AR-REHAB: An Augmented Reality Framework for Poststroke-Patient Rehabilitation

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***Abstract*—This paper proposes a novel approach based on augmented-reality (AR) technologies that can increase a stroke-patient's involvement in the rehabilitation process. The approach takes advantage of virtual-reality technologies and provides natural-force interaction with the daily environment by adopting a tangible-object concept. In our framework, the patient manipulates during the treatment session a tangible object that is tracked to measure her/his performance without the direct supervision of an occupational therapist. We called this framework AR-based REHABilitation. In this paper, we introduce the core architecture of the framework and its subsystems that provide more convenience to patients and therapists. We also present two exercises, a shelf exercise and a cup exercise, as examples and perform preliminary usability study. In addition, we introduce assessment measurements such as task-completion time, compactness of task, and speed of hand movement by capturing the patients' hand movements with the tangible object.**

***Index Terms*—Augmented reality (AR), haptic applications, medical instrumentation and measurement, occupational therapy, stroke-patient rehabilitation, stroke rehabilitation, virtual reality (VR).**

I. Introduction

HEMIPLEGIA is a medical condition in which a patient suffers from a total or partial paralysis of the arm, leg, and trunk of a side of the body. Brain stroke is one of the most well known causes of hemiplegia. Stroke happens when blood supplies to the brain are interrupted, causing permanent damages to the human brain and resulting in death or permanent disabilities. Most of the people who survived a stroke are suffering minor to major disabilities in their functional motor capabilities. Therefore, most of them are unable to maintain their daily life activities [1].

In a recent study, stroke was found as the major cause of disabilities among adults in Canada. The Canadian health-care system spends more than 2.7 billion dollars in poststroke therapy. On average, patients spent three million hours a year in hospitals to get treatments for disabilities after the stroke [2]. In the study jointly carried out by Sharma and the Caro Research Institute, they anticipated that in the next 20 years, more than 160 thousand strokes can be avoided and then at least 60 thousand people in Canada can avert disabilities if stroke care is properly coordinated. Moreover, net savings of eight billion dollars could be achieved as well [3].

People with upper or lower extremity disabilities undertake treatment courses (motor rehabilitation) to recover all or some of their functional motor capabilities. The aim of this type of therapy is to tolerate patients' disabilities to let them normally carry out their daily life activities. Patients are usually seen in rehabilitation centers for half-hour sessions, once or twice a day, in order to be treated. During these sessions, therapists conduct special type of exercises to teach patients to recover their basic motor skills, e.g., how to handle a cup and move it to a shelf. While doing the exercises, therapists measure and assess the patients' achievements using standard tests to coordinate next-level exercises [4], [5].

However, most of the traditional (noncomputer-based) stroke rehabilitation is carried out in rehabilitation centers located in hospitals or medical institutes [6]. Since these centers are usually located in urban areas, patients who live in rural areas have to travel to be treated. Therefore, stroke patients who have restricted mobility would have difficulties in getting to the centers, and, in some cases, they may not be able to get the treatment. In addition, traditional rehabilitation methods need a lot of facilities and human resources because every exercise needs different equipment, and a therapist can treat only one stroke patient at a time [7]. Several studies proved that duration, capacity, and intensity of exercise sessions are the most important factors for effective motor rehabilitation [8], [9]. In other words, only steady and intense exercises can effectively help patients recover their motor functions. However, if patients cannot have enough access to treatment due to lack of therapists and facilities, efficient treatment is not guaranteed.

Furthermore, most of the stroke patients who are undergoing some traditional therapies lose their interest in the program shortly. Since these types of treatments concentrate on patient-body's motor functionality, their exercises comprise trivial and boring tasks that need to be repeated, such as moving a hand back and forth. Therefore, motivating patients to continue the exercises is important to accomplish successful treatment [7].

In order to overcome these problems, a computer-based virtual-reality (VR)-based rehabilitation system was introduced. Since the early 90s, VR technologies have been used to provide entertaining environments for stroke patients to recover basic motor functions. Then, haptic technologies were incorporated with virtual environments to allow patients to feel

Manuscript received July 20, 2009; revised May 6, 2010; accepted May 19, 2010. The Associate Editor coordinating the review process for this paper was Dr. Domenico Grimaldi.

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Digital Object Identifier 10.1109/TIM.2010.2057750

and touch virtual objects in order to additionally provide the patient with more natural interaction mode and a chance to improve their motor strength. However, the bulkiness of haptic devices, i.e., CyberGlove [10], have limited the usage of the technology, particularly for stroke patients [11].

In this paper, we present an augmented reality (AR)-based REHABilitation (AR-REHAB) framework that utilizes AR technology to provide patients with an entertaining and natural environment for treatments. In addition, we adopt a tangible object into the framework and enable patients to touch and interact with the real and virtual environment all together. We superimpose virtual objects in motivating scenarios designed to consider the use of real environment setup (e.g., real kitchen shelf). These scenarios require the patient to use tangible objects (e.g., a kitchen cup) to accomplish their objectives. Using AR-REHAB, patients are able to experience real force while they perform their exercises. In addition, displaying fully immersive virtual objects in real-world scene promotes engagement of patients in their treatment sessions.

The remainder of this paper is structured as follows: Section II explains the rationale for the development of this framework and depicts some related work. Section III explains the design philosophy and the implementation details of AR-REHAB. Section IV describes the scenarios of the cup and the shelf exercises that are part of our framework. Section V presents the result of the usability study we conducted for AR-REHAB that involved 15 healthy subjects. Section VI discusses the time-based analysis we conducted to analyze the subject's performance in the shelf and the cup exercises. Finally, in Section VII, we summarize this paper's contents and provide perspective for future work.

II. Related Work

A. VR-Based Rehabilitation

The VR rehabilitation systems can change the traditional boring rehabilitation exercises into entertaining ones, carrying out visual and auditory motivational components [7]. In addition, these components are preprogrammed to encourage patients by producing motivational messages (visual or audio) in response to events a patient may trigger. Events are classified based on how much a patient may progress in her/his correspondent exercise. A therapist defines events based on the exercise scenario [12].

Using VR in rehabilitation, we can accommodate more than one exercise setup in one system. This shall save space, cost, and efforts needed to set up these exercises in a real rehabilitation center with the ability to carry out infinite repetition of the exercises. The variables of the exercise are controlled as needed without limitations. In addition, such system can be used by many patients, and more than one system can be supervised by one therapist. Thus, proper coordination of stroke rehabilitation can be achieved to provide health services to a larger group of patients [13].

Moreover, VR systems can be moved to a patient when a patient cannot attend her/his treatment session in the rehabilitation center. Such systems have semiautomated capabilities to interact with and guide the patient on her/his own without continuous supervision of the therapist. All that is needed to run these systems is access to a computer. Some VR systems may incorporate special hardwares most of which are easy to use and do not need special training. Internet can be used as a communication medium between the therapist and patients. For example, patient movements are captured using a sensory hardware system directly tied to the VR system that provides precise and effective performance readings. Therapists are provided with their patients' progress and can instruct the system to update the quantity, intensity, and duration of the patients' exercises at any time [7], [13].

Several studies highlighted the use of the VR technology in brain-damage therapy, and it is clear that many systems have been developed to serve this purpose. It is not the objective of this paper to enumerate all the previous VR-based systems. Readers are advised to look into more elaborate reviews [14]–[16]. In addition, Sveistrup, in [12], has reviewed the current VR-based systems that are developed specifically for motor-function rehabilitation. In her study, she explained the effectiveness of such VR systems in improving specific motor functions.

B. Haptic-Based Rehabilitation

Although VR-based rehabilitation systems motivate patients persistently to conduct the exercises in a motivational way, they have a disadvantage in that the patients are unable to feel or touch the virtual objects even if motor rehabilitation is a process of recovering physical motor skills by touching and moving. In this section we will take a look at some well-known VR rehabilitation systems that take advantage of haptic technology. Then, a discussion of the pros and cons of such approach will follow.

Several systems have been developed that incorporate haptic technologies in rehabilitation. These systems have proved the suitability of haptics in the field of rehabilitation. One of the earliest attempts was the work done by Burdea *et al.* [17], [18] in the development of haptic exercises for upper-limb rehabilitation using the Rutgers Master II force-feedback glove. The system consists of four different rehabilitation exercises that were designed to train specific hand movements. The performance parameters of those movements include the following: range of motion, speed of movement, finger fractionation, and strength of movement. The study showed that patients who used the system as part of their treatment program have improved [19], [20]. In addition, the same authors have developed in [21] a lower extremity rehabilitation system using two Rutgers Ankle platforms. Preliminary results showed that patients improved their strength capabilities. However, not enough evidence has been shown to prove task-level improvements of the patients.

The authors in [15] and [22] have developed simulated tasks for poststroke rehabilitation. First, some movement patterns have been recognized based on their functional goals. Then, haptic-based simulated tasks for these movements are developed. While a patient is practicing these simulated exercises, the system collects different types of data that can be used later for movement evaluation. Current implementation of the system includes exercises developed to work with the PHANToM and the Cybergrasp haptic interfaces.

El Saddik *et al.* developed a rehabilitation framework that consists of multiple exercises for hand-motor rehabilitation. Unlike other attempts, this framework was built based on well-established exercises that are used in the Jebsen Test of Hand Function and Box and Block tests [23]. The framework comprises four components: 1) the sensory component that interfaces with the haptic-device application programming interface (API); 2) the haptic-simulation component that is responsible for haptic/graphic scene synchronization; 3) an application component that hosts the exercises; and 4) the haptic data component that acts as a haptic data repository [24], [25].

Gentle/s is a machine-mediated therapy system that was developed and funded by the European Commission. The system used the HapticMaster that is a robotic arm with gimbals allowing patients to put their hands and move it, which is located beside an exercise table. Study showed that subjects were motivated to exercise more times when using the system [26]. In addition, Rydmark *et al.* [27] have developed some haptic-based exercises for brain-injured patient. Results proved that using such system could promote rehabilitation [28].

Haptic-based rehabilitation inherits the advantages of VR-based rehabilitation because haptic systems usually incorporate VR environment as a main component of its system setup. In addition, the patient is able to touch and manipulate the virtual objects using such systems [7].

From our literature review, we found that most of the existing systems for rehabilitation of hand-motor function use hand-wearable haptic devices that support multipoint haptic interaction. Mostly, these devices tend to be bulky and require a significant effort to wear even by healthy people. This is a serious problem to stroke patients as they have difficulties in moving their fingers freely. In addition, hand-wearable haptic devices are not only costly but also are attached to special supportive machines that prohibit its associated system from being portable [11]. This is not only the problem with such devices; their continuous usage results in tiredness and some fatigue in the arm and shoulder of patients. Thus, some patients may start to lose their interest in these systems, particularly those who are in senior ages. Additionally, such haptic devices require a calibration process that takes time and require patients to make difficult gestures with their affected hands [11].

Furthermore, collision-detection and haptic-rendering algorithms for multipoint haptic interaction are not mature enough to detect all details of interaction between hands and virtual objects. Sometimes, subjects have difficulties in realizing that their hands are penetrating virtual objects without feeling them. This will deteriorate the realism of the haptic-based exercises [11].

C. AR-REHAB

AR is known as the process of overlaying computer-generated virtual objects onto a real captured scene of the world. In other words, AR technology enables virtual objects to be seamlessly blended into the real world by capturing and digitally processing a real scene with the use of motion-tracking technologies, such as motion sensors or fiducial-marker recognition, using machine vision. Therefore, AR resides in the middle between the VR, where immersive virtual objects can be utilized, and the real world with which human can interact intuitively and naturally [29]. Thus, the AR system may have the advantages of both the virtual and real worlds at the same time, providing motivating virtual environments and natural-force interaction with real-world objects in the rehabilitation process.

From our knowledge in the field of rehabilitation using computer systems, we think that incorporating AR in the rehabilitation procedure brings the advantages of all approaches: traditional, VR-based, and haptic-based. In AR-REHAB, we assume that users see real-world scene and manipulate real objects in their exercises. Therefore, users will experience real force instead of computer generated one which may distort the force perception producing artifacts and make the system unstable, hurting the users in haptic-based rehabilitation systems. Excluding haptics from the system will decrease the hardware and software complexities of the system but with no price to be paid. This is because users are still able to touch the real objects and items they are manipulating in the AR-based systems. In the meantime, users will not lose their interest in performing the rehabilitation exercises because the system is capable of presenting superimposed virtual motivating objects in front of them. Thus, the system is capable of achieving the important objectives of VR- and haptic-based systems with reduced complexity. In addition, no bulky or sophisticated devices are necessary to produce artificial forces toward the users in contrast to the haptic-based systems [30], [31].

To the best of our knowledge, a few attempts were made to develop AR-REHAB systems. Researchers in [32] developed an AR system to train a stroke patient for grasp-and-release tasks. The system renders the patient's real-hand inside a virtual environment using a head-mounted display (HMD) for the patient to grasp and move virtual objects. In addition, this system is equipped with an assistive glove to help the patient extend their fingers during the grasp-and-release task. Using a joystick, a therapist can modify positions, orientations, and sizes of virtual objects in the virtual environment to best fit the patient's needs [33]. In another system for motor and cognitive rehabilitation [34], a musical game that employs AR to stimulate the memorization of colors and sounds was developed. The aim of the game is to follow a sequence of sounds and colors produced by the virtual objects that constitute a musical instrument. The game renders virtual cubes with different colors over a real-world scene captured by a Webcam. When the patient's hand overlaps one of these virtual cubes, the system plays the corresponding melody. In addition, the system allows the therapist to control, assign, and generate music melodies through its user interfaces.

The authors in [35] have developed a custom-designed (fully immersive) visualization tool called VR mirror. This tool allows the patient to relearn hand flexion/extension movement from their unaffected (healthy) hand movement with promising result [36]. The tool captures the movement of the healthy arm and then asks the patient to rehearse that movement through a constructed 3-D model presented by the custom display of the

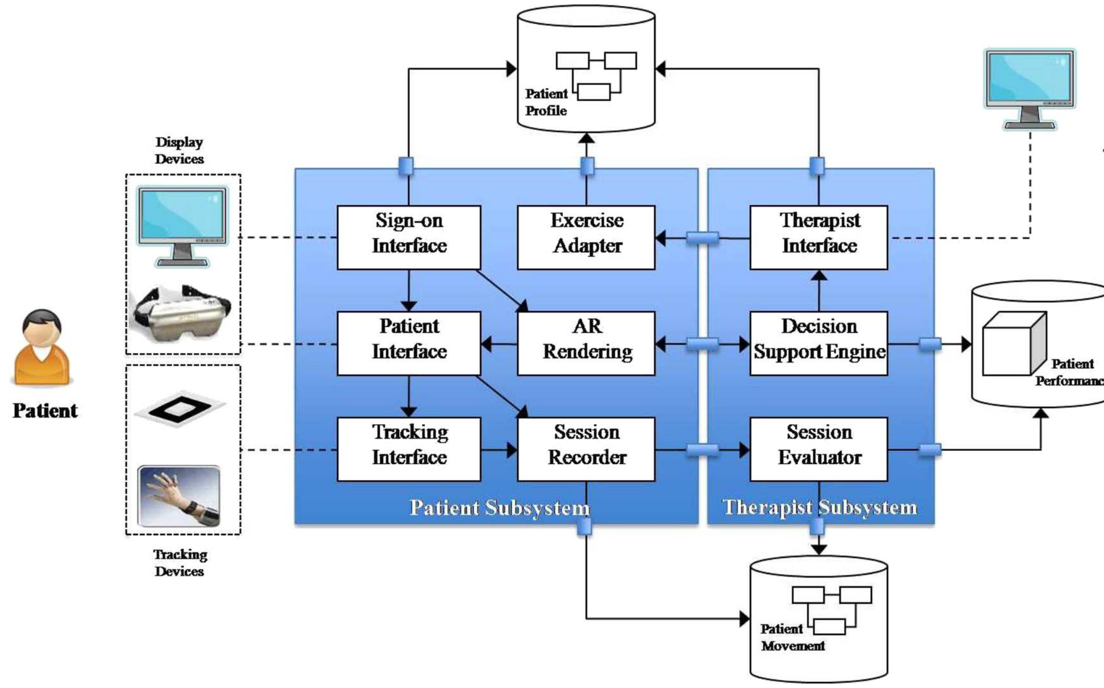


Fig. 1. AR-REHAB architecture as a subsystem view.

tool. Then, the patient moves her/his affected (impaired) arm using the imagery data she/he gathered through the rehearsal phase.

III. AR-REHAB Framework

Our proposed framework is called AR-REHAB. It provides a set of exercises developed using AR technologies and used for poststroke-patient rehabilitation of her/his hands and arms. In addition, it contains supportive components used to track and record the patient's hand movement. These data are analyzed by a component called `Session Evaluator` that is responsible for evaluating the patient's progress during the treatment. Later on in this paper, we will present the result of evaluating a subject's progress through the current implementation of this component. In this section, we will explain the underlying system architecture and technology used in implementing our framework.

A. Architecture

In a broader view, the AR-REHAB framework consists of two subsystems, a patient subsystem and a therapist subsystem, as shown in Fig. 1. The first subsystem is the `Patient Subsystem` which includes components that are mainly responsible for rendering the proper exercise for each patient registered in the framework. The subject/user must login into the framework using a `Sign` – on component that accesses the patient-profile database for verification. On successful login, the `Sign` – on module checks information from the patient's treatment plan (which is part of the patient-profile database) and feeds it to the `AR Rendering` component to formulate proper exercise for the patient. Basically, this information includes all type of exercises that the patient should undertake as well as the number of sessions she/he should perform for each exercise. Based on this information, the `AR Rendering` identifies the current status of the patient in her/his treatment plan and consequently loads a correct exercise session for him/her. After the right exercise is selected, the `AR Rendering` component constructs a virtual environment and augments it onto a captured real scene in front of the patient. The position and orientation of the virtual environment is set based on fiducial markers, the pose of which is calculated using AR technique. By doing this, the virtual objects seem to be on the real environment seamlessly.

The augmented scene is rendered to the patient by the `Patient Interface` component that is capable of rendering it through regular display or HMD. The rendered scene represents one of the four exercises currently in the framework. While the patients are performing their exercise, the `Tracking Interface` captures the hand movements and passes them to the `Session Recorder` that applies some filters before they are permanently stored in the Patient Movement database in order to reduce the amount of data. The `Exercise Adapter` component listens periodically to requests of changes sent by the `Therapist Interface` and modifies the patient profile or treatment plan according to these requests.

The second subsystem is the `Therapist subsystem` that consists of three different components. The `Session Evaluator` starts after the patients finish their session and extracts useful values for a predefined list of measurement factors and stores them as patient performance data [31]. Periodically, the `Decision Support Engine` checks the patient's performance and sends recommendation messages to the assistant therapists through the `Therapist Interface`, which in turn allows the therapists to update the patient's profiles and view performance results. In the following, we explain the mechanism adopted by our `AR Rending` components to produce the scene for the exercises explained before.

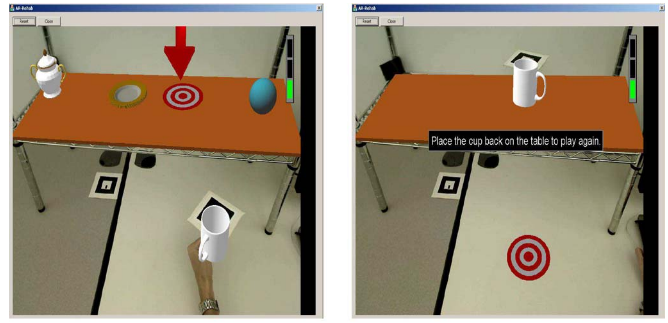
B. Implementation

Our framework is developed in C++ and is implemented based on a multithreading platform that allows concurrent execution of different processes that belong to different subsystems. The main AR Rendering mechanism is implemented using four APIs, ARToolKit [37], CHAI 3D [38], Open Dynamics Engine (ODE) [39], and VirtualHand SDK [40]. We used the ARToolkit API to capture video scenes and search for suspected marker pattern(s). A marker is a preidentified image label through which the ARToolkit can compute the pose information of the camera in relation to that marker and identify the 3-D pose (position and orientation) where a virtual object needs to be augmented. The pose of the tangible object is also obtained by using the ARToolKit to track the hand movement and assess the performance. The ARToolkit comes with a mechanism to render virtual objects using pure OpenGL command and Virtual Reality Modeling Language framework, but this is not sufficient in dynamically creating a variety of virtual environment for each exercise and hierarchically rendering complex virtual objects. Thus, we integrated CHAI 3D as a graphic manager and renderer. Basically, CHAI 3D manages a scene graph of the virtual environment and overlays the virtual environment onto the real scene using the computed marker pose. In addition, in order to create a responsive virtual environment, for example, game-like exercise, we used ODE that detects collisions between objects and computes responses. If preconfigured by the therapist, the VirtualHand SDK, from Immersion Inc., provides the pose of the hand through the CyberGlove. However, the default configuration for tracking in our framework is through the ARToolkit by tracking a marker attached to the real object that the user is grasping.

For extensibility and scalability purposes, we strictly followed the component-based development guidelines in the framework development [41]. Therefore, we encapsulated the AR rendering mechanism inside the AR Rendering component of the Patient Subsystem. In addition, we implemented our framework exercises as a higher application layer on top of this component. Thus, we simply need to extend this component in order to implement a new exercise in our framework, making it relatively easy to increase the pool of exercises in our framework.

IV. AR-REHAB EXERCISES

Exercises that are included in the current framework are mostly derived from daily life activities, e.g., handling a cup and moving it into a kitchen cupboard [42]. The framework includes five exercises in its current state of implementation: cup, shelf, cannonball, air-hockey, and block exercises. The exercises are divided into two categories: nongame-based (cup and shelf) and game-based (cannonball, air-hockey, and block) that have scenarios where the subject will play a game to finish the task of the exercise. In the game-based exercise, the patient will play against the computer and try to score the maximum goals, while in the other type, the patient will be asked to perform a simpler static scenario. In this paper, we will introduce only two static exercises to demonstrate how the framework works and will conduct a usability study.



(a) (b)

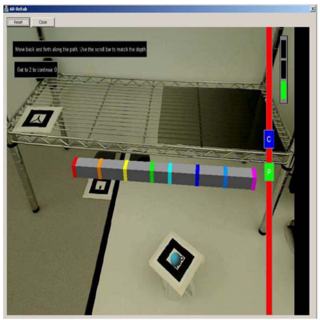
Fig. 2. Shelf exercise (a) The objects have been placed randomly, and it is waiting for the subject to place the cup on the shelf. Objects will begin to appear on the screen accompanied by a sound effect of chimes as if they are placed "magically" and within a visual-fading action. (b) The cup has been placed on the target, and the subject must now place it back on the table.

A. Shelf Exercise

The objective of the shelf exercise is to reenact the motion of placing and removing an object on a shelf through an AR environment with biofeedback (Fig. 2). This exercise consists of a desk, a one-layer shelf and a mug. In order to let the framework know where the shelf is, we put a fiducial marker on the left-front corner of the shelf. Since the structure of the shelf is known by measuring, we can locate the shelf easily. In addition, since the marker is directly on the desk, the framework can know the relative position of the desk with respect to the shelf. Based on the position of the shelf and the desk, the framework could render virtual objects on the shelf and the desk seamlessly, for example, a pot or a dish on the shelf, as shown in Fig. 2.

The pose of the mug is also tracked by attaching another marker on top of it. By doing this, the hand movements of the subjects can be monitored and recorded. In addition, there will be a virtual mug wrapping the real mug to allow the user to see the mug in front of virtual objects. This is because the real-life objects cannot be shown in front of virtual objects since the virtual objects are simply placed onto the camera feed. The scenario of the shelf exercise is as follows.

1) The shelf and the mug are the only virtual objects that are visible in the beginning, except for a traffic light that is always visible at the top-right corner of the screen. AR-REHAB uses the traffic light to let the subject know when the game is not ready or when it is about to begin. The traffic light will remain red until it recognizes the mug if the mug is not in the line of sight of the camera.
2) Once the camera recognizes the mug, the traffic light will turn yellow. After 5 s, the traffic light will turn green, and the game will begin.
3) AR-REHAB places objects randomly on the shelf. There are five virtual objects that can be placed on the shelf: a vase, a teapot, a ball, a stack of plates, and a fork. Only three from the five objects will begin to appear on the screen accompanied by a sound effect of chimes and within a visual-fading action while moving downwards as if being placed onto the shelf.
4) AR-REHAB displays a target with an arrow above the shelf. The arrow moves up and down to attract more



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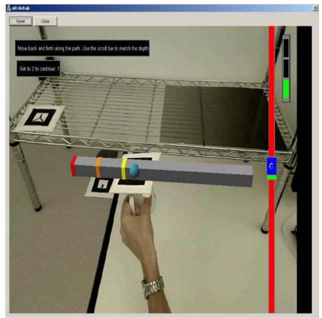

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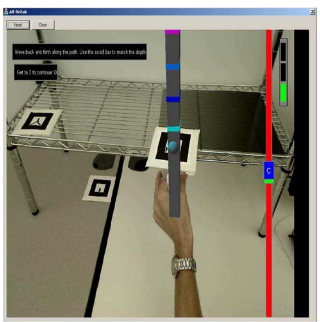

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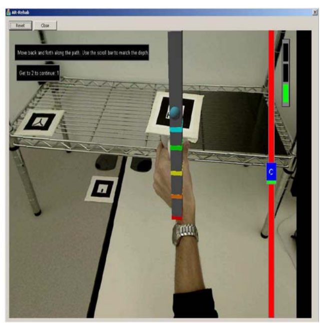

(d)

Fig. 3. Cup exercise (a) AR-REHAB first turns on once it has waited 5 s after seeing the mug. (b) Subject has already gone from left to right and is now on his way back. (c) Path has switched to vertical, and the user is halfway up the path starting from the bottom. (d) Subject has already gone from the bottom to the top and is now on his way back down.

attention and to insinuate that the cup needs to be placed there.

5) The subject should move the cup onto the target.
6) Once the subject does so, AR-REHAB plays a cheering sound effect and shows another target on the table.
7) A message will appear telling the patient to now place the cup back onto the table.
8) Once the subject does so, the traffic light will turn yellow, wait 5 s, and then turn green again.
9) AR-REHAB restarts the scenario again, with another random set of objects placed randomly on the shelf.
10) This will go for the current set amount of times, which is five, and then the AR-REHAB ends the exercise session.

The entire time of the exercise session is stored in a database as well as the time it takes to complete each reach movement in the exercise, the position of the cup and target during the whole exercise, the position of objects in the environment, and whether the cup have collided with any of them during the exercise session. At any time, the user can reset the game, which will begin a new recorded session; however, unless a game-over situation is reached, the number of remaining sessions in the treatment plan will not be reduced.

B. *Cup Exercise*

The objective of the cup exercise is to evaluate the subject's ability to follow a precise prescribed visual path. As shown in Fig. 3, the subject follow the same hand motions as in the shelf exercise; the difference here is that the motion is more precise to evaluate the subject's ability to visually guide her/his hand–arm movement. The only real objects for this exercise is the mug with two markers; one attached to the mug and the other is placed on the table to be able to calculate the proper space coordinates. The following is a typical interaction scenario that may occur between the subject and the framework during a one-time play of the cup exercise.

1) When AR-REHAB first loads the cup exercise, the traffic light will illustrate whether the camera can recognize the mug. Once it does, the traffic light will turn yellow and then green to indicate that the exercise scenario will begin.
2) AR-REHAB displays a vertical bar in the middle of the screen with a series of colored markers on it. In addition, it presents a label in the top-left corner which tells the subject that the goal is to move the mug back and forth along the path.
3) The subject must move along the visual path a small ball placed on the top of the mug. As a visual aid for interpreting depth, there is a scroll bar on the right-hand side of the screen. It has two markers that must be lined up to be at the appropriate depth on the path. One marker indicates the depth of the path and the other displays the depth of the cup.
4) In order to play the game, the subject starts from the left side of the path and must hit each colored marker on the path. Each time the subject hits a marker, the marker disappears and AR-REHAB plays a sound for that, which is an incremental C-scale. Each succeeding sound that it plays will be higher on the C-scale.
5) Once the subject reaches the other end of the path, AR-REHAB flashes the path and the markers will appear again.
6) The subject must now go back along the path from right to left and cause each marker to disappear again.
7) After the subject traverses back and forth the horizontal path, it will vanish and a vertical path will appear.
8) The subject traverses the vertical path, the same as with the horizontal path except that now, the subject must move up the path starting from the bottom.
9) After the subject does each path twice, a label will appear stating that the exercise session is finished.

As with the shelf exercise, our framework session recorder captures the time stamps, such as the time it takes to move along the paths, the position of the cup, and whether they collided with the path. In addition, it captures the position of the cup and the visual path at all times.

V. AR-REHAB Usability Study

In this section we present the result of a usability study we conducted on our framework. The objective of this study was to verify that our framework is a motivating tool for rehabilitation.

A. *Experiment Setup*

Fifteen subjects (average age of 30, age range from 22 to 37 years; 12 males and 3 females), who are all students at the University of Ottawa, took part in this experiment. All

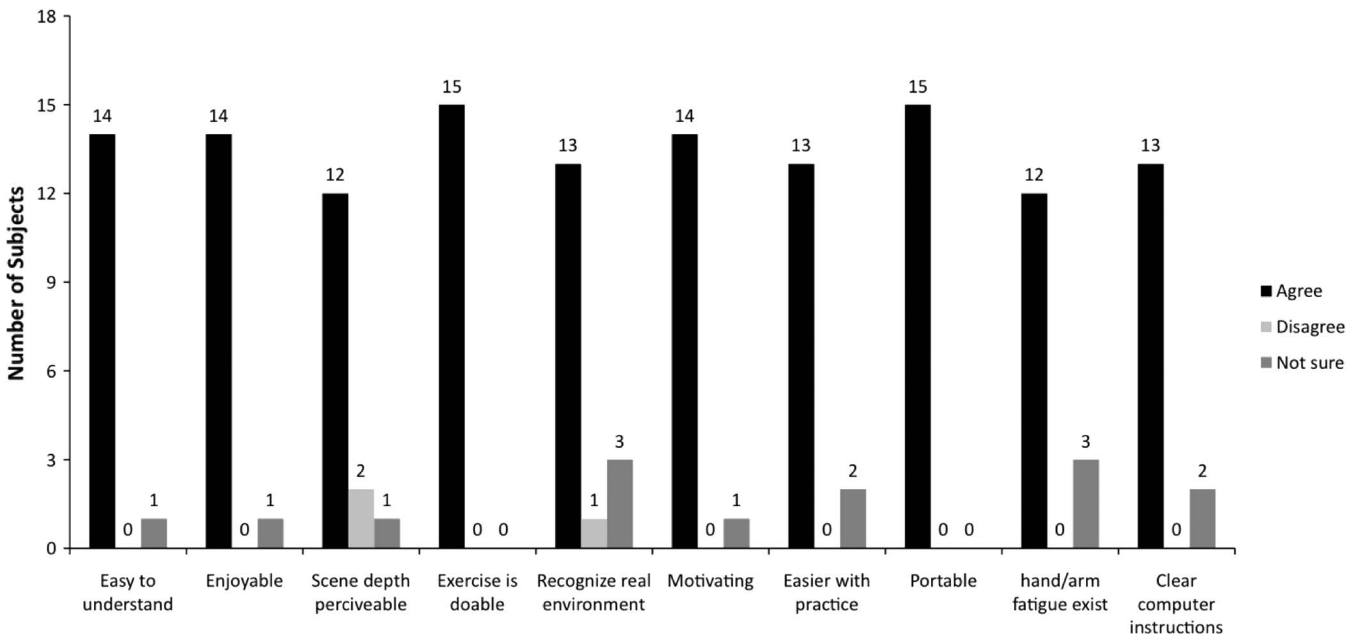

Fig. 4. Result of questionnaire analysis for the shelf exercise.

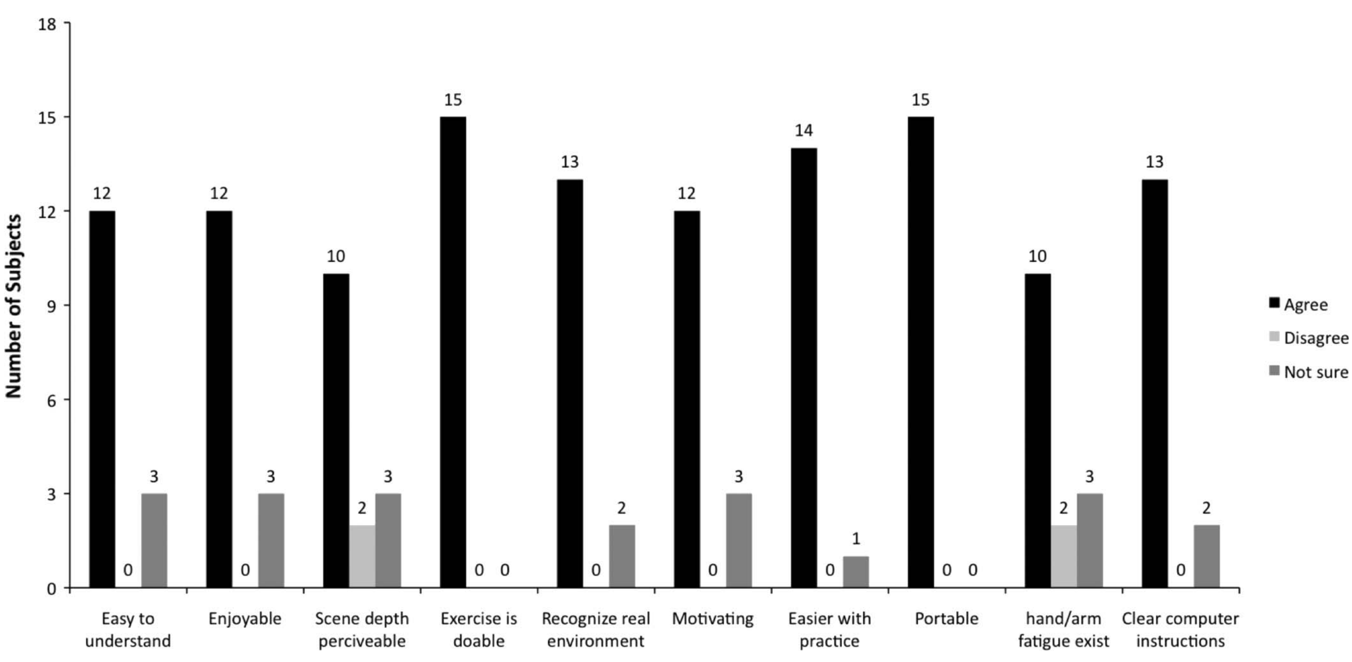

Fig. 5. Result of questionnaire analysis for the cup exercise.

the subjects have self-reported a normal or corrected-to-normal vision and a normal sense of touch. All the participants were right handed. To perform the test, a subject was asked to sit in front of a regular computer desk wearing an HMD and to grab a real mug. The HMD was iWear VR920 [43] that has a clip-on high-resolution camera called the iWear CamAR [44] from Vuzix Corporation. Every subject was tested one time for both exercises in which she/he undertook five consequent sessions of treatments per exercise. All the subjects were new to the designed framework and AR prior to the test. The subjects did not take part in any medical examination or review before participating in the test. We requested every subject to fill in a questionnaire designed for this purpose once she/he finishes the test. We described the questionnaire in Appendix A of this paper.

B. Result Discussion

We can clearly see from Fig. 4 for the shelf exercise and Fig. 5 for the cup exercise that most of the subjects were interested in the exercises. From the analysis of the questionnaire, we found that all the subjects were motivated to conduct the exercises. In addition, all the subjects perceived the environment as a real environment and not a virtual environment. Most of the subjects found that the computer instructions produced by the framework were useful and clear. Lastly, we noticed

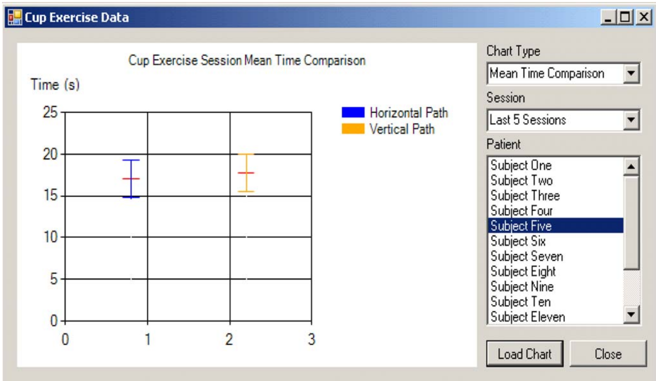

Fig. 6. Mean and standard deviation for horizontal and vertical movement times for the last five sessions of cup exercise for the fifth subject in the usability study.

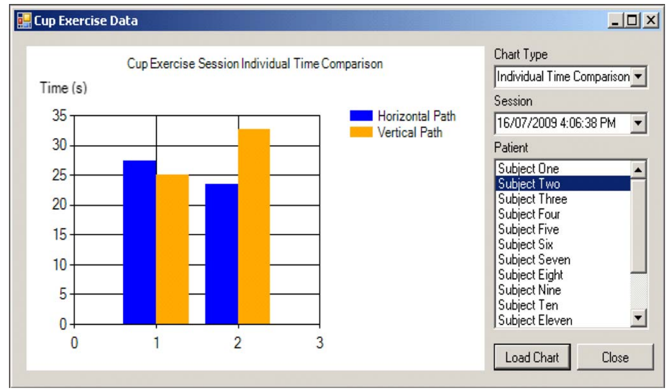

Fig. 7. Time-completion comparison of the cup exercise for the second subject (third session).

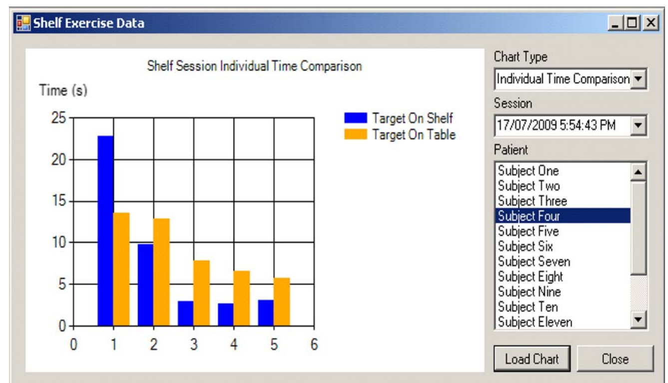

Fig. 8. Time-completion comparison of the shelf exercise for the fourth subject (second session).

that one subject was unable to comfortably perceive the depth information from the augmented video. Moreover, all subjects confirmed that such a framework is portable and can be used at homes and rehabilitation centers safely and easily.

Only one subject felt annoyed in performing the task of the shelf exercise because some trials in the sessions randomly requested him to move the mug to the left edge of the shelf where the subject could not easily reach. In addition, two subjects were not sure if the depth-perception aids provided in the cup exercise are enough to help subjects in performing such a scenario. The reason is that they were not intuitive enough, and they had to always check the sidebars. However, the difficulty in the depth perception was considerably overcome as all the subjects agreed that the exercise becomes easier by practicing.

In the shelf exercise, one subject complained of hand and arm fatigue, while others finished the task of the exercise without any noticeable fatigue. However, four subjects suffered from fatigue in the arm or hand in the cup exercise because the task requires the subject to lift the mug for a longer time compared with the shelf exercise. However, the weight of the tangible object can be easily replaced by any other objects based on the performance result and subjects' report.

VI. Time-Based Analysis for Cup and Shelf Exercises

A commonly used evaluation parameter by the therapists is the task-completion time (TCT). It measures the time it takes for the patient to successfully finish a specific task.

For the cup exercise, we compute the mean and standard deviation of the time taken to complete all the trials of horizontal movement and compare it with the mean and standard deviation of the time taken to complete all vertical movements. It helps to recognize possible difference with the subject's ability to move in horizontal and vertical movement. Moreover, we present them for the last 5, 10, and 20 sessions performed by the subject, so the therapist can see the history of the subject's performance. Fig. 6 shows the subject's five mean and standard deviation for horizontal and vertical time comparison of the last five sessions.

In addition, we compute the time taken by the patient to move her/his hand along the guiding axis (vertical/horizontal) for one complete trial by moving back and forth along the access. It allows a therapist to recognize possible significant drop or increase in the time, which may indicate fatigue or weakness in hand. Fig. 7 shows the time completion recorded for the second subject in his third session of the usability study.

In our framework, we also enabled the therapist not only to see the patient's performance within one session but also for multiple sessions. We compute the TCT value (as described earlier) and store it for each session and allow the therapist to see them for any number of sessions.

Similarly, in the shelf exercise, we compute the length of time needed by the subject to make a complete movement of the kitchen mug to the shelf after having all the virtual objects presented. In addition, we compute the time needed by the subject to move the mug back to the table. The framework allows the therapist to see a chart for every session with this information presented (Fig. 8). In addition, it captures the TCT value and computes the mean and standard deviation for every session and presents it to the therapist as a comparison between multiple sessions done by the same patient (Fig. 9).

VII. Conclusion and Future Work

In this paper, we have proposed an AR-REHAB framework that takes advantages of the VR-based and the real-world-based rehabilitation processes with an additional 2-D web camera and fiducial markers. We described the implementation and test

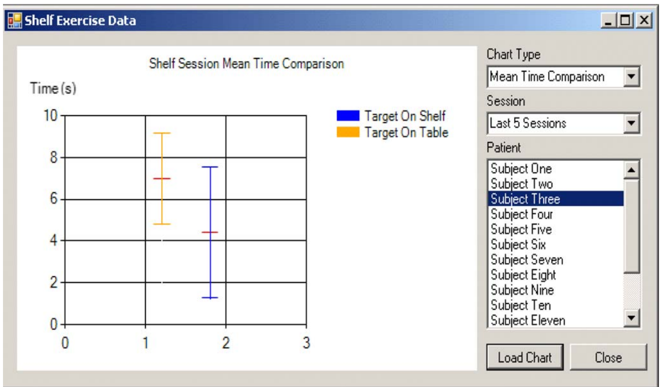

Fig. 9. Mean and standard deviation of last five sessions of the shelf exercise done by the third subject.

of two exercises, the shelf and the cup exercises. Motivating virtual objects are overlaid on top of the real scene so patients are efficiently encouraged to repeat boring and tedious rehabilitation procedures in a more pleasant way. The preliminary usability study has shown that these two key advantages are fulfilled quite well in the implemented framework. However, as some subjects pointed out, the occlusion problem that deteriorates the user's depth perception needs to be resolved in the AR research area, although overlaying a virtual object on the user's tangible object partially overcomes this issue.

With this framework, we could also measure some important performance factors that can be used to assess the progress of the patient's treatments. Since patients grab and move a tangible object to complete tasks and the position of the object could be measured in real-time through image processing, patients do not have to wear any extra hardware with difficulty. However, in order to read the finger angles that are also important parameters for assessment, we need to develop a vision-based finger-measurement system to avoid difficulties in wearing [45].

Appendix A
Questionnaire

In the usability study that we conducted, we evaluated the framework by literally asking the subject right away after the test. The subject scored every question of the following based on a numerical score where [1] represents that the subject strongly disagrees with what have been asked and [5] means that the subject strongly agrees on what been asked.

1. I have tried AR application or systems before this time.
2. I experienced a feeling of enjoyment or interest.
3. I can see and acceptably perceive the depth in the scene.
4. I was successful in performing the exercise task.
5. I recognized the real environment as part of the exercise setup.
6. The instructions given by the computer are clear.
7. I was motivated to complete successfully the task of the exercise.
8. The environment setup of the exercise is annoying.
9. I felt some arm/hand fatigue while doing the exercise.
10. I felt discomfort while doing the exercise.
11. Extra notes to report:

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