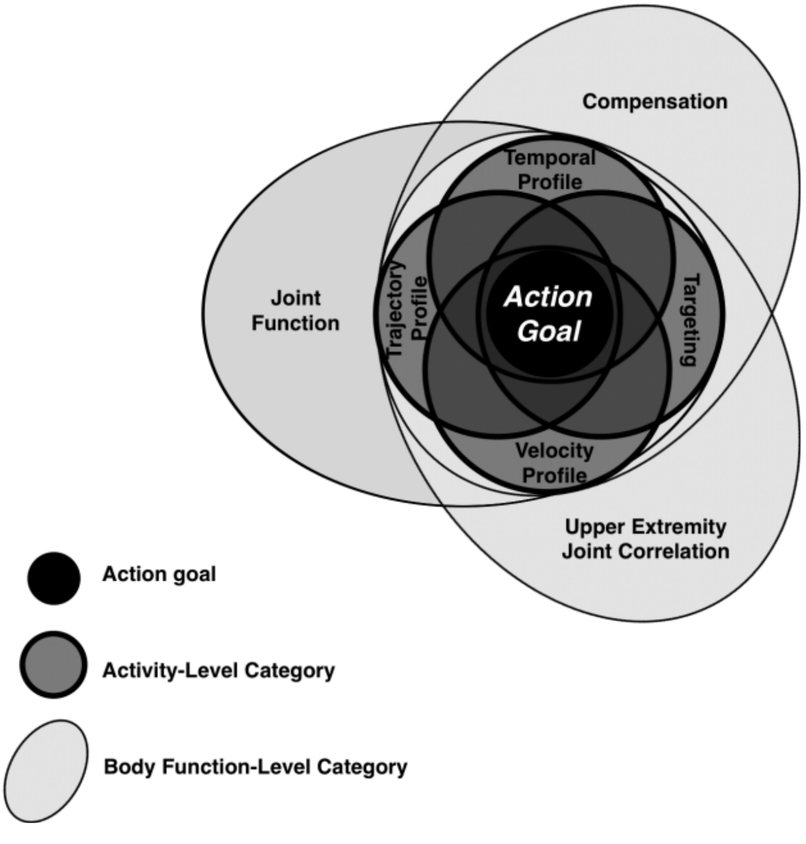

Figure 2. Simplified action representation for a reach and grasp movement. Distance relative to the center indicates importance of each category relative to achievement of the action goal. Overlap among categories illustrates potential generalized correlation among categories.

attributes. However, each stroke survivor's movement patterns will produce a distinct visualization (eg, 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.[11]

Activity level categories

The 4 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. Because 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 3 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 premorbid movement patterns of specific body structures. The 3 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.

Computational assessment of the movement

The stroke survivor's movement performance during the reaching and grasping task is evaluated by using a novel computational measure: the kinematic impairment measure (KIM). This evaluation is a real-time, standard measure that maps an individual's movement to a normalized value between 0 (*idealized movement*) and 1 (*maximal deviation from the idealized movement*). The idealized movement reference was derived from a sample of unimpaired individuals performing the reaching task. An attribute-specific continuous model, based on data collected from stroke patients of varied impairment, is then used to map the raw kinematic values to the KIM values. The maximal deviation refers to the estimated greatest possible impairment while still being able to physically attempt the movement. This estimate and the models for computing each attribute KIM are constantly updated and improved as more data are gathered.

KIM measures are computed using the kinematic data of attributes contained within the simplified movement representation. Each attribute (eg, peak speed, torso flexion compensation) is assessed individually to create "attribute KIMs." **Table 1** shows example mappings of raw values to KIM values for peak speed, horizontal trajectory error, torso flexion compensation (as measured beyond average unimpaired flexion during reaching), and upper extremity joint correlation. Note that 2 ranges are shown for each peak speed KIM range because both reduced and excessive speed can

Table 1. Correspondence between kinematic impairment measures (KIMs) and raw values for 4 example attributes

Attribute KIM value	Peak speed (m/s)	Horizontal trajectory error (cm)	Torso flexion compensation (°)	Upper extremity joint correlation
KIM = 0.0	0.42–0.60	0.0–1.5	0.0–3.1	0.95–1.00
0.0 < KIM ≤ 0.3	0.38–0.42 0.60–0.64	1.5–2.7	3.1–5.8	0.88–0.95
0.3 < KIM ≤ 0.7	0.35–0.38 0.64–0.67	2.7–3.7	5.8–8.2	0.80–0.88
0.7 < KIM ≤ 1.0	< 0.29 > 0.67	> 3.7	> 8.2	< 0.80

be indicative of impairment. The attribute KIMs are then grouped, exactly as in the movement representation, as a weighted average to create category KIMs to measure performance within a kinematic category (eg, compensation, temporal profile). The category KIMs are ultimately averaged to measure the participant's overall movement performance to create a composite KIM.

Analysis of attribute KIMs and category KIMs, with respect to the composite KIM, allows for identification of how each movement attribute or kinematic category contributes to the user's functional impairment. The KIM measure has the advantages of measuring the difference between a stroke survivor's movements and idealized, unimpaired movements, a standard way to calculate and compare performance between and across participants, while also tracking rehabilitation progress quantitatively over time and across multiple kinematic dimensions. Our 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. 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.[15]

Interactive feedback for participant self-assessment

The AMRR system uses digital audio and visual feedback to intuitively communicate to the stroke survivor levels of his or her performance and direction for improvement. Individual audio and visual feedback mappings correspond to different kinematic attributes within the action representation (**Figure 2**). Whereas each feedback mapping communicates performance of an individual kinematic attribute, all feedback mappings integrate into 1 audiovisual narrative, which communicates the stroke survivor's overall performance.

Feedback is communicated through an LCD screen and 2 speakers. Each reach begins with a digital image appearing on the screen, which breaks apart into many minute segments of the image, called *particles*. The movement of the participant's hand toward the target translates into a visual representation of the particles being "pushed" to the center of the screen to reassemble the image (**Figure 3**); the speed of the hand's

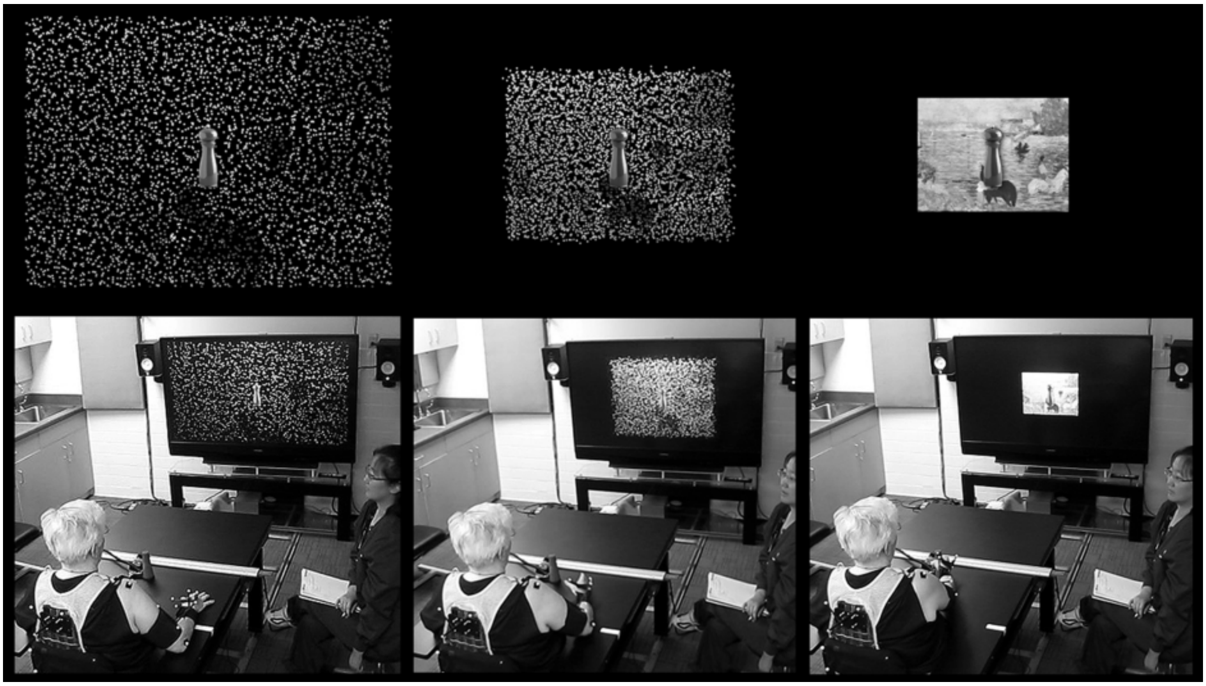

Figure 3. Illustration of the interactive visual feedback. As the stroke survivor performs a reach, her movement pushes particles on the screen back in space to form an image. This example of a visual feedback mapping communicates the progression of the hand from rest position to the target position.

movement simultaneously controls the execution of a musical phrase. Visual feedback is mainly used to communicate information about the spatial aspects of the endpoint movement. Audio feedback is mainly used to communicate temporal aspects of the endpoint movement and to provide indicators of body function performance and task completion. The amount of error required to produce each type of corrective feedback can be independently adjusted to fit the therapy needs of the individual. There are 7 explicit mappings between kinematic attributes and feedback.

- *Trajectory:* If the participant's hand deviates from an efficient, idealized trajectory in any direction (up, down, left, right), the particles of the image will "follow" this deviation. The image will not reassemble completely until the participant corrects this trajectory error.
- *Targeting:* If the target is reached, the image reassembles fully inside a frame on the screen, and a success sound is played.
- *Hand speed:* The speed at which the hand is moving controls the rhythm of a musical phrase, structured to promote smooth acceleration and deceleration.
- *Torso and shoulder compensation:* Excessive (as compared with average movements of unimpaired individuals) torso compensation, from either flexion or rotation of the trunk, and shoulder compensation, from either elevation or protraction of the shoulder, activate a unique, unpleasant sound. This sound interrupts the otherwise pleasant music generated by the reaching movement.
- *Range of motion:* Elbow extension increases the volume and harmonic richness of a second musical phrase that accompanies the main musical phrase controlled by the hand speed. The participant's forearm supination angle is directly coupled to the orientation of the image and particles on the screen.

Information about kinematic attributes that do not have explicit mappings is implicitly communicated through the combination of multiple direct feedback mappings or feedback sequences. For example, information about the hand's velocity profile (the shape of the hand's acceleration and deceleration pattern during reaching) is communicated through the integration of audio feedback related to hand speed and visual feedback of the hand's trajectory. Improvements in joint correlation may be seen as the participant begins to connect the timing of the elbow extension musical phrase with the velocity and trajectory feedback. The details of mapping between kinematic features and audiovisual feedback can be found elsewhere.[16,17]

Some movement aspects that are not measured by the system directly can be addressed through the training of related or contributing attributes. For example, ataxia may be reduced by training trajectory efficiency and accurate targeting during the reach.[18] There are also certain clinically relevant movement aspects, such as spasticity and weakness, that are not yet measured or fully addressed by the current feedback structure, and the incorporation of these features into the AMRR system is a future goal. However, the therapist is always present to provide any verbal or physical guidance necessary to address the rehabilitation requirements of the individual.

Clinician adaptation of therapy and interaction with patient based on observations and knowledge

The AMRR system is adaptable to maintain a level of challenge and engagement appropriate for each stroke survivor's impairment and progress. Reaches are performed in sets of 10, and the clinician can adapt each set in a number of ways. The therapist can focus the training on any set of kinematic attributes by activating the related explicit mappings (or group of mappings for implicit feedback). Turning on a particular feedback stream will not necessarily produce an immediate, sustained improvement in the corresponding kinematic attribute, as the participant needs time to understand and process the new feedback, but it should lead to an overall improvement across the duration of the therapy. The individual feedback sensitivities can also be adjusted to gradually increase or decrease the challenge of the task, depending on the participant's progress. The therapist decides how many sets will focus on a specific task or kinematic attribute and whether the training of the selected aspects will be continuous or intermittent. The clinician may make any of these adaptations after each set of 10 reaches, and the clinician's decision is based on the KIMs,[15] graphical visualization[19] of kinematic values (eg, trajectory, velocity, joint angles), and direct observation of the stroke survivor's performance. The therapist may also use physical or verbal cues when the feedback is not being clearly understood by the participant.

AMRR training can be done at 4 target locations. Each target location requires the use of a unique combination of joints, ranging from a simple to a more complex joint space. The targets are as follows: ipsilateral (on the right side of a right-handed participant) and on the table (Target 1), to the participant's midline and on the table (Target 2), ipsilateral and 6 inches above the table (Target 3), and to the participant's midline and 6 inches off the table (Target 4). The physical target may be either a cone or a large button to be pressed, both of which can sense the user's touch through sensors that measure contact and force. Three types of training environments may be used: a purely physical environment (no audio or visual feedback with a physical target), a purely virtual environment (audio and/or visual feedback provided on the movement without a physical target), or a mixed environment (audio and/or visual feedback provided on the movement with a physical target).

Clinical Application of AMRR Therapy with Two Stroke Survivors

A current clinical study aims to compare our AMRR system with traditional reaching therapy. To demonstrate the clinical implementation process and provide a proof of principle of our system, we present baseline movement impairment profiles, customized rehabilitation training regimes, and kinematic and clinical scale results from 2 stroke survivors who have completed 1 month of therapy using the AMRR system. These 2 participants were chosen to represent distinctly diverse levels of impairment. Our intent is to demonstrate favorable improvements in kinematic, impairment, and quality-of-life measures.

Both participants were chronic stroke survivors who had right-sided upper extremity hemiparesis and were right-hand dominant before the stroke. 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. 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. Clinical categorization of these participants was made by 2 experienced rehabilitation clinicians based on their observations during an hour-long screening test that included a writing task and a measurement of active and passive range of motion of the right arm and hand. Both stroke survivors were unfamiliar with the system prior to the rehabilitation, and each received 1 hour of AMRR therapy, 3 times a week for 1 month, for a total of 12 therapy training sessions. The rehabilitation sessions were led by a therapist and a media specialist who each had at least 1 year experience applying our system to rehabilitation with stroke survivors. The participants also underwent evaluation sessions within 3 days before the start of therapy (pretest) and within 3 days following the month of therapy (posttest). These evaluation sessions involved reaching and grasping, while motion capture data were collected, to the 4 different targets and standard clinical scales for evaluating upper extremity in stroke. The clinical scales include the Motor Activity Log (MAL),[20] a validated scale (0 = *not used* to 5 = *used/performed as much/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; the full Stroke Impact Scale (SIS),[21] a normalized, validated scale (0 = *no recovery* to 100 = *full recovery*) to measure the self-reported impact stroke has had on areas of living such as social interaction, emotion, motor function, and cognition; the Wolf Motor Function Test (WMFT),[22] a validated scale administered by a therapist that rates (a functional activity score of 0 = *could not perform* to 5 = *normal movement*) and times functional tasks and arm movements related to functional tasks; and the upper extremity Fugl-Meyer,[23] a validated scale (0 = *no function* to 2 = *full function*) that rates ranges of joint movement and pain, sensation and proprioception, and motor function of the affected arm.

Following the pretest evaluation, the attending rehabilitation physician and therapist determined the participant-specific movement impairment profile based on their observations, clinical scale scores, and the KIM scores. The movement impairment profile ranks the movement aspects (eg, 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 use 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.

Participant 1

Movement impairment profile and training plan

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 physician and therapist determined the elements and ranking of Participant 1's movement impairment profile as follows:

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

This ranking prioritizes the movement attributes that are important to Participant 1's functional recovery of the reach and grasp movement.

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 because 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 4B**. 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.

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[15,17] (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[24] make extracting direct correlations between training foci and local improvements difficult. However,

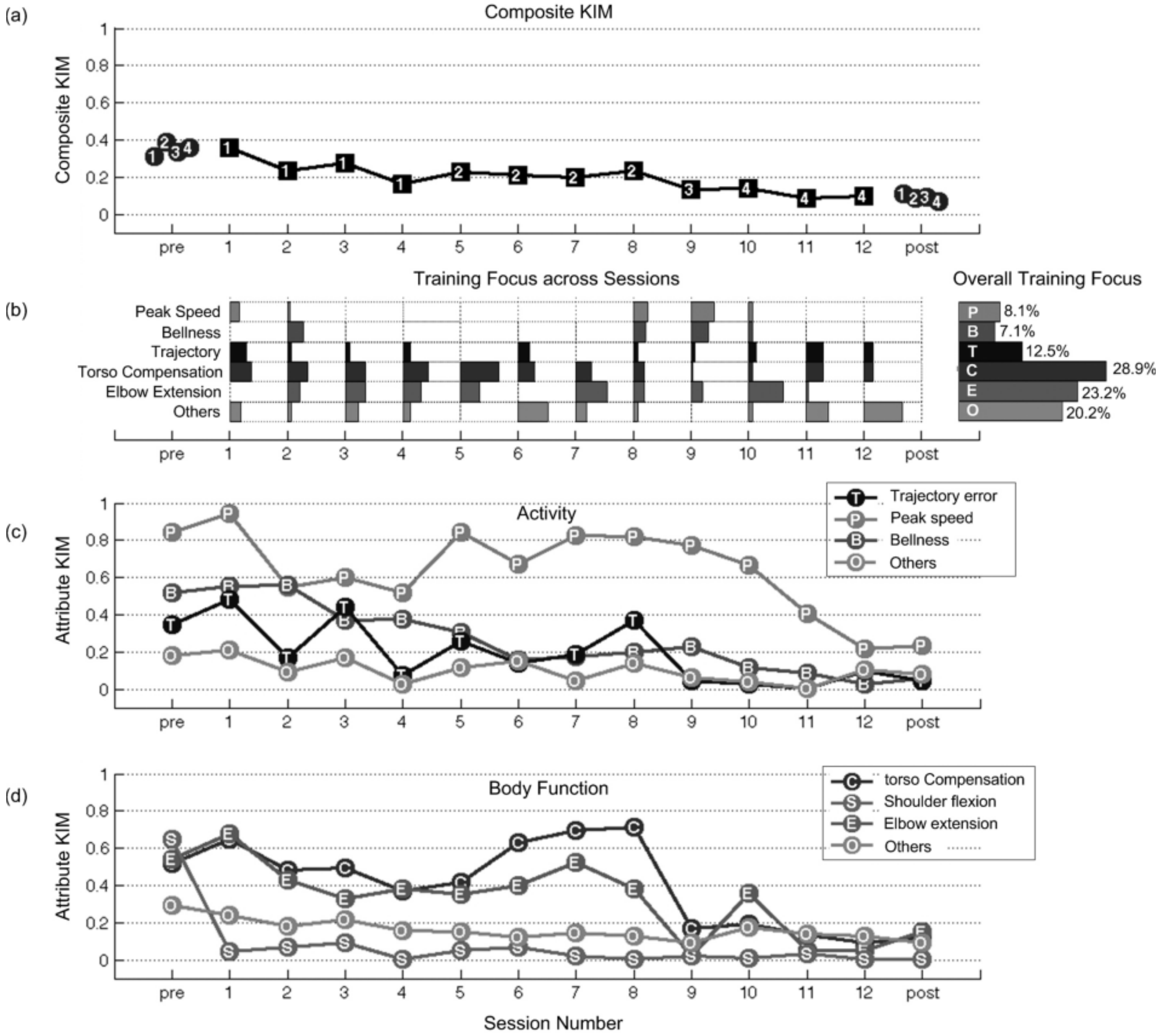

Figure 4. Participant 1 case study results: (a) composite kinematic impairment measure (KIM), with numbers shown in the composite KIM graph indicating which number target was evaluated at the beginning of that session (all 4 targets were evaluated during the pre- and posttests, and these are all shown as the grouped circles in the graph); (b) attribute focus throughout therapy; (c) activity level attribute KIMs; and (d) body function level attribute KIMs throughout therapy, including the pre- and posttest evaluations. All measurements made during the initial set of 10 reaches (before training started, no audio or visual feedback).

there is a trend for consistent improvement in his composite KIM (shown per target) throughout the therapy (**Figure 4A**). The percentage of each training focus used during each session, along with the overall training foci across all sessions, is shown in **Figure 4B**. **Figure 4C** shows how the 3 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 4D** reveals how the 3 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 (eg, trajectory error, peak speed, bellness) and body level parameters (eg, shoulder flexion, torso compensation, and elbow extension) can be found in Duff et al.[17] Note that for KIM values (**Figure 4A, 4C, 4D**), a smaller number corresponds to less impairment and therefore better movement performance. If the composite KIM value is close to 0, the participant's overall movement performance is close to an unimpaired movement.

Kinematic and clinical scale pre- and posttest results

Participant 1 improved many kinematic parameters substantially, resulting in an overall impairment reduction (**Figure 5**). 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 2** also shows pre- and posttraining raw values and KIM values for 5 kinematic attributes on which the training was focused. Participant 1 had a mixed result in his clinical scales (see **Figure 6**). Both self-reported scales, the MAL and 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 WMFT,

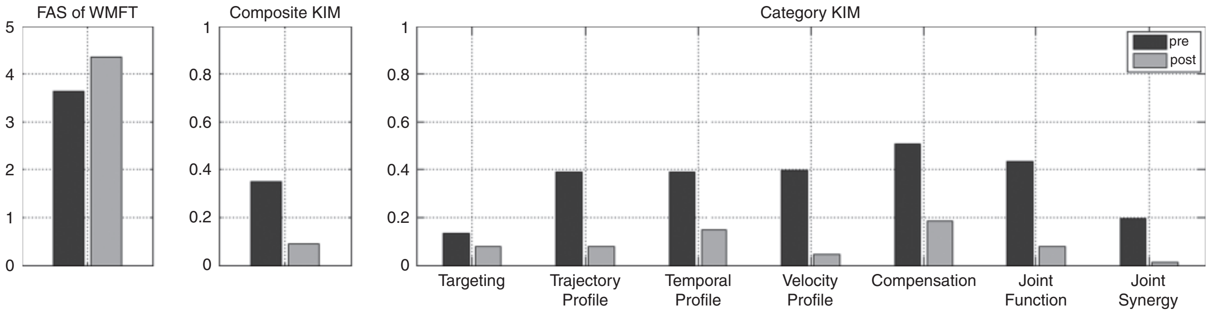

Figure 5. Left: improvement in Participant 1's composite kinematic impairment measure (KIM); right: improvement within each of the category KIMs. FAS = functional activity score; WMFT = Wolf Motor Function Test.

Table 2. 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		Elbow extension		Shoulder flexion		Torso flexion	
	Peak m/s	Speed KIM	Raw value	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

Note: Number of phases refers to the number of distinct sections in the velocity profile due to hesitations while reaching; % AAR is the percentage of range of motion achieved compared with active assisted reaching. AAMR = adaptive mixed reality rehabilitation; KIM = kinematic impairment measure.

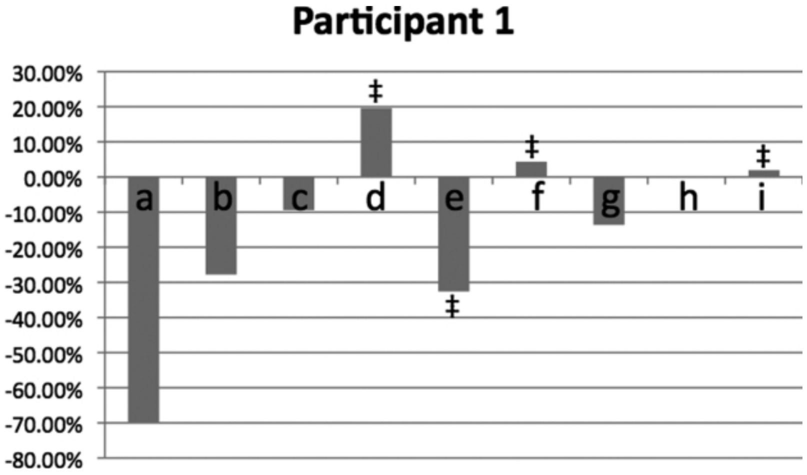

Figure 6. Participant 1's percent change from the pretest to the posttest for 4 different clinical scales. (a) Motor activity log amount of use; (b) motor activity log quality of motion; (c) Stroke Impact Scale; (d) Wolf Motor Function Test functional activity score; (e) Wolf Motor Function Test task 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.

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.

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 4**, the key attributes (eg, torso compensation, elbow extension, speed) appear to require 8 sessions to show consistent improvements compared with 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 posttest indicates 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 4D**) 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, **Figures 4B**, **4C**, and **4D** show some clear overarching relationships between these factors. For example, torso compensation was heavily trained during the first 7 therapy sessions. Whereas the torso compensation KIM did show an improvement during the first 4 sessions, when the target changed from Target 1 to Target 2 (**Figure 4D**, session 5), torso compensation began to worsen. However, with consistent training, this attribute began to improve again after session 8 and continued to be very low throughout the remainder of training and during the posttest, regardless of the target location.

Overall, the composite KIMs (shown per target in **Figure 4A**) 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 4 sessions, and Target 3, which was only trained during 1 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 increased by almost 20%, and his total task completion time was reduced by over 30%. Both results are relevant to his training because he focused on improving his movement quality and increasing his task speed during the AMRR therapy. The Fugl-Meyer showed mixed results, which was not unexpected given the short 1-month duration of our therapy. The Fugl-Meyer also measures many aspects of the upper extremity that our therapy was not intended to address, such as pain and sensation.

Although 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 pretest to the posttest. The AMRR system is designed to make participants 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 posttest evaluation could have more favorably influenced his health-related quality-of-life impression.

Participant 2

Movement impairment profile and training plan

Participant 2 presented with an inability to smoothly reach to the target, caused by a reduced range of motion, impaired interjoint coordination, and ataxia. He had insufficient elbow extension, shoulder range of motion, and supination; consequently, he 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 ranking prioritizes the movement attributes that are important to Participant 2's functional recovery of the reach and grasp movement.

Participant 2 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 endpoint 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 and 4), the trajectory error and torso compensation increased as a result of the more complex joint space and the need 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 7B**.

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 are shown in **Figure 7B**). **Figure 7** 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

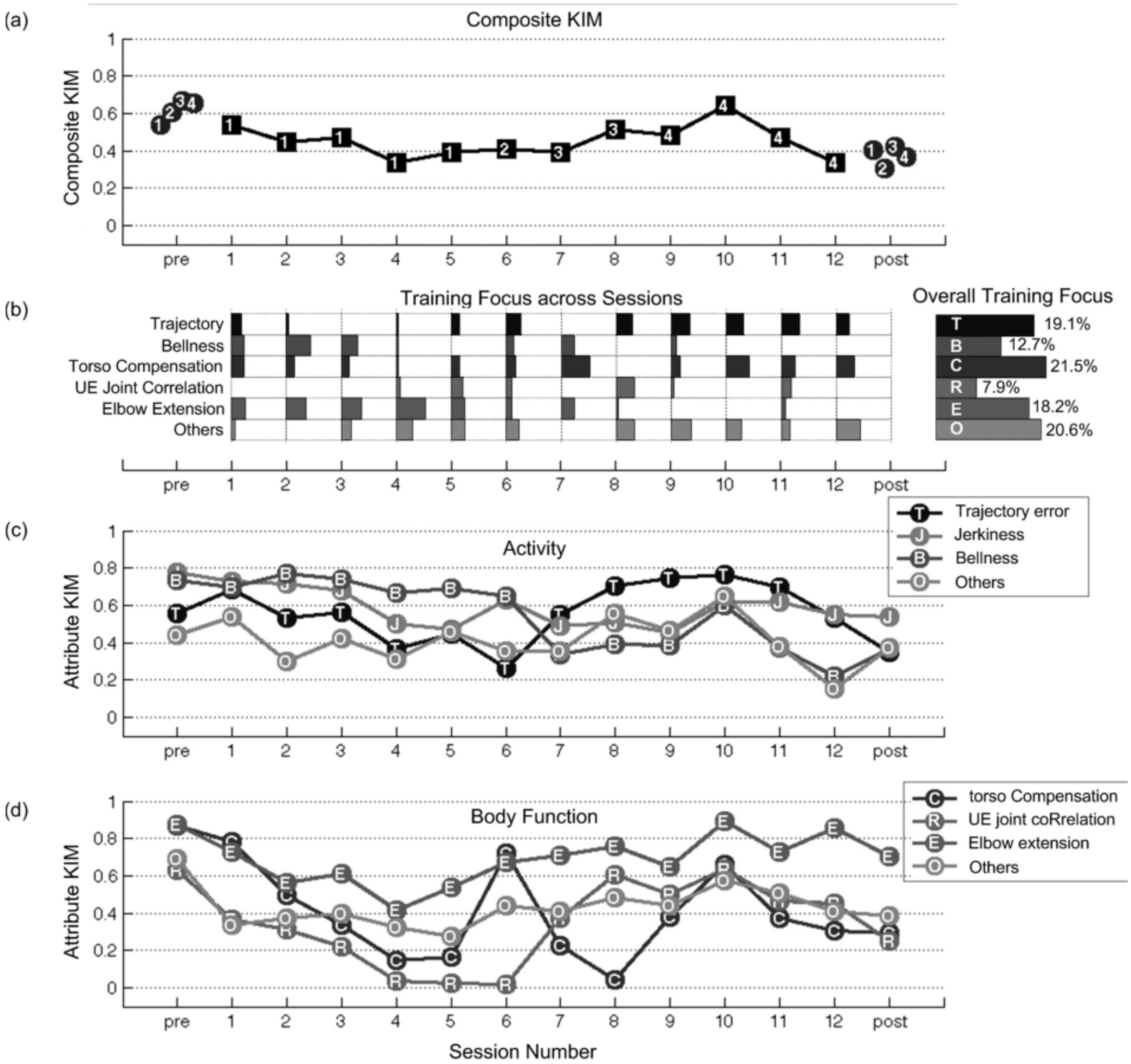

Figure 7. Participant 2's case study results. (a) Composite kinematic impairment measure (KIM). All 4 targets were evaluated during the pre- and posttests, with these values shown as correspondingly numbered circles. The numbered boxes show the KIM value measured at the beginning of the training session at that number target; (b) attribute focus throughout therapy; (c) activity level attribute KIMs; and (d) body function level attribute KIMs throughout therapy, including the pre- and posttest evaluations. All measurements were made during the initial set of 10 reaches (before training started, no audio or visual feedback).

a trend toward improvement in his composite KIM throughout the therapy (**Figure 7A**). Composite KIM improved for all targets from pretest to posttest. The 3 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 7C**). The 3 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 7D**).

Kinematic and clinical scale pre- and posttest results

Participant 2 improved in many kinematic parameters, resulting in an overall impairment reduction, as seen in **Figure 8**. This participant reduced his composite KIM by 40% and reduced his category KIMs by at least 40% in 5 out of 7 categories. **Table 3** also shows pre- and posttraining raw values and KIM values for 5 kinematic attributes on which the training was focused. Participant 2 also had positive changes in a majority of his clinical scale results. 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 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).

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. Although his improvements were not consistent throughout the therapy, with many attributes varying in KIM values from session to session, most of the attributes trended toward 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 the trajectory error returned to levels comparable with 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 posttest. The category KIM results from the pre- and posttest

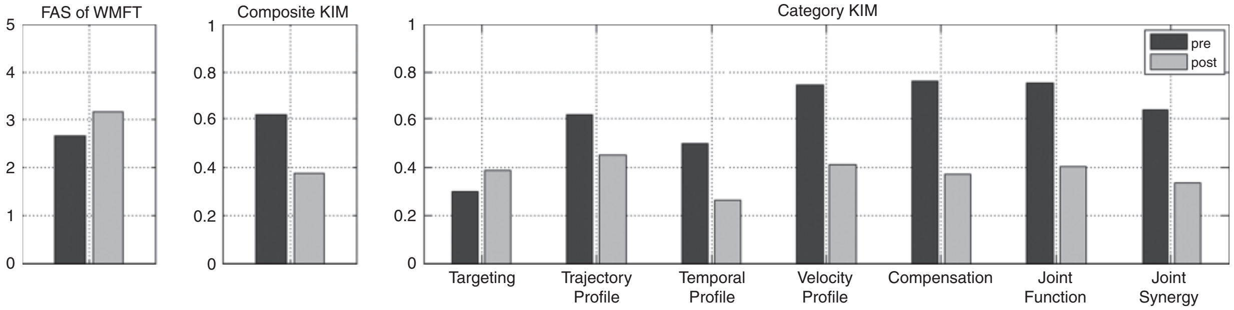

Figure 8. Left: Participant 2's overall kinematic impairment measure (KIM) improves from the pre- to posttest; right: change in each KIM category from the pre- to posttest. FAS = functional activity score; WMFT = Wolf Motor Function Test.

Table 3. 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

	Horizontal trajectory error		Number of phases		Elbow extension		Upper extremity		Torso flexion	
	cm	KIM	Raw value	KIM	% AAR	KIM	Raw value	KIM	Degrees	KIM
Pre	4.6	0.72	6.6	0.79	42	0.87	0.81	0.57	12.6	0.87
Post	3.1	0.44	2.3	0.29	60	0.90	0.90	0.19	4.6	0.28

Note: Number of phases refers to the number of distinct sections in the velocity profile due to hesitations while reaching; % AAR is the percentage of range of motion achieved compared with active assisted reaching. AAMR = adaptive mixed reality rehabilitation; KIM = kinematic impairment measure.

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 7A**) 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 1 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 posttest (**Figure 8**). 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 by the development of these new patterns. Because our system tracks and displays such detailed kinematic data, this information can be used to assess whether additional therapy is needed and on which aspects of the movement consequent therapy should focus. For example, additional

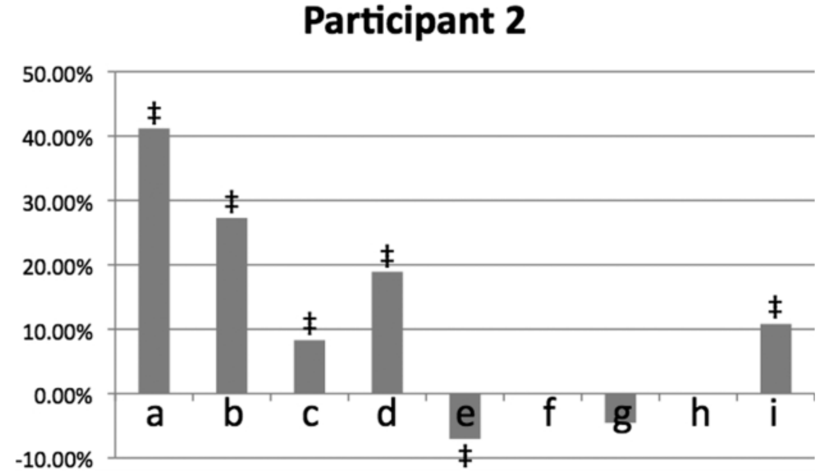

Figure 9. Participant 2's percent change from the pretest to the posttest for 4 different clinical scales. (a) Motor activity log amount of use; (b) motor activity log quality of motion; (c) Stroke Impact Scale; (d) Wolf Motor Function Test functional activity score; (e) Wolf Motor Function Test task 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.

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 functional activity score of the WMFT and over 5% decrease on his total task completion time (results shown in **Figure 9**). The completion time improvement is relatively low because this participant was unable to perform 2 of the complex tasks of the WMFT during both the pre- and posttest, 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 2 tasks that he could not do in the pretest. Additionally, he increased his ratings on many other tasks by 1 point. Anecdotal evidence from this participant indicates that he was very self-motivated and would often practice therapy tasks at home, which may have contributed to the improvements recorded in his health-related quality-of-life measures.

Discussion

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 2 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 1 or 2 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 WMFT. Compared with the pretest, 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, as well as tools for intuitive self-monitoring of their progress, to ensure that their daily activities and internal sense of quality of life are also being positively affected 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 data from these 2 participants are also part of a larger clinical study that is currently under way. The study aims to compare kinematic and clinical scale results from a group of stroke survivors who received AMRR therapy with a group who received traditional repetitive reaching task therapy. We hypothesize that the real-time, integrated feedback presented by the AMRR system will induce greater improvements in both kinematic and clinical scale scores, as well as promote generalizable movement strategies that can be used in related but different upper extremity tasks. We also believe the KIM and visualizations of kinematic features will help the therapist to identify and respond to impairments and improvements in a more efficient way.

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 (eg, 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 present study.

Our lab is also working on creating computational assistive tools to help the therapist to analyze the participant's rehabilitation progress and to aid in making therapy adaptation decisions. These tools will use correlations between the therapist's previous use of different feedback streams and the resulting kinematic improvements to predict how current kinematic impairments should be addressed. The decisions are based on comprehensive prior usage data as well as the specific participant's previous experiences with the system. Another assistive tool will create data summaries and visualizations to communicate therapy outcomes to the therapist in an intuitive and efficient way.

Conclusion

The AMRR system supplies useful and engaging feedback, based on precise kinematic measurements, during a reach and grasp rehabilitation task. The therapy afforded by this system can be continuously adapted to fit the needs of each participant. As shown from the improvements made by both participants, the AMRR system can help improve the kinematic and functional performance of the upper extremity. However, further research is needed to ensure these improvements are actively practiced outside of the clinic, including the development of a home-based AMRR system.

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REFERENCES

1. Schmidt RA. Motor learning principles for physical therapy. *Contemporary Management of Motor Control Problems: Proceedings of the II STEP Conference.* 1991:49–62.
2. Holden MK. Virtual environments for motor rehabilitation: review. *CyberPsychol Behav.* 2005;8:187–211.
3. Sveistrup H. Motor rehabilitation using virtual reality. *J NeuroEngineering Rehabil.* 2004;1:10–17.
4. Subramanian S, Knaut LA, Beaudoin C, McFadyen BJ, Feldman AG, Levin MF. Virtual reality environments for post-stroke arm rehabilitation. *J Neuroengineering Rehabil.* 2007;4:20–24.
5. Jung Y, Yeh S, Stewart J. Tailoring virtual reality technology for stroke rehabilitation: a human factors design. *Conference on Human Factors in Computing Systems.* 2006;929–934.
6. Piron L, Tonin P, Piccione F, Iaia V, Trivello E, Dam M. Virtual environment training therapy for arm motor rehabilitation. *Presence: Teleoperators Virtual Environ.* 2005;14:732–740.
7. Cirstea MC, Levin MF. Improvement of arm movement patterns and endpoint control depends on type of feedback during practice in stroke survivors. *Neurorehabil Neural Repair.* 2007;21:398–411.
8. Jack D, Boian R, Merians AS, et al. Virtual reality-enhanced stroke rehabilitation. *IEEE Trans Neural Syst Rehabil Eng.* 2001;9:308–318.
9. Wagner JM, Rhodes JA, Patten C. Reproducibility and minimal detectable change of three-dimensional kinematic analysis of reaching tasks in people with hemiparesis after stroke. *Phys Ther.* 2008;88:652–663.
10. Pridmore T, Green J, Hilton D, Eastgate R, Cobb S. Mixed reality environments in stroke rehabilitation: interfaces across the real/virtual divide. In: *Proceedings of the 5th International Conference on Disability, Virtual Reality & Associated Technology,* Oxford, UK, 2004:1–17.
11. Lehrer N, Attygalle S, Wolf SL, Rikakis T. Exploring the bases for a mixed reality stroke rehabilitation system: part I. a unified approach for representing action, quantitative evaluation, and interactive feedback. Submitted for publication.
12. Cirstea MC, Levin MF. Compensatory strategies for reaching in stroke. *Brain.* 2000;123:940–953.
13. Roby-Brami A, Fuchs S, Mokhtari M, Bussel B. Reaching and grasping strategies in hemiparetic patients. *Motor Function.* 1997;1:72–91.
14. Levin MF, Kleim JA, Wolf SL. What do motor "recovery" and "compensation" mean in patients

following stroke? *Neurorehabil Neural Repair.* 2009;23(4):313–319.

15. Chen Y, Duff M, Lehrer N, et al. *A computational framework for quantitative evaluation of movement during rehabilitation.* International Symposium on Computational Models for Life Sciences; October 2011; Japan.
16. Lehrer N, Attygalle S, Chen Y, Wolf SL, Rikakis T. Exploring the bases for a mixed reality stroke rehabilitation system: part II. Application of principles for the design of interactive feedback for upper limb rehabilitation. Submitted for publication.
17. Duff M, Chen Y, Attygalle S, et al. An adaptive mixed reality training system for stroke rehabilitation. *IEEE Trans Neural Syst Rehabil Eng.* 2010;18(5) :531–541.
18. McPartland DD, Krebs DE, Wall C. Quantifying ataxia: ideal trajectory analysis – a technical note. *J Rehabil Res Dev.* 2000;37(4):445–454.
19. Xu W, Sundaram H. Information dense summaries for review of patient performance in biofeedback rehabilitation. Paper presented at: SIG ACM Multimedia; September 2007; Augsburg, Germany.
20. Uswatte G, Taub E, Morris D, Light K, Thompson PA. The Motor Activity Log-28: assessing daily use of the hemiparetic arm after stroke. *Neurol Rep.* 2006;67:1189–1194.
21. Duncan PW, Wallace D, Lai SM, Johnson D, Embretson S, Laster LJ. The Stroke Impact Scale version 2.0: evaluation of reliability, validity, and sensitivity. *Stroke.*1999;30:2131–2140.
22. Wolf SL, Catlin PA, Ellis M, Archer AL, Morgan B, Piacentino A. Assessing Wolf Motor Function Test as outcome measure for research in patients after stroke. *Stroke.* 2001;32:1635–1639.
23. Fugl-Meyer AR, Jaasko L, Leyman I, Olsson S, Steglind S. The poststroke hemiplegic patient: 1. a method for evaluation of physical performance. *Scand J Rehab Med.* 1975;7:13–31.
24. Krakauer JW. Motor learning: its relevance to stroke recovery and neurorehabilitation. *Curr Opin Neurol.* 2006;19:84–90.