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Haptic Exercises for Measuring Improvement of Post-Stroke Rehabilitation Patients

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Abstract
Rehabilitation exercises supervised by Occupational Therapists (OTs), involve applying task-oriented forces to the injured/disabled area to regain, for instance, strength and range of motion. Haptic interfaces have shown clear benefits in imitating therapists' exercises with the possibilities of position, grasping angles and force capturing. In this paper, we present two haptic-based virtual reality exercises for stroke patients undergoing rehabilitation to recover all, or some, of their lost hand functions. The two exercises, the squeeze ball exercise and the maze exercise, were implemented using the CyberForce system. The squeeze ball exercise helps patients recover the action of hand grasping whereas the maze exercise aims at increasing the steadiness of the patient's movement. Our measurements of these exercises show that we can continuously evaluate the patient's improvement.

Keywords – Medical Instrumentation, Physical Rehabilitation Systems, Haptic Application in Medical Systems, Medical Virtual Environments.

I. INTRODUCTION

While the number of patients who need rehabilitation has increased in recent years, available resources have unfortunately reduced [1]. Reducing the duration of therapy and the lack of timely interventions can lead to permanent disabilities in many reversible or treatable cases [2]. Stroke patients are typically seen for one or two half hour sessions per day. This is a hardly enough time for a patient to recover, especially when that is reduced to once or twice a week if the patient is seen as an outpatient. The time elapsed from admission to discharge is around 42 days. For instance, at the Ottawa General Hospital, the average length of a rehabilitation session for a patient runs for about an hour. This number is double that of the average session length in a US private healthcare facility [19].

Inherently, rehabilitation is a repetitive process. However, repetition by nature can be fatiguing and causes the wearing down of the patient's mind and reduces his/her motivation. Also, traditional rehabilitation is expensive since it is a one-to-one process; for each patient there is one therapist that is working with him/her [3]. Finding a close therapy center may sometimes be difficult, especially for patients living in non-urban areas. The increasing number of patients seen by each OT can also delay the start of the therapy and results in shorter sessions. On the other hand, if a part of the patient's therapy is done at home or away from the therapy center, there is no way to monitor the patient's progression of recovery.

Integrating haptic technology with Virtual Reality (VR) composes a virtual rehabilitation tool through which new motor skills can be acquired. By adding the sense of touch and force feedback, haptic devices has introduced a new dimension in human-computer interaction, which is essential in the case of skillful tasks related to basic motor functions.

In virtual rehabilitation, a haptic device can be used for multiple VR rehabilitation exercises that are targeted to treat patients suffering from a variety of diseases. VR-based rehabilitation provides a patient, at all times, with the required intensive exercises that are repetitive in nature, which is necessary for recovery. Moreover, such VR-based rehabilitation systems enable therapists to analyze the patient's behavior data that will help them in devising better solutions and rehabilitation schemes depending on the patient's personal preferences and needs. It also provides OTs with enough material to derive characterizing patterns for certain groups of patients; that might open the door to new hypothesis in rehabilitation. Finally, engaging a patient in haptic-based VR exercises will maintain the motivation necessary to complete the repetitive exercises on a daily basis with the same level of enthusiasm while producing consistent data that will materialize into highly accurate analysis and help in the help measurement of the patient's overall progress. This is in addition to the instant feedback that will help OTs in designing and instrumenting therapy applications that are unique for each patient [4].

In this work, we show the suitability of the haptic-virtual reality based systems for rehabilitation by developing two exercises for post-stroke patients. The proposed exercises provide the patient with the means to train his/her stroke-afflicted hand while providing continuous measurement and evaluation of data that can be used to analyze the interaction between the patient and the environment during the exercise. The resulting evaluation will help a therapist to detect crucial signs about the patient's status and provide him/her with in-depth information and minute details about the hand; for instance, a problem with bending a certain finger. We also present our evaluation methodology and preliminary measured results.

The remainder of this paper is organized as follows: section II discusses related work in the field. In section III, we describe the developed exercises and their envisioned contributions towards facilitating the OT task. Section IV presents and discusses the performance results derived from experimentation with 5 subjects. Finally, in section V, we summarize the paper contents and present our immediate future work.

II. RELATED WORK

For many years, VR technology has proven its ability as an engaging and adaptive tool for interaction with computers. Furthermore, it provides an interactive environment where a subject can practice repetitively [5]. It supplies an interface to the real world and a more realistic environment, which can be seen as an extension of the current computer imagery technology. This synthetic image system supports a VR application to recreate an essential scenario for rehabilitation activities. VR offers the potential to create systematic human testing, training and treatment environments that allow the precise control of complex dynamic 3D stimulus presentations, behavioral tracking, performance measurement, data recording, and analysis.

Therefore, VR enables therapist to create new virtual exercises, presents a customizable variety of stimuli, and measures the performance and analyzes the data collected from the patient [6]. Eventually, a therapist can use VR as an instrument for assessment and rehabilitation of brain injury disabilities resulting from stroke: Parkinson’s disease, acquired brain injury, or muscular sclerosis. For instance, VR has been used extensively in the assessment and rehabilitation of psychological disorders, and has resulted in satisfactory performance [7].

At the same time, a cutting-edge technology, called haptic technology, has been recently employed in many VR applications. Haptic, which is derived from the Greek verb “haptesthai” meaning “to touch”, refers to the science of touch and force feedback in human-computer interaction. The evolution of haptic devices emphasizes that these devices are getting cheaper, more flexible, and more compact in size. This enables the opportunity to build more practical haptic-based applications and empower current ones with this type of interaction. Virtual environments can be strongly linked with haptic-based systems, because they require the visual sensory channel to produce more realistic sensations; namely, tactile and touch sensations.

It has been shown that haptic devices can continue to improve a stroke patients’ recovery [8, 9, 10]. Some research has been done on haptic-based rehabilitation of certain body parts for stroke patients, such as the hand [4, 8, 11, 12], arm [13] and ankle [10]. Mostly, the exercises for hand rehabilitation consisted of a series of game-like tasks to address certain parameters of hand movement. For instance, fine and gross motor skills, range of movement, speed, finger fractionation and grip force were measured to assess patients’ performance.

Unlike other exercises – such as those investigated in [4, 8, 11], our exercises have been designed based on well established and common exercises such as the Jebsen Test of Hand Function [14] and the Box and Block test [15]. These tests were designed to assess hand functions used in daily activities and address all the parameters mentioned earlier in this section. Moreover, OTs have been using these tests for a long time. Two exercises based on these tests have already been addressed in [12]. The first exercise consisted of a user moving a cup along the x or y-axis, and the second exercise consisted of a user arranging cubes according to their surface color. The two exercises described and analyzed in this paper, along with the previous ones, can be combined to measure hand deficits and suggest improvements.

III. THE EXERCISES

To develop the two haptic-based exercises, we have used our previously designed instrumentation framework that includes two basic exercises: the cup and cubes exercises described in [12, 16]. The framework consists of four components: a sensory component that is embedded within the haptic and visual interfaces, a haptic/software simulation component that is responsible for rendering the haptic/graphic scenes, an application component, and a haptic/behavioral data component acting as a haptic data repository.

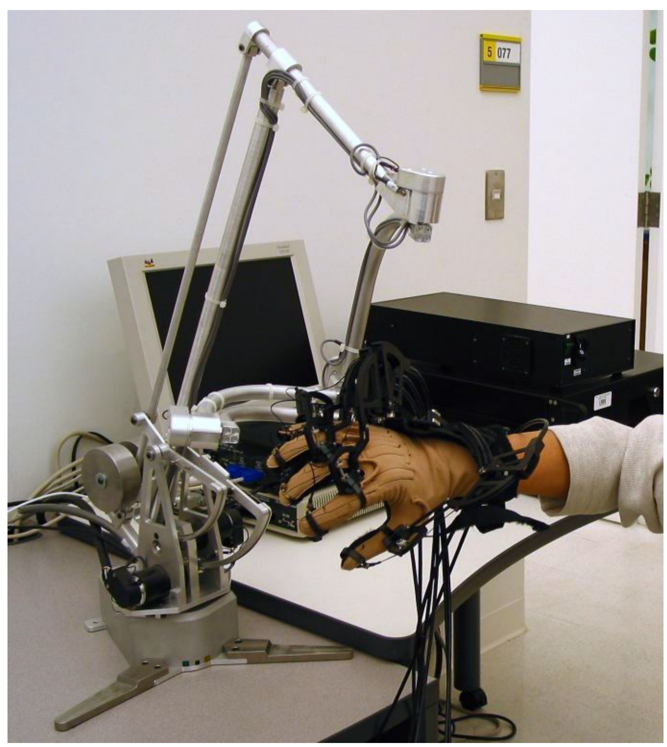

Fig. 1: Immersion’s CyberForce® System

The haptic interface used for the two exercises is the CyberForce system [17], developed and marketed by the

Immersion Corporation (see Figure 1). The CyberForce station consists of three pieces of hardware: the CyberGlove, CyberGrasp and the CyberForce armature. The CyberGlove is equipped with sensors to read spatial coordinates of individual fingers to construct the human hand avatar in the virtual environment. The CyberGrasp provides force feedback to the fingers using actuators. The CyberForce is a robotic armature that locates the position of the hand in space and simulates inertia.

The exercises have been designed to measure certain abilities of the subject. The simplicity of the exercises is critically important to help the stroke patient recover hand function abilities through an easy-to-do task. The exercises are diverse enough to allow for a combination of tasks that can be appointed by an OT according to each patient's case.

As shown in Figure 2, the first exercise uses a squeezable ball where the subject is asked to grip the ball according to a predefined pattern of locations and repetitions. The virtual squeezing ball consists of a virtual elastic ball that the patient grasps with a virtual hand, which is designed to strengthen the patient's finger flexion movement. The exercise difficulty is adapted by controlling the stiffness and elasticity of the virtual ball. Initially, the ball is configured to be very soft and easy for the subject to squeeze. The ball is located in the virtual environment in the middle of a triangle so the subject can locate it easily. The second exercise is a virtual maze solving process where the subject handles a stick to navigate through the maze's paths to reach the end. As shown in Figure 3, the subject sees a maze and a stick with a thin cylindrical shaped handle. In addition to grabbing the stick, the main task here is to navigate the maze using the stick. This exercise's main function is to improve the steadiness of the hand while performing a task, which also requires some concentration to avoid collision with the walls.

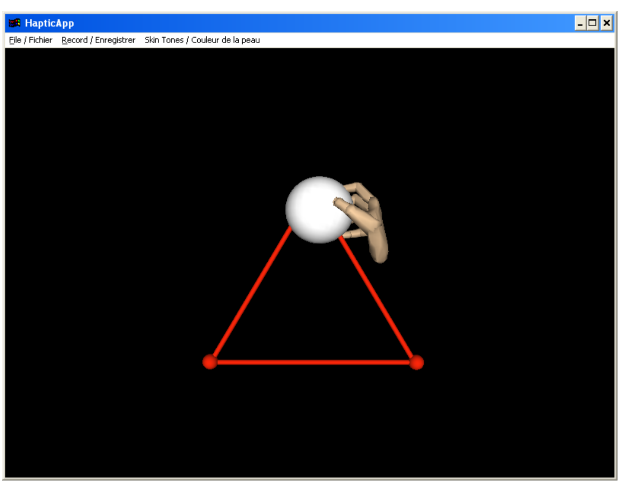

Fig. 2: The squeeze ball exercise

The data recorded throughout the exercises provide information about the X (width), Y (length), and Z (depth) position of the hand on the screen, the proximal angle (middle phalange) made by each finger, and lastly, the time elapsed during the course of the exercise. More information was extracted from this set of raw data: velocity along each of the X, Y, and Z-axis; overall distance covered across each axis; and the idle time for each finger during an exercise.

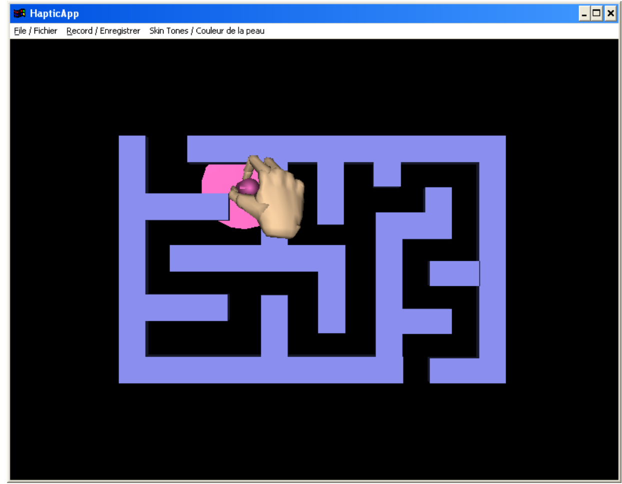

Fig. 3: The maze exercise

IV. ANALYSIS AND FINDINGS

This section presents a quantitative evaluation of the two proposed exercises. We were mainly interested in measuring the range of finger motion, the gripping patterns, and the task completion times. Five healthy subjects participated in the evaluation process and all the results are obtained from averaged trials.

A. The Squeeze Ball Exercise

The subjects were asked to complete the task of squeezing a virtual ball 25 times. The Task Completion Time (TCT) for every subject was recorded. We were also interested in evaluating the degree of recovery of the hand and fingers by measuring the average of fingers bending. The finger bending is defined, as described in [18], as the summation of the proximal joint angle and the distal joint angle, and is called the grasping angle (θ). Figure 4 shows the grasping angle (θ) as a function of time for the five subjects. This diagram shows that by performing intra-personal analysis we can quantitatively define the grasping characteristics (patterns) for individual users, and consequently use them as reference to see if any progress has been made. Also, we can derive an average 'healthy' grasping pattern and use it as a reference measurement to judge if a patient has completely recovered.

To find out the threshold of normal grasping angles per healthy subject, we have computed the average of the 25 maximum bending angles. The average and standard deviation of the grasping angle for each subject are plotted in Figure 5. This information helps in identifying the intra-personal grasping angle and thus acts as an indication of the patient's progress to achieve healthy grasping. Furthermore, the time for completing the task can be used to check if the patient can perform the task in reasonable time. Table 1 shows the TCT for the five subjects. Therefore, the grasping angle and the TCT of a task can be used to quantitatively measure the patient's performance.

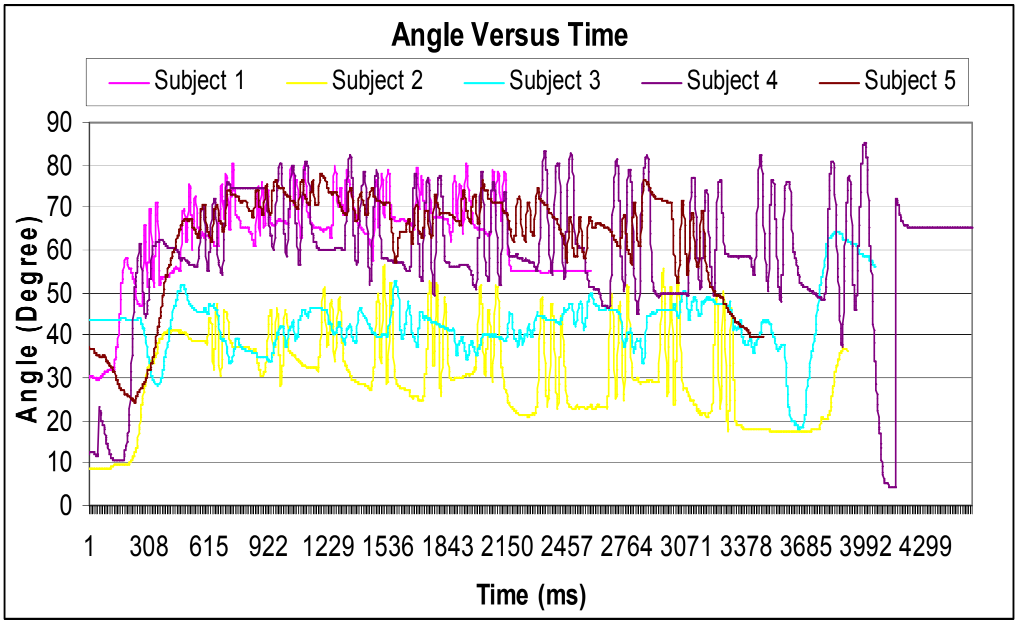

Fig. 4: The grasping angle as function of time

B. The Maze Exercise

The main objective of this exercise is to improve the steadiness of the patients' hand movements. The subjects were asked to hold a stick and navigate the maze by moving the stick from the entry to the exit without colliding with the maze walls. We measured the TCT as the time interval from entering the maze until the user reaches the end point. Another good indication of how well the subject was able to solve the maze is the number of collisions (errors) s/he makes with the maze walls. This is shown in Table 1. Figure 6 shows the TCT and the number of collision made by every subject after completing the maze task. This information (TCT and number of collisions) help in quantitatively describe the patient's steadiness and speed by setting up thresholds after which the user's activity is considered 'normal'.

Table 1. The task completion time for the 5 subjects

Subjects	Task Completion Time (Sec)
Subject 1	19.90
Subject 2	29.59
Subject 3	29.89
Subject 4	39.06
Subject 5	28.17

We have also determined the deviation between the path followed by the subjects and the optimal reference one (the path that passes through the middle of the maze tunnels). This deviation error is calculated as the absolute value of the difference in the xy-plane between the stick trajectory and the reference path. Notice that whenever this error exceeds a specific threshold (half the tunnel width in the xy-plane, 0.3 in our case), a collision will be detected.

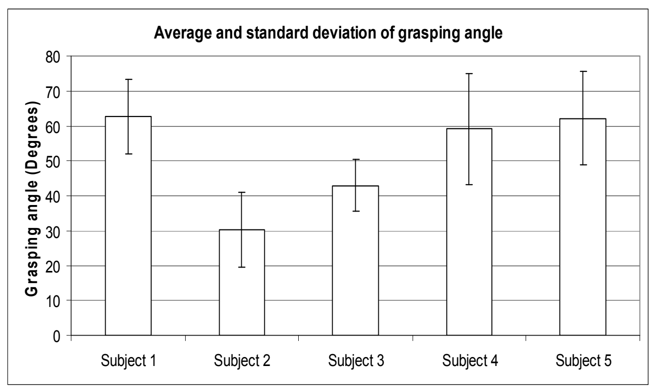

Fig. 5: The average and standard deviation of the grasping angle

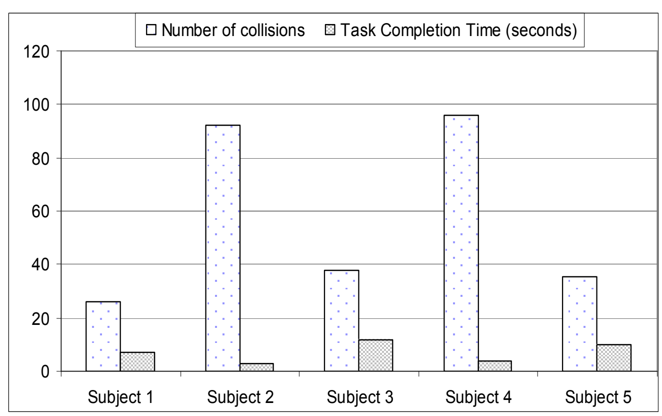

Fig. 6: The TCT and the number of collisions per subject

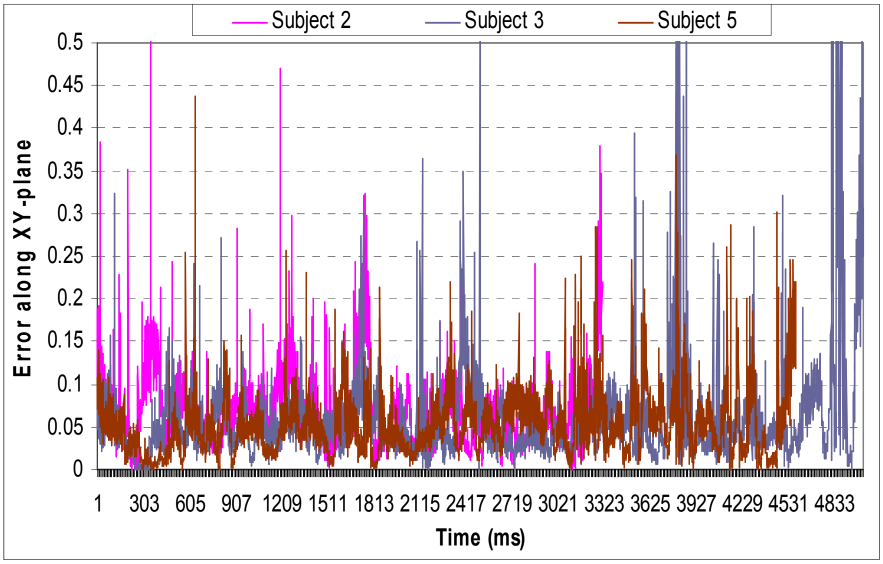

Fig. 7: Error functions along the XY-plane versus time

Figure 7 shows the deviation of the subject's hand from the reference path as function of time (subjects 2, 3, and 5 are plotted as sample patterns). This graph can easily track the patient's hand movement and quantize the steadiness of each patient, for instance by measuring the average and standard deviation of each user's performance. Optimally, if the standard deviation is very small, the patient has a steady hand movement. Again, a threshold for what a normal hand movement can be estimated and eventually acts as a reference measurement to measure the steadiness of the patients hand movement.

V. CONCLUSIONS & FUTURE WORK

In this paper, we proposed two haptic-based virtual reality exercises for stroke patient rehabilitation. The designed exercises provide users/patients with many clear benefits such as providing a wider choice of objects (shapes and sizes), types of exercises (vertical, horizontal, and patterned motion), and manner of testing (repetitiveness and severity of exercises).

As per future work, we will be performing an in depth analysis of the designed exercises to define quantitative thresholds for evaluating the patient's level of recovery. For instance, we are planning to perform intra-personal and inter-personal analysis to compute a reference grasping angle (θ_{ref}) that defines how much finger bending characterizes 'normal' grasping. We believe that (θ_{ref}) will be a function of the geometrical and physical properties of the grasped object. Another problem that we are faced with is the CyberForce device itself; in many cases, the collision detection approximation yields unrealistic haptic interactions or more severe instabilities in the device. Finally, we are planning to test our exercises with real patients from the Ottawa General Hospital. This requires improving the settings to make the apparatus less bulky and more comfortable for patients to use.

Another important trend we are investigating is to build a Decision Support Engine (DSE) for the designed experiments. The DSE will be responsible for reading different data captured by the session recorder and drawing conclusions or recommendations regarding the progress of the patient based on intelligent algorithms, and possibly adapting the application based on the patient's progress.

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