Design of a Home-based Adaptive Mixed Reality Rehabilitation System for Stroke Survivors

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Abstract— **This paper presents the design of a home-based adaptive mixed reality system (HAMRR) for upper extremity stroke rehabilitation. The goal of HAMRR is to help restore motor function to chronic stroke survivors by providing an engaging long-term reaching task therapy at home. The system uses an intelligent adaptation scheme to create a continuously challenging and unique multi-year therapy experience. The therapy is overseen by a physical therapist, but day-to-day use of the system can be independently set up and completed by a stroke survivor. The HAMMR system tracks movement of the wrist and torso and provides real-time, post-trial, and post-set feedback to encourage the stroke survivor to self-assess his or her movement and engage in active learning of new movement strategies. The HAMRR system consists of a custom table, chair, and media center, and is designed to easily integrate into any home.**

I. Introduction

STROKE is a leading cause of disability in the United States. On average, every 40 seconds, someone suffers a stroke in the US, leaving millions of people in the US with chronic upper-extremity impairments [1]. The extent and severity of these impairments varies across stroke survivors, necessitating comprehensive rehabilitation systems that can provide meaningful experiences based on individual needs. However, repeated visits to receive clinical-based therapy can be costly, both financially and logistically [2]. Recent research has led to the development of telerehabilitation systems for home-based therapy. These systems utilize technologies such as virtual environments [3], hand-adorned sensors [4], and robot-aided therapy [5], while providing informative feedback to the stroke survivor about his or her movement. Current telerehabilitation systems generally lack automated real-time system adaptation of tasks and feedback in response to participant performance and progression, instead relying on constant therapist adjustment and telepresence. The optimal type and content of the feedback, as well as a structure to ensure consistent participant engagement, are areas of ongoing research.

The Home-based Adaptive Mixed Reality Rehabilitation system (HAMRR) attempts to address the shortcomings of current home-based therapy systems. HAMRR is based on the theories and results acquired from an Adaptive Mixed Reality Rehabilitation system (AMRR) also developed at Arizona State University. The AMRR system is an interactive, experiential environment that integrates physical elements with interactive audio and visual feedback to train reach-and-grasp tasks and promote active motor learning, which has been shown to enhance healing and recovery of lost functionality [6]. Preliminary results from the AMRR system show improvement in the stroke survivors' movement quality and Wolf Motor Function Test (WMFT) scores [7]. Furthermore, improvements in movement quality are highly correlated to the associated media feedback [8].

HAMRR has many novel features that compliment training at the hospital and allow participants to continue their therapy by training reach, reach-to-touch, and reach-to-grasp tasks over multiple months of therapy at home. One key feature of the system is that therapy sessions require minimal preparation and instruction. Another key feature is an easily adaptable configuration. The system can integrate into any home environment. Also, the participant can easily change the physical setup to customize the types and locations of targets used for a therapy session. A third key feature is the system's multimodal sensing methods for measuring hand trajectory, hand speed, target manipulation, and torso movement. Smart objects coupled with infrared optical sensing provide a robust understanding of the participant's interaction with the system without infringing on privacy. Furthermore, the system provides a novel interactive feedback framework across different timescales to facilitate self-assessment over long-term training. Audio and visual feedback streams provide real-time, post-trial, and post-set task information. The system also supports semi-automatic training adaptation. A computational adaptation component automatically customizes weeklong therapy sessions based on the therapist's goals for the participant. At the same time, the therapist can shape the weekly training goals by reviewing the stored kinematic and performance evaluations of participant progress.

II. System Design

HAMMR features a modular physical setup, which includes a custom-designed media center that provides the audio and visual feedback, a custom table and chair setup, and a core computational architecture.

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A. Physical Design Components

The media center is a slender aluminum tube frame with a cantilevered base that supports the computer, speakers, and motion-capture cameras. A 27-in iMac is utilized for all computational processing, as well as the production of audio and visual feedback streams. Two Bose Companion 2 speakers were selected for their high-quality audio and compact, simple interface. Three Natural Point Opti-Track cameras, mounted above the speakers and computer, track a reflective marker worn on the participant's wrist.

The table is constructed from an aluminum tube frame and 8 ply MDO. The tabletop is 103 cm by 110 cm, with a height of 75 cm. The detachable table is lightweight and can be removed from the media center. The table has a semi-circular cutout, which is designed to provide support for the hand and arm throughout movements. The left arm support is hinged to provide a means for the participant to get in to and out of the chair. The table leg under the hinged arm acts as a grip to help support the participant as he or she stands up or sits down, as seen in Fig. 1.

Fig. 1 HAMRR media center and table

The table houses a contact switch rest position pad, ensuring the reaching task is initiated from approximately the same location, and two capacitive touch buttons, for interaction with the on-screen system dialog. The table features a recessed box to house the electronics for the embedded sensors and the target objects. The table accommodates three pre-determined target locations, based on individual reaching ability. The participant can use the unaffected arm to easily interchange the various target objects at each location to create different task scenarios.

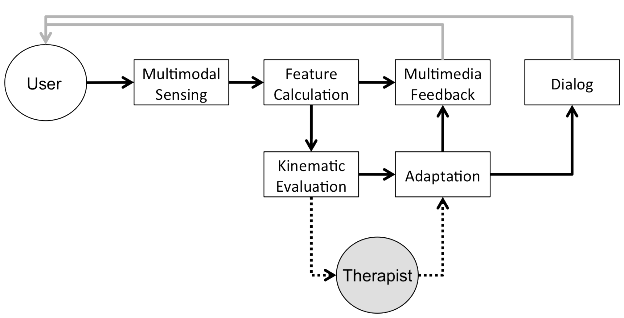

Fig. 2 HAMRR system diagram

B. Computational Architecture

HAMMR architecture features six main components, as seen in Fig. 2. The sensing component collects 3D marker position of the participant's wrist, sensor data from the tangible objects, and force magnitude from the chair. These data streams (also used to create feedback) provide the basis for feature extraction of hand position, velocity, and coarse torso position during movement. The system creates an evaluation report based on the participant's performance data, which can be reviewed as needed and used to customize the adaptation framework.

C. Training Procedure

The therapy is structured in to *trials*, *sets*, and *sessions.* A *trial* represents a single task (reach, reach-to-touch, or reach-to-grasp) to one of the three pre-determined target locations. A *set* is a group of sequential trials for which the task and feedback parameters are unchanged. A set features groups of four to ten trials, depending on the therapy goals. A *session* represents the entire therapy conducted during a day, with approximately 80 to 100 trials throughout a session.

In between sets, there is a *demo* component. This feature presents a demonstration of the current task and feedback. Every time a new task or feedback stream is introduced, the participant is presented with a demo. As part of the interactive demo, the participant is asked binary questions in order to observe understanding of the feedback mappings. The participant uses the non-impaired hand to select an answer using the embedded touch sensitive buttons.

III. Sensing and Kinematic Analysis

The HAMMR system utilizes multiple sensing modalities to extract kinematic features of a participant's movement to provide a cost-effective and robust sensing solution for unsupervised, private home training.

A. Multimodal Sensing

HAMMR uses three Opti-Track FLEX:V100 R2 cameras and Tracking Tools software to track the participant's wrist movement at a rate of 100Hz and with a spatial resolution of millimeters. Object interaction is sensed though a capacitive touch sensor in the button object (used in reach-to-touch tasks) and an array of force sensing resistors (FSRs) on the cone object (used in reach-to-grasp tasks). The chair is covered with 1.5 in square FSRs and the data from these sensors is used to determine coarse torso movement. The chair sensors are connected to the computer through an XBee connection, with a sampling rate of 70Hz.

B. Kinematic Analysis

The kinematic features provide a quantitative measure of participant performance, which informs the adaptation framework for the selection of future tasks and feedback environments. After a task is concluded, a numerical Kinematic Impairment Measure (KIM) is calculated, relating aspects of the participant's targeting, trajectory, and velocity. This evaluation framework, already used within the AMRR system, has been shown to correlate with the functional activity score (FAS) of the WMFT [7].

IV. Design of Multimedia Feedback

HAMRR is designed to provide training in the home over a time period of approximately 12-24 months. The extended involvement time requires a dynamic feedback experience that evolves over time, incentivizes training, facilitates active learning, and accommodates more complex tasks.

HAMRR is designed to provide this feedback structure by providing information about the movement in real-time, as a post-trial summary, and as a post-set summary.

A. *Real-Time Feedback*

Real-time feedback is provided in response to the participant's hand trajectory efficiency and speed, which are aspects of the movement correlated to efficient completion of the activity goal [9]. Real-time audio feedback is provided in response to the participant's hand speed. The ecological coupling between a person's movement speed and the auditory feedback of a system relies on note density [10]. HAMRR correlates hand speed to note density. The sound is designed to allow for alternating soundscapes in order to reduce auditory repetition and maintain active engagement [11]. During the reaching task, the harmonic intervals and attributes of the sound design are altered accordingly, based on the participant's performance. This creates an emotional connection between audio feedback and movement performance.

As the participant reaches towards the tangible device, LEDs embedded within the base of the tangible change color based on wrist location in space compared to a reference trajectory. Green signifies minimal deviation from the reference trajectory, yellow signifies moderate deviation, and red signifies large deviation. The objects also have embedded task completion indication lights to signify when the required interaction has been performed.

B. *Post Trial Summary Feedback*

Summary feedback is necessary to reduce dependency on the real-time feedback, while also facilitating planning of future actions. Immediately after the reaching task is complete, a visual display summary of overall trajectory performance is shown on the screen. The visual summary emphasizes the magnitude, direction, and distance to target for each error in trajectory, and is communicated by the color and spatial distribution of stones in water, shown in Fig. 3a and 3b. This display summary connects the feedback for real-time movement performance observed in the tangible object to a static visual summary, to help the participant connect strategy to execution. Through its use of contextual imagery, the display summary also introduces the interactive narrative, driven by participant performance.

C. *Post Set Summary Feedback*

Post set summary feedback is designed to engage the participant in self-evaluation of performance across multiple trials. An affective summary, defined within this paper as an emotional response, refers to media feedback that expresses aspects of performance across multiple trials, while utilizing media stylization to convey an affective tag associated with overall movement quality [12]. The affective summary is provided only after the participant completes a set without assistance from real-time or display summary feedback. It contains both an audio and visual synthesis.

Sonic images, or affective tags, are provided within the affective summary level to indicate fast movement, slow movement, reach time inconsistency, and non-smooth movement. Parameters such as harmonicity, attack and decay, texture, and note density are used to differentiate the sonic images. Within each sonic image, both reactive and predictive models of performance are conveyed through dual-layered compositions, with the lower voice aurally depicting an ideal movement strategy and the upper voice aurally depicting deviation from the ideal. The ultimate goal is to be rewarded with the voices accompanying each other in a pleasing, non-dissonant composition. For example, if after a set, the participant has consistently performed ballistic movements, the upper voice would contain short, tin-sounding notes, dissonant intervals, and fast-moving density of notes as opposed to the lower voice, which would contain the sound of a gentle, rolling ocean. The two voices would not match in speed or in timbre, and therefore the participant would be able to assess performance and plan future tasks accordingly.

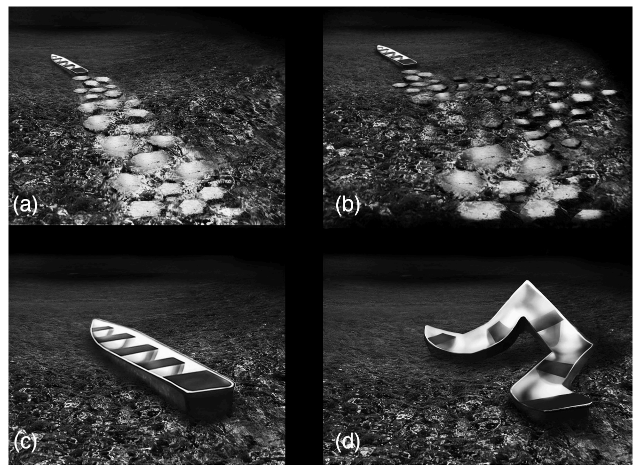

Fig. 3 (a) shows an efficient reach and (b) shows trajectory error to the right, each after a trial. (c) depicts efficient and consistent task completion and (d) depicts segmented movement with trajectory error, each after a set.

Affective visual summaries are provided for trajectory inaccuracy, tremor, segmentation, and task incompletion. The affective stage extends the post trial feedback by manipulating the boat at the end of the rock path. The ultimate goal is to create a boat with an appropriate shape, which is achieved by performing efficiently and consistently across trials, seen in Fig. 3c. The affective summaries of performance are therefore manifest within the boat's structure by manipulating visual attributes to render a scene with emotional content associated with the type of error. For example, segmented movement induces tension within the scene, articulated through abrupt changes in the boat's contour, seen in Fig. 3d.

V. DESIGN OF AN ADAPTATION FRAMEWORK

HAMMR is designed to provide therapy with only a weekly therapist review of participant progression. The type of tasks, tangible objects and locations, feedback streams, and feedback sensitivities are designed to be adaptable in order to offer a challenging and engaging personal daily experience. HAMMR employs a utility function to determine the sequence of sets and parameters based on (a) a prior established week-long sequence of tasks, (b) the history of foci and tasks for each set, and (c) the participant's performance.

The adaptation is structured as a semi-supervised framework, using a probabilistic graphical network representation. Each node represents a vector of kinematic computation, feedback mapping, and sensitivity parameters for a set. Each edge represents an adaptation option that is a directional transition between nodes. When determining which neighboring node to choose for the next set, the neighbor that maximizes the utility function is selected. After the therapist reviews the participant's movement evaluation, he or she can customize parameters in the adaptation framework, such as training focus and sequence, which will result in changing the weights of the utility function components. More information on the adaptation can be found in [13].

VI. Functionality Testing

The functionality of the HAMRR system was tested in-house with three non-impaired subjects. Kinematic analysis required less than 5ms of processing time, which is less than the time interval between sequential camera frames (10ms for one frame at 100Hz). Processing time for post-trial kinematic analysis was determined to take less than 0.5 seconds of processing time, which is well below the 2-3 second rest time between trials. Each subject used the system for over an hour without software or hardware issues.

VII. Conclusion and Future Directions

The home-based adaptive, mixed reality rehabilitation system is a minimally intrusive therapy device that features core-tested functionalities of a more complex AMRR system. The HAMRR system is specifically designed to fit within a home environment, with the resulting constraints on feasible sensing modalities. The utility of real-time feedback and post-trial summary within the AMRR system has been shown to be an effective motor training tool. A previously developed and deployed home therapy system showed encouraging results in terms of usability and desire for a home rehabilitation system, necessitating the design of the more comprehensive HAMRR system [14]. Based on this knowledge and the design considerations that build off the strengths of these systems, the HAMRR system is expected to provide a useful and engaging means for home rehabilitation. In addition, its adaptability and customizable features will allow for iterations across multiple needs for various rehabilitation scenarios.

The significance of affective feedback is currently being evaluated with an unimpaired user study of 10 participants above the age of 30, with an intended user study of two stroke survivors who will use the system for one month. The purpose of these studies is to determine if there is a discontinuity between understanding post-trial feedback streams versus post-set feedback streams. The user study with stroke survivors will assess the integration and usability of the HAMRR system within the home environment.

Future work will include the development of narrative summary to provide feedback streams about the performance of sequences of various trials, where the stroke survivor is controlling the media's narrative. These sequences of trials will include practicing known task patterns (revealed prior to execution) and unanticipated patterns (hidden prior to execution). The audio and visual components will be used to drive the narrative as they do within a traditional film structure: the visuals communicate the explicit narrative, while the musical score directs the overall time-based progression and emotional affect associated with the story [12].

Current work is also being conducted to reduce sensing costs by determining the ability of the Microsoft Kinect camera to track hand and body movement.

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