MAGNI[*]: A Real-time Robot-aided Game-based Tele-Rehabilitation System

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Abstract. During the last two decades, robotic rehabilitation has become widespread, particularly for upper limb physical rehabilitation. Major findings prove that the efficacy of robot-assisted rehabilitation can be increased by motivation and engagement, which is offered by exploiting the opportunities of gamification and exergaming. This paper presents a tele-rehabilitation framework to enable interaction between therapists and patients and is a combination of a graphical user interface and a high dexterous robotic arm. The system, called MAGNI, integrates a 3D exercise game with a robotic arm, operated by therapist in order to assign in real-time the prerecorded exercises to the patients. We propose a game that can be played by a patient who has suffered an injury to their arm (e.g. Stroke, Spinal Injury, or some physical injury to the shoulder itself). The experimental results and the feedback from the participants show that the system has the potential to impact how robotic physical therapy addresses specific patient's needs and how occupational therapists assess patient's progress over time.

Keywords: HCI, Upper-limb rehabilitation, Gamification

1 Introduction

Stroke is the fourth leading cause of death and the leading cause of serious, long term adult disability in the United States, with approximately 795,000 individuals experiencing a new or recurring stroke every year [1]. Numerous

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[*] The Norse God of strength

adfa, p. 1, 2011.

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studies have discovered that based on the concept of neuroplasticity, the brain's ability to reorganize by forming new neural connections [2, 3], stroke patients' motor function improves with continuous rehabilitation of the extremities affected by hemiparesis [4, 5]. It has been shown that the intensity of training has a positive effect on regaining motor function. This has constituted a main motivation for use of robots in aiding rehabilitation of stroke patients [6, 7].

In this work we contribute technically in building an end-to-end prototype for the user's real-time tele-rehabilitation experience by conducting experiments that allows the therapist to administer the patients remotely through a virtual exer-game. Our algorithmic rehabilitation motion analysis contribution and the empirical studies of health-related information provide an important innovation in the Human Computer Interaction (HCI) community. The upper limb health data captured from the user's whole arm, coordinated with the data visualization of the user's hand, performances, and scores, provides valuable information to physical and occupational therapists for the patient's rehabilitation progress. The data collected will be used to provide input to the therapist for both monitoring the patient's progress over time and for offering recommendations about the next course of treatment. Surveys were given to the subjects to evaluate and deliver feedback on our prototype. The results and conclusions from the surveys will be incorporated in our final system that can potentially be used in a clinical environment to improve the communication and interaction of a therapist and a patient in robot-aided therapy.

We evaluate the users' exercises according to the prescribed therapist exercises using the Barrett WAM Arm [29] in order to capture range of motion of the users' upper limb. The purpose of this assessment tool is to motivate the user to perform some of the exercises, assigned in real-time by the therapist, using a 3D carnival-themed game. The contribution of this work is that wraps the Patient-Robot-Game (PRG) Interaction, Analysis and Database together in an integrated GUI that can be used in real-time by patients and therapists (Figure 1). Our research presents an innovative tele-rehabilitation system that tracks movements on a highly dexterous robotic platform to evaluate range of motion associated with patient's upper-limbs.

2 Related Work

The use of rehabilitation robots began in the late 1990s [8] and offers various benefits over manually supported motor rehabilitation: increased patient motivation; repetitive and intensive movement exercise capability; adjustability of assistance or resistance forces based on patients' progress [9]; and acquisition of data that can be used to objectively quantify the improvement of motor function [10, 11]. Multisite clinical studies have shown that the outcome of robot-aided rehabilitation is at least equal to, and in some aspects better, than the outcome of traditional rehabilitation with a therapist [12].

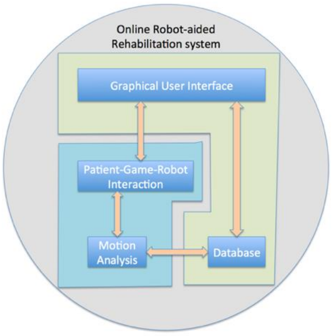

Fig. 1. The MAGNI system consists of four crucial parts – A Patient-Robot-Game (PRG) Interaction subsystem, an Analysis and Movement tracking engine, a Graphical User Interface and a Database.

Rehabilitation robots developed for the upper extremity fall into one of two categories based on their kinematic structure: end-effector type and exoskeleton devices. End-effector type devices were the first of these to be implemented and tested in stroke rehabilitation research due to their more straightforward design [13, 2]. Powered exoskeletons, on the other hand, carry the distinct advantage of enabling both accurate measurement and application of torques to specific joints, as well as precise recording and monitoring of individual joint motion trajectories [14, 15]. Within the context of traditional stroke rehabilitation, the term "engagement" has a variety of meanings. One common interpretation of engagement is motivation for undergoing rehabilitation. An important finding is that highly motivated patients are more likely to attribute themselves a more active role in rehabilitation [16, 17, 18]. A strong motivator for the use of robotic devices in rehabilitation is that they facilitate clinical assessment by recording and measuring the kinematics and kinetics of human movements (speed, position and force) with high resolution [19, 20, 30].

Several User Interface (UI) tools have already been developed to be used by therapists. In [21], authors developed a UI to allow therapists to perform balance exercises using a balance board and a motion tracking system for use in fall detection and prevention. The therapist can select which patient, choose which tests to run, and view any important information either instantaneously or later. This system, however, does not have a game-like interface to keep the patient engaged. The authors in [22] provide therapists with a system to view Electronic Health Records (EMR). This system is very extensive providing many features such as viewing and editing patient profiles, adding any notes necessary, scheduling and billing of sessions, and allowing the patient to see results also through a web portal. This system however is not directly linked to a game, nor does it automatically save data from sessions. All information has to be input from the therapist's notes. In [23], authors did work with Autism patients during therapy sessions. The interface developed here allowed therapists to set the order of expressions of a robot that will be displayed to patients from a monitor. The therapist can also change the expressions of the robot by use of a remote control. This system does not automatically collect information about the patients as the information gathered was in the form of notes written by the therapist. Also, there was no interface to view the information about current or previous sessions, but only a single session control interface.

3 System Setup

Our game consists of moving one hand to hit a sequence of targets that are placed along an exercise gesture path. To make this more interesting, we borrow the aesthetics from traditional ball-toss carnival games. In these games, you toss a ball at a series of targets (cans, round target, or other visually intriguing objects) in an attempt to knock them down or break them. This is nearly identical to the actions we need the patients to complete. Additionally, as there are a wide variety of visually distinct carnival games with similar goals, we can easily alter the visuals of our virtual carnival game while keeping our gameplay the same. This provides more visual and audio variety to the user keeping them interested for longer.

To provide a large degree of adaptability for therapy sessions, our system utilizes two screens at the same time. One screen is for the patient and displays only the game (Figure 2 - Left). This screen may be visible by the therapist depending on if he is in the same location/facility as the patient. The second screen (Figure 2 - Right) allows the therapist to adjust the exercise program in real time by drag and drop of the exercise trajectories in the exercise list on the right side of the screen. Running along the top of the therapist's screen is a horizontally scrollable section that visually shows the sequence of exercises for this session as a series of pictures, placed sequentially in the order that they have been or will be completed. The exercises that have been completed are located on the left side of the list. The exercise currently being performed by the patient is after the completed exercises and is indicated by a yellow border. The exercises that have yet to be completed are located on the right side of the list, after the current exercise. These uncompleted exercises are changeable and can be reorganized at will.

4 Exercise Analysis

Dynamic time warping (DTW) [24] is a robust algorithm for measuring similarity between two sequences which may vary in time or speed. We use the Multi-Dimensional DTW algorithm for the purpose of measuring the distance between the time-series representations of the exercise trajectories. These trajectories are the spatial coordinates received from the Barrett Arm corresponding to its location at any given time. The authors in [25] have used the same warping technique for sign language recognition and we incorporate the same analysis for measuring the exercise trajectory deviation.

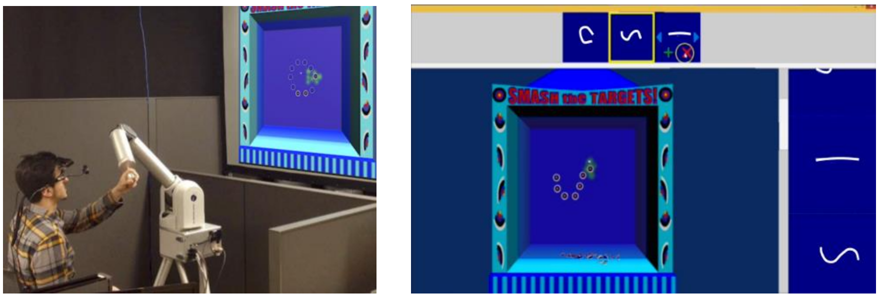

Fig. 2. Left – Patient, Game and Robotic Arm interaction, Right – Therapist's screen for online session adaptability that displays duplicate view of the patient's game-play (center), current exercise program (top) and available exercises (right).

Let R be an exercise trajectory. Here we can represent R as a time series $(R_1, \ldots, R_{|X|})$, where each R_t is the spatial coordinate of the Barrett arm. Given a reference trajectory R and patient trajectory P, DTW computes a warping path W that forms correspondences between features of R and P:

$$W = ((r_1, p_1), \ldots, ((r_{|W|}, p_{|W|})) \tag{1}$$

Here $|W|$ is the length of the warping path, and pair (r_i, p_i) shows that feature r_i of R corresponds to feature p_i of P. The warping path follows rules as shown below:

- Boundary Conditions: This states that the first elements match $(r_1 = 1, p_1 = 1)$ and the last elements match $(r_{|W|} = |R|, p_{|W|} = |P|)$.
- Monotonicity and Continuity: This states that the alignment cannot go backwards and the alignment cannot skip elements $(0 \leq r_{i+1} - r_i \leq 1,\ 0 \leq p_{i+1} - p_i \leq 1)$.

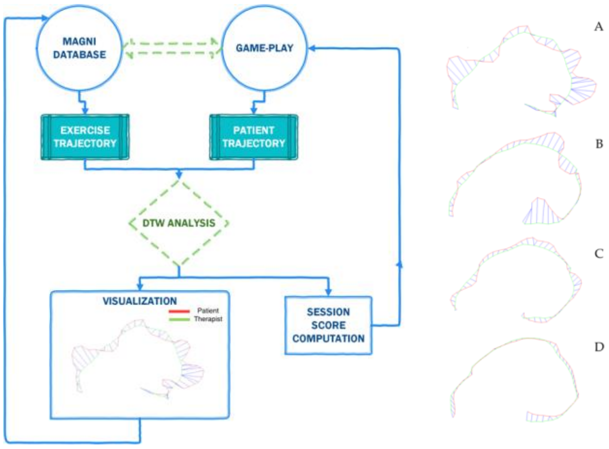

Fig. 3. Left - Exercise Analysis Flow Diagram; Right – Patient's recovery progress in four sessions. The score error deviation over sessions are A.) 52.38, B.) 25.83, C.) 8.31 and D.)7.53

The cost measure $D(W, R, P)$ of a warping path W is the sum of individual local optimal distances $d(R_{ri}, P_{pi})$, corresponding to matching each R_{ri} with the corresponding P_{pi}. The local distance is the Euclidean distance between the corresponding features of the two trajectories. The DTW distance between trajectories R and P is defined as the cost of the lowest-cost warping path between R and P. We use this distance to calculate score for the game. This enables accurate score calculations for trajectory time series with similar shapes even if they may be out of phase in the time axis. We visualize the Multi-Dimensional DTW optimal alignment to provide the therapist a better understanding of the patient trajectories' error deviations. Figure 3 above shows the overall flow of the exercise analysis that is performed in our system and an example of the patient's score and recovery progress over multiple sessions.

5 Experimental Setup And Results

In Human-Computer Interaction (HCI), role-play is a useful technique to develop an understanding of users' needs and to evaluate design prototypes where access to users or environments is limited. In our work, we use therapeutic role-play [26] technique with our participants in order to gain feedback about the design of our system. Here we imply a procedure similar to the Goldfish bowl role-play technique where there are two participants in the role-play and many observers. We use two participants in the role-play, one as the therapist and the other as the patient. The developers of the system are the active and engaged observers who receive feedback from the participants on the design of the interface and the game-play experience. The system was tested with 10 participants (3 females and 7 males) who actively took part in the therapeutic role-play technique while using our system and then providing feedback by filling out two surveys, namely “MAGNI Game Survey” and “MAGNI Therapist User Interface Survey”. Both surveys contained Likert-like questions with 10 points scale with “1” being “Very Easy” and “10” being “Extremely Difficult”. Our participants were all students from Computer Science Department with good vision and physical condition. Instructions were given to the participants in order to inform them what are the disabilities of stroke patients related to the arm movement, such that they could successfully participate in such a role-play. Each participant first played the game in the role of the patient and then used the user interface of our system in the role of the therapist.

The hardware that we require for our infrastructure is the Barrett WAM Robotic Arm, a Linux desktop computer to control the Arm, a Windows desktop computer to run the game and contain the database, one projector monitor and networking hardware (LAN cable and router). All experiments of the User Interface were conducted on an Intel i5 4690 CPU @ 3.5GHz machine with 16 Gigabytes of main memory, running Windows 8.1 with NVIDIA GeForce GTX 780 graphics card.

5.1 3D Perception

As the patient smashes each target in the sequence, their arm follows a preset path that equates to performing a therapy exercise. While it is extremely easy to convey the horizontal and vertical position of each target on a 2D screen, intuitively communicating the depth of the targets proved to be more challenging. Our initial attempt at conveying depth was to place thin columns below each target that stretched to the bottom of the game box (Figure 4 - Left). A column was also attached to the hand position indicator which moved at the same pace / to the same location as the indicator.

While this did show how far back in the play-field each item was, the single thin point of contact was often quite far below the target/hand. This required the user to take extra time to repeatedly glance down at the bottom of the play-field then back up to the targets to keep track of where they were located. Additionally, numerous volunteers had trouble understanding how the columns indicated depth.

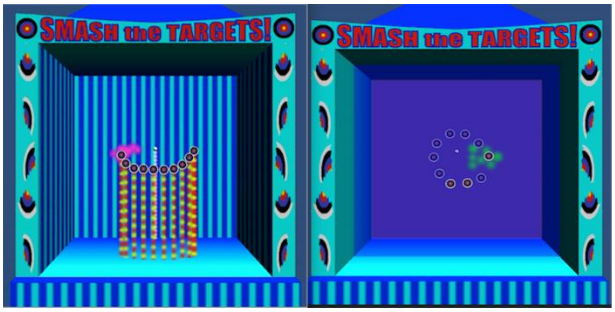

Fig. 4. 3D visualization and perception. a.) To the left is the initial 3D attempt. Here, the object illuminated in pink is the target and depth is indicated using columns, b.) To the right is the final depth plane visualization. Here, the target is displayed by green visual cues, depth is indicated using color fields and brightness of a point indicates it's depth relative to the depth plane.

Our second attempt at conveying depth involved two transparent colored fields (Figure 4 - Right). Both fields cover the width and height of the play-field. The first field was colored blue and would move to the depth of the current target needing to be hit. The second field was colored orange and would move to the depth of the hand position indicator. As the fields are transparent, it is easy to see both fields at the same time by looking through whatever field is currently in front. The transparency also allows the user to see the targets and hand indicator through the fields. Due to the sheer size of each field, peripheral vision allows the user to see the depth of the current target and hand without looking away from the targets. Most importantly, as the hand moves behind and in front of the current target, the main visible color of the fields will switch between orange and blue depending on whether the hand indicator or the target is in front. This allows the user to intuitively tell if they need to move their hand more to the front or to the back. The tests with participants showed good results for the second way to convey depth, as this system was much more intuitive to understand. The GUI and the 3D video game that the participants used are shown in the following link:
https://www.youtube.com/watch?v=tCjntdBC2BY

5.2 Role-Play Survey Results

Table 1 shows some of the questions that were presented during the two surveys. Figure 5 shows the mean value of the results taken from the surveys. This shows that the responses to our game and interface were mostly positive with the lowest mean being approximately 7.40. The higher values may be caused by the participants having prior experience with games and their work in other areas of Computer Science.

The participants also provided additional comments on both the game and interface. The most common response was to grant the therapist the ability to manipulate the graphs. This way, the therapist can pan, rotate, or zoom in on the graph to see certain portions of the graph clearer. Another common response was about the depth perception of the game. Even though the game was a 3D game, it appeared to the participants as if it was 2D, making it difficult to understand the depth of the target. Lastly, participants wanted some additional information when adding or updating patients in the interface, such as user prompts and error messages that pop up and provide additional information.

6 Conclusion And Future Work

In this work we combine the robot-assisted rehabilitation with a 3D video game that motivates the user in a GUI operated by therapists and allows them to interact in real-time with the patient. We evaluate the users' exercises according to the prescribed therapist exercises using the robotic arm in order to capture the users' upper limb range of motion and disabilities.

Our prototype demonstrates that 3D game in combination with robotic end-effector enhances the compliance of user by proving motivation to continue through the prescribed exercises. Visualizing the error of patient's exercise trajectory compared to the therapist's recorded reference exercise trajectory helps therapists to understand where the patients had issues during performing exercise that can be addressed in further treatment sessions. Finally, the accurate recovery outcomes exported after each rehabilitation session provide the therapist with the recovery progress of the patient's upper limbs and visual exercise cues in order to plan their next rehabilitation session.

As a future work, we plan to implement the changes recommended by the participants during the survey, especially the manipulation of graphs and improving the depth perception of the game. This will allow a therapist to view the patient's progress in more detail. We also plan to deploy an adaptation module, which will be responsible for the session personalization and adaptation. Each session consists of a certain amount of exercises as prescribed by the therapist. The system will be able to adapt the exercise type and difficulty based on the subject's performance and facial expressions (e.g. pain).

Table 1. Questions Given During Survey

Label	Question
Q1	Was it easy to understand the trajectory deviation between the therapist and the patient?
Q2	How easy was it to understand the interface during gameplay?
Q3	How easy was it to keep track of the patient's progress during gameplay?
Q4	Was the calibration phase easy to understand?
Q5	How easy was it to understand how to play?
Q6	How easy was it to understand how to play?
Q7	How easy was it to control the game/hit targets?

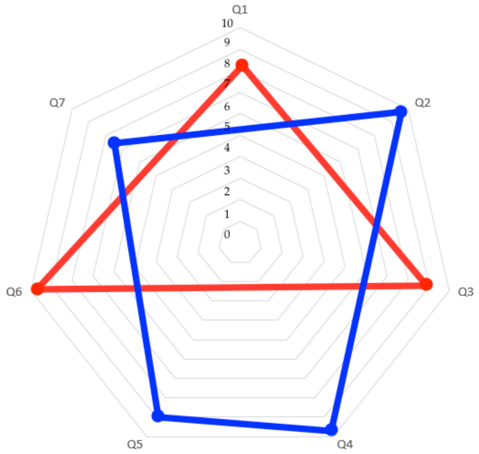

Fig. 5. The mean value of the responses from the survey (The red lines correspond to the therapist interface answers and the blue lines with the patient interface).

Furthermore, we plan to use the force deviation to apply active motion control to the patients' arm in order to help them gain more control of their motor function. In more advanced stages of rehabilitation, the user will be able to apply forces to move the robotic arm, and the robotic arm will exert an amount of resistance adapted to the specific user's activities [27]. Finally, the usage of remote eye tracking may provide a valuable measurement of users' cognitive engagement and concentration rates over time for smart rehabilitation [28].

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