A Decision Model of Stroke Patient Rehabilitation with Augmented Reality-based Games

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***Abstract*—Computer-based systems for stroke rehabilitation can potentially reduce complexity in rehabilitation processes. One of important issues among the rehabilitation systems is how to continuously evaluate patient's performances from such systems. Without a proper measurement for patient's performance, therapists suffer from accurate decision making in patient treatments. Therefore, the main focus of this paper is to develop a rehabilitation system that can minimize therapist supervision. To this end, we develop augmented reality-based rehabilitation system that can automatically capture patients' performance as well as visually monitor patients' progress. We also propose performance measurements of patients to improve decision making abilities of therapists. By analyzing performance data, we discover useful rules for further enhancement of the patients' treatment plan.**

***Keywords*—stroke rehabilitation, augmented reality, patient analysis, rehabilitation game, decision support**

I. INTRODUCTION

Stroke rehabilitation is an important issue in healthcare because the stroke is the major cause of disabilities among adults in Canada [1]. In general, traditional stroke rehabilitation needs a lot of facilities and human resources. In fact, every rehabilitation exercise needs different equipment and a therapist can only treat one stroke patient at a time. Therefore, patients cannot receive enough treatment and thus efficient treatment is not guaranteed [2]. In addition stroke patients who are undergoing some traditional therapies often lose their interest in the program shortly [3]. To address these problems, computer-based rehabilitation applications have actively designed and developed using emerging technologies such as virtual reality (VR), augmented reality (AR), and haptics [3][4]. Since these applications support fully or partially immersive virtual environment with entertaining rehabilitation, patients can continue to interactively participant in rehabilitation processes with some interests [5].

Nevertheless, if the systems do not provide a mechanism that continuously assess and monitor patient's performance in their treatments, therapists will suffer decision making with quality evaluation of patients. There is a need for providing a mechanism that allows the therapists to quantitatively measure treatment progress of the patients. To deal with this issue, we propose AR-based rehabilitation system that can support better utilization of rehabilitation resources and a reduction in the overall patient service time. In addition, to improve patient care quality, we analyze certain features to be used as a decision model and define performance measurements for evaluating patients' progress. The rest of this paper is organized as follows: The next section review previous studies related to stroke rehabilitation. In section 3, we present a detailed description of how we evaluate the patient performance to monitor patients' progress. Finally, conclusions are presented and future work is discussed in section 4.

II. RELATED WORK

In computer-based systems for stroke rehabilitation, three approaches have mainly been developed: VR-based rehabilitation system, haptics-based rehabilitation system, and AR-based rehabilitation system.

In the late-1990s, VR was used to provide motivating environment for motor stroke patient rehabilitation [5][7]. In addition, it was proven that motor knowledge obtained in VR learning environment can be used in the real physical world [8]. Subsequently, many studies followed after to explore the effectiveness of VR system for rehabilitation tool to measurement of motor performance in motivating and safe environment [9][10][11][12]. Following the proposal of the VR systems, haptic technologies were used in VR rehabilitation exercises to provide the patient with more natural interaction mode and a chance to improve their motor strength. Different systems were developed by utilizing haptic technologies in rehabilitation recovery of stroke patients with disability in upper extremity, including [14][15][16], and in lower extremity [18][19]. Jack et al. developed haptic exercises for upper limb rehabilitation, and defined set of parameters to evaluate the patient's performance using their exercises [38]. The system consists of four different rehabilitation exercises that were designed to train specific hand movements. Performance parameters of those movements include: Range of motion, speed of movement, finger fractionation, and strength of movement. The study showed that patients who used the framework as part of their treatment program have improved using the performance parameters defined. This improvement was clear in finger fractionation and range of motion when pre

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and post test where compared [13]. Alamri et al. developed a haptic-based rehabilitation framework that consists of multiple exercises for hand motor rehabilitation [17]. They implemented five different exercises: moving a cup following horizontal and vertical reference path; stacking four colored cubes to form one bigger unified color cube; navigating a maze; squeezing spongy ball; and lifting virtual weight dumbbell. Authors tested the framework with ten normal subjects and result showed that subjects were motivated during experimentation. Furthermore, the testing with subject showed promising result to define a normative metrics for healthy subjects, which used to assess patient treatment progress. They tested the framework with three stroke patients with excellent result for both performance perdition and decision suggestion. However, the complexity and bulkiness of haptic devices, i.e. CyberForce [20], have limited the usage of this technology especially for stroke patients [21]. To gain advantages of both the VR and hapics, fewer attempts were made to use AR in motor rehabilitation of stroke patients [36][37]. However, none of these attempts have considered games in AR reality setup by capturing real world scene and superimposing motivating objects. In addition, to the best of our knowledge, most of the above-mentioned rehabilitation systems do not provide a mechanism that continuously assess and monitor patients' performance in their treatments by utilizing certain performance measurements. Similar to our study, in [10], authors developed a media adaptation framework for stroke patient rehabilitation. In their framework, the patient is asked to make reach movement, which tracked and evaluated by the framework in real-time, and an immediate audio/visual feedback is generated. The biofeedback is adapted before rendering to reflect the degree of correctness of the patient reach movement. Thus, the feedback in used to inform the patient how well their reach movement without the therapist intervention. They trained a Dynamic Decision Network (DDN) using previous sessions for online adaptation. Then, they defined three parameters that control the adaptation decision: spatial accuracy, hand trajectory, and hand velocity. Differing from this work, our goal is to automatically capture patient performance from interactive games designed for AR-based rehabilitation exercises with real and virtual objects.

From our literature review, a better rehabilitation system should motivate patients to complete their rehabilitation process, as well as, provide them with all possible informative feedback (visual, audio, and haptic). It should provide patients with exercises or games that designed specifically to enhance some cognitive and/or motor skill. In addition, it should also support a decision model to improve decision making abilities that utilizes certain performance measurements for monitoring patients' progress of treatments. Therefore, a rehabilitation system with the decision support that utilizes AR-based games may obtain real benefits for utilizing directly in daily activities in real physical world [33].

III. Patient Analysis using AR-based Games in Stroke Rehabilitation

In the previous study, we proposed an AR-based rehabilitation framework that can increase the patient involvement in the treatment process [18]. In this paper, we extend functionalities of the system that measure patient performances without the direct supervision of a therapist. By decomposing the complex movements into multiple primitive movements and analyzing them, we compute the quality of patients' performance after they perform AR-based games.

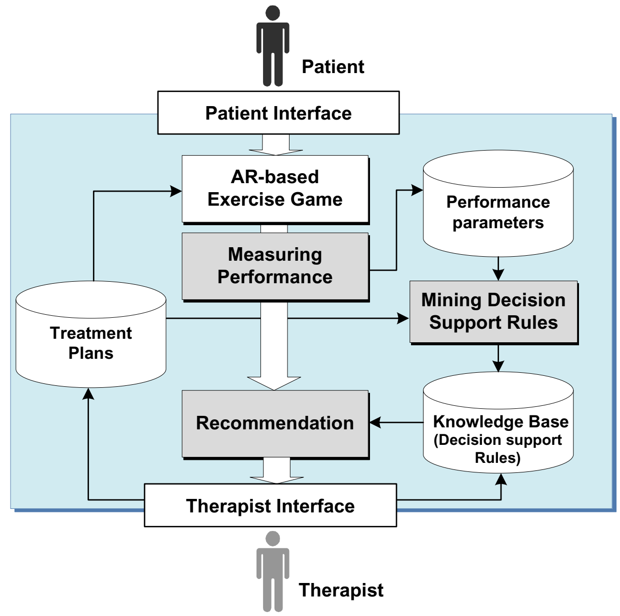

Figure 1. System overview for decision support in AR-based stroke rehabilitation

Figure 1 illustrates the overview of the proposed framework. According to a treatment plan of each patient, the framework provides a set of serious games for exercising developed using AR technologies and used for post-stroke patient rehabilitation of hands and arms. Since the system contains supportive components used to track and record patients hand movement, it continuously tracks objects and captures events, e.g., hand movements, time stamps, the position of objects, virtual paths of objects, etc., while the patient performs the game. Once the session of the game is completed, performance of this session is measured and stored. These measured data are analyzed not only to evaluate patient progress during the treatment but also to discover decision support rules. To assist decision making of a therapist, the system suggests new games with different level of difficulties depending on the result of the current performance by utilizing decision support rules in Knowledge Base (KB). At the same time, the system provides useful tools for the therapist not only to monitor patients' progress in their treatment process but also to change and/or view the patients' profiles and treatment plans.

A. Augmented Reality-based Exercise Game

Currently, the framework includes five games as interactive exercises to motivate patient and to measure their progress: namely Cup, Shelf, Cannon-ball, Air-Hockey and Block. The games are divided into two categories: guided (Cup and Shelf) and unguided (Cannon-ball, Air-Hockey and Block). In the guided games, a patient plays the game by following a predefined scenario steps, and the game ends when the last step is completely finished by the patient. In the unguided game, the patient plays against a computer controlled opponent. The opponent who achieves the maximum score wins the game scenario. The unguided games employ some intelligence to simulate the computer opponent and the dynamic movements of the virtual objects. Every game in the system is developed to enhance the motor function capability of the patient hand, at the same time; it monitors the treatment progress by evaluating his/her performance parameters.

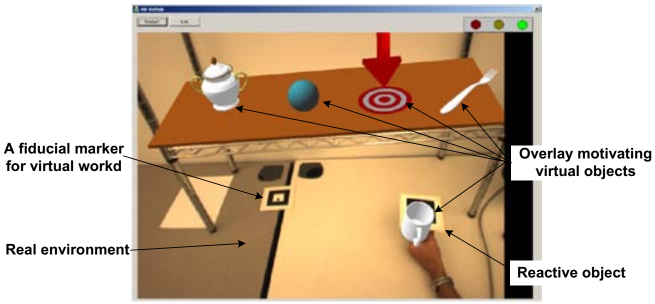

Figure 2. An example of the Shelf game designed to real and virtual objects

Figure 2 shows an example of the Shelf game designed as augmented reality game where we make use of both real and virtual objects. Considering space limitation, we refer the reader to [18][19] for the descriptions of the games.

B. Performance Measurements of Stroke Patients

For the decision model of stroke patients, we define seven performance measurements for the above-mentioned games. These parameters are: task completion time [19], eye-hand coordination, hand motion smoothness, hand motion curvature, hand steadiness [22], hand range of motion and hand strength. In this paper, we present tree parameters used to design the support model in details.

1) Eye-Hand Coordination

Eye-Hand Coordination (EHC) is defined as the precision level of human ability to move his/her hand following a prescribed visual cue or straight toward a target [23]. Scientists have found that the hand reach movement is planned based on the sensory inputs from visual and tactile human perceptual systems. Thus, EHC is crucial factor for human to carry the everyday activities such like picking-up an object from a shelf [24]. With the absence of such ability, the human hand movements become fumbling approximation movement rather than precise movement [25].

The EHC factor is quantified by calculating the error of hand movement relative to the straight line connecting the start with target points of the movement (the shortest path). Then, the hand-path error value for a specific reach (rest-to-rest) movement in the XY plane is computed by the following equation [26]:

$$hand-error_{cont} = \int_{t_i}^{t_f} |x(t)| \cdot |y'(t)| \cdot dt \quad (1)$$

Where $x(t)$ is the hand movement continuous function in X axis, and $y'(t)$ is the first derivative (velocity) of hand movement continuous function in Y axis. The corresponding Equation 1 for discrete function is defined as:

$$hand-error_{dis} = \sum_{t=i}^{f} \left(\Delta x \cdot \frac{\Delta y}{\Delta t} \right) \quad (2)$$

Where Δx is the change of position coordinates in X axis, and $\Delta y/\Delta t$ is the rate of change of position coordinates in Y axis over time.

In this paper, the error is calculated in 3D space not only for one plane. However, a patient is located in perpendicular to Y in our environment, and thus, most of the reach movement occur along the Y axis not in X or Z axis. Thus, one can compute the hand-error by computing the error in the planes YX and YZ. In addition, the EHC factor is assumed to be the arithmetic average for all error scored during all reaches performed throughout the treatment session. Thus, the adapted Equation 2 to calculate the EHC value is as follows:

$$EHC = \frac{1}{N} \sum_{m=0}^{N} \left\{ \sum_{t=i}^{f} \left(\Delta y \cdot \frac{\Delta x}{\Delta t} \right) + \sum_{t=i}^{f} \left(\Delta y \cdot \frac{\Delta z}{\Delta t} \right) \right\} \quad (3)$$

Where $|\Delta y|$ is the change of position coordinates in Y axis, $|\Delta x|/|\Delta t|$ is the rate of change of position coordinates in X axis over time, and $|\Delta z|/|\Delta t|$ is the rate of change of position coordinates in Z axis over time. N is the number of times the patient is performing the reach movement during the exercise session.

2) Hand Motion Smoothness

Smoothness of hand moving toward a target (HMS) is defined as the measure of abrupt changes in hand movement acceleration. A normal reach movement start by accelerating towards a target and keep increasing until a point where it start to decrease the speed until it reaches the target with speed approaching zero [27].

Many mathematical models have been developed to measure the smoothness of hand movement including the minimum jerk model [28], the minimum joint torque change model [29], and the optimally smooth transport model [30]. Every model requires certain range of inputs to determine the smoothest hand movement among finite set of hand movements. Thus, one can use such mathematical model to measure the smoothness of hand movement by supplying the suitable inputs. In this paper, we adopted the minimum jerk model to measure hand smoothness as it is widely accepted and used. In addition, while other models require more sophisticated inputs, such as joint angels and torques, the input required by this model is only the Cartesian coordinates of the hand movement. Jerk is defined as the rate of change of acceleration. According to [28], the cost function that defines this model is as follows:

$$C = \frac{1}{2} \int_{t_i}^{t_f} \left(\frac{d^3 x}{dt^3} + \frac{d^3 y}{dt^3} \right)^2 dt \quad (4)$$

Where x and y are the Cartesian coordinates of the hand rest-to-rest (reach) movement in the XY plane, and t_f is the time at the final destination of the reach movement. Previously, jerk has been used before in stroke rehabilitation by [10] to measure and adapt multimedia content presented to patients while they perform their treatment sessions. In our system, a patient plays one of five exercise games each session during a treatment plan. These games are defined in the 3D space (with three different 2D planes: XY, YZ, and XZ). Therefore, we adapt Equation 4 to suit in the measuring of the smoothness of patient hand in the 3D space as follows:

$$HMS = \frac{1}{2N}\sum_{m=0}^{N}\int_{t_i}^{t_f}\left(\frac{d^3x}{dt^3}+\frac{d^3y}{dt^3}+\frac{d^3z}{dt^3}\right)^2 dt \qquad (5)$$

Where N is the number of times the patient is performing the reach (rest-to-rest) movement during the exercise session. x, y, and z are the Cartesian coordinates of the hand rest-to-rest (reach) movement in the 3D space, and t_f is the time at the final destination of the reach movement.

3) Hand Strength

Brain lesion caused by a stroke has decreased significantly muscle strength in contralateral and ipsilateral side of human body[31]. However, this muscle strength of patients can be increased while they finish treatments by taking training sessions in rehabilitation centers [32]. Thus, measuring hand strength is very important to make a decision about the recovery of a stroke patient. Our system uses the total work distribution over time for patient hand movement as a measure of hand strength [17]. It is a trapezoidal function due to the fact that the total work remains the same until a threshold, after which the quality of performance starts decaying. The total work is defined as the work done by a variable force in the human hand. This force varies in magnitude and direction during the reach movement. Thus, the work done by such force in X-axis can be determined by the following equation [33]:

$$W_{x_{session}} = \int_{x_i}^{x_f} F_x \cdot dt \qquad (6)$$

Where F_x is the x component of the force driving the movement of hand while performing one reach movement starting from x_i position along the x axis and ending at x_f. The force $\underline{F_x}$ is calculated as the mass of the moving object multiplied by the acceleration of the hand along the X-axis. In our system, the object is the patient hand holding the real object (e.g., mug) and moving it toward a target. Thus, the mass of the object is equal to the mass of the hand and the real object. The mass of the real object is neglected since it is varying from one exercise to another and negligible when compared to the mass of the hand. The mass of the hand is estimated to be 0.447kg for male and 0.35kg for female according to a study that performed for 100 subjects to identify the mass for different part of human body [34]. In addition, the acceleration of hand is considered along the three dimensions since the hand is moving freely in the 3D space. Thus, the total work for a complete session is the integral of the work for the complete time interval of the session, and can be calculated by the following equation:

$$Hand_{strength} = \sum_{m=0}^{N}\left(\int_{x_i}^{x_f} F_x \cdot dx + \int_{y_i}^{y_f} F_y \cdot dy + \int_{z_i}^{z_f} F_z \cdot dz\right) \qquad (7)$$

Where F_x, F_y, and F_z are the x, y, and z components of the force driving the movement of the hand while performing the exercise session. N is the number of times the subject is performing the reach (rest-to-rest) movement during the exercise session.

C. Supporting Decision of Theraphists

The objective of the decision support is continuously reading and analyzing performance of patients and sending recommendation alerts to the therapist with the following cycles:

- Triggered right after any change made to patient performance parameters
- Make a decision of a patient progress from Knowledge Base (KB).
- If recommendations which include the type of game, a number of session, and the difficulty of the game is made, notify the recommendations to a therapist
- If the therapist accepts the recommendations, update the patient treatment plan

In the proposed system, there are two types of decision support rules oriented to stroke rehabilitation: 1) class association rules that are discovered using data mining technology from the performance database and 2) heuristic rules that are directly generated from therapists.

For the class association rules, in this paper, we periodically apply the mining process based on the following assumption: each transaction corresponds to a session of each game and items in transaction are performance parameter-value pairs measured from the game. The values of the performance parameters measured are continuous numeric values i.e., quantitative attributes [39]. Therefore, before the mining process, the parameter values are discretized where the numeric values are replaced by interval labels. Even though discretization of continuous attributes can be done by using many existing machine learning algorithms [39], in the current stage of the system, therapists manually define the interval through interface. From the descretized values, we discover associations between conjunctions of the attribute-value pairs and class labels, known as class association rule mining [40][41], that occur frequently in patients' performances.

For the heuristic rules, therapists can directly generate some default rules according to their rich experience. In addition, we support the therapists to evaluate the recommendation so that they determine whether or not the mined rules defined in KB are useful. According to their judgment, the existing rules can be modified or confirmed through the therapist interface.

IV. CONCLUSION AND FUTURE WORK

In this paper, we have presented a stroke rehabilitation system with AR-based games that assess and monitor the patient's performance in their treatments. We also proposed useful performance measurements that can be used for evaluating patient progress and making a decision of therapists. The major advantage of the proposed system in stroke rehabilitation is that it supports not only game-based interactive exercises but also quantitatively measurements of patients' treatment progress.

For future work, we intend to explore haptic/tactile feedback to rehabilitation processes. We expect to improve our system further by considering patients' feeling of virtual objects. Therefore, we plan to embed haptic/tactile actuators into the real object that can react with vibration to inform the patient of being interacting with virtual objects.

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