Haptic Virtual Rehabilitation Exercises for Poststroke Diagnosis

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***Abstract*—Nowadays, stroke is one of the most frequent causes of severe adult disability in the world. Virtual reality and haptic technologies have emerged as promising assistive tools for effective diagnosis and rehabilitation intervention. The objective of this paper is to develop and test a set of five virtual exercises on top of a framework, which is designed for the diagnosis and rehabilitation of patients with hand impairments. We have implemented task-oriented exercises based on well-established and common exercises, namely the Jebsen Test of Hand Function and the Box and Block Test. These include moving a cup, arranging blocks, navigating a maze, training with a dumbbell, and grasping a rubber ball. Furthermore, key performance measures (metrics) are proposed for each exercise to quantitatively evaluate and judge the performance of stroke patients. Our evaluation of these exercises shows promising potential to define "golden" reference metrics for healthy subjects, against which the performance of a patient is compared. This will facilitate the ability of occupational therapists to assess the patient's progress.**

***Index Terms*—Haptic applications, medical instrumentation and measurement, occupational therapy, stroke rehabilitation, virtual reality (VR).**

I. INTRODUCTION

STROKE is a primary cause of adult disability in the world nowadays and is anticipated to remain a leading problem in the years to come [1]. In addition, stroke is the third leading cause of death in developing countries, and studies aim at an increasing of this neurological injury, particularly in such countries [2]. According to the National Stroke Association [3], nearly 5 million people in the United States today have survived a stroke, and around 700 000 Americans have a new or repetitive stroke each year. The aging of the population and its negative impact on disabilities have led to an expected rise in the number of patients that will need rehabilitation in the coming years; as a consequence, available resources have unfortunately reduced [4].

According to Ottawa General Hospital, stroke patients are typically seen for one or two half-hour sessions per day, which is hardly enough time for a patient to recover, particularly when this is decreased to once or twice a week if the patient is seen as an outpatient. The reduction in the duration of rehabilitation and the lack of timely interventions can lead to permanent disabilities in certain cases of treatable or reversible conditions [5]. On the other hand, the effectiveness of intensity and repetitive exercises also has a significant impact on the patients' recovery. In one of the first works, Langhorne *et al.* studied the effects of changing levels of therapy intensity with approximately 600 patients [6]. The results showed that a more intensive physical therapy leads to greater improvements.

Virtual reality (VR) technology is increasingly playing an important role in many areas. This technology allows users to interact with computer-simulated environments, and although it has traditionally been focused on game and entertainment applications, recently, it has been extended to other fields. In addition to VR systems that provide 3-D virtual environments within which the user can navigate, haptic devices enhance the level of user interactivity experienced in such environments and improve task performance [7].

Beyond the traditional therapies, the main advantages of VR-based rehabilitation or virtual rehabilitation were highlighted in [8], e.g., repetition, feedback about performance, and motivation. Repetition causes the decoupling of the patient's mind and reduces his/her motivation, so patients must be motivated. The use of game-based features into virtual environments has been reported to enhance motivation during therapy [9], [10]. Moreover, auditory and performance feedback can help patients be motivated [11]. Whereas virtual rehabilitation continues to develop, recent studies with stroke patients have proved how VR can positively contribute in the neural organization and recovery of functional motor skills [12], [13].

Haptic, a term that was derived from the Greek verb "haptesthai," meaning "to touch," adds the sense of touch and force feedback in human–computer interaction. Haptic-based systems enable a user to manipulate objects in virtual environments in a natural and effective way and can provide information which cannot be completely described with visual or audio feedback, such as stiffness, texture, or weight of objects.

In occupational therapy, the aim is to help people with disabilities improve their ability to perform tasks in their daily living and working environments. By helping patients improve their basic motor functions and devising abilities to compensate for permanent losses of function, patients can achieve independence and a better quality of life. Due to the force feedback provided by haptic devices, haptic-virtual-based systems are well suited for simulating user interactions related to basic motor functions [14]. In addition to the advantages of virtual rehabilitation, adding force feedback information within a

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virtual environment helps to objectively measure performance and to tailor performance-based exercises for each patient. This potential to assess the patient's performance, by measuring different parameters, which cannot be evaluated in traditional rehabilitation, can be of benefit to both patients and occupational therapists (OTs).

In 1998, Burns *et al.* defined tele-rehabilitation as "the use of telecommunications technology to provide rehabilitation and long-term support to people with disabilities" [15]. This includes the possibility of building new home-based systems where users can carry out physical exercises at home, without going every day to the clinic, and training as many times as they wish. In such situations, data about the patient's performance should be monitored for the OT's evaluation, and, in that way, conclusions or appropriate modification of the exercise difficulty based on the patient's progress should be reported.

In this paper, we present the results of testing five virtual hand exercises with ten healthy subjects from the University of Ottawa. These virtual exercises have been designed based on well-established tests, which are frequently and commonly used by OTs for evaluating hand disability and recovery after training. In particular, the purpose of this paper is to define key performance measures (metrics) for these virtual exercises to quantitatively assess a stroke patient's recovery. This will contribute as a further step toward the tele-rehabilitation and evaluation of the patient's progress over a long distance.

The remainder of this paper is structured as follows. In Section II, we review related work in the field of haptic virtual rehabilitation and highlight how our work is differentiated from others. Section III introduces the designed framework and its software architecture. The five task-oriented exercises are described in Section IV. Section V elaborates the quantitative diagnosis analysis to evaluate the patient's state using the recorded haptic data. Finally, we conclude by summarizing our findings and suggesting recommendations for future development.

II. RELATED WORK

In recent years, much research that involves VR and haptic devices has been addressed in medical rehabilitation and tele-rehabilitation. For instance, VR has been extensively used in the assessment and rehabilitation of brain injury disabilities, such as cognitive abilities [16] or motor rehabilitation [8]. These disabilities can be resulting from stroke, Parkinson's disease, acquired brain injury, muscular sclerosis, and/or paraplegia. In the area of psychological disorders, VR has also been applied as a treatment for overcoming agoraphobia, acrophobia, and fear of flying, as well as for obese patients [17].

In the case of haptic virtual rehabilitation for stroke patients, some research has been done on the rehabilitation of upper and lower extremities, such as the hand [9], [18]–[22], arm [20], or ankle [23]. These haptic virtual systems help patients with upper or lower extremity weakness to relearn perceptual and physical daily activity actions. Furthermore, different studies on haptic virtual rehabilitation have shown its potential to continue to improve recovery after stroke [9], [23].

Often, the virtual exercises for hand rehabilitation consisted of a series of game-like tasks to address certain parameters of hand movement [5], [9], [18], [19], [24]. Moreover, one of these works has studied how VR training transferred to real-world activities by using the Jebsen Test of Hand Function (JTHF) [24]. Unlike these exercises, our tests have been designed based on well-established and common exercises, such as the JTHF [25] and the Box and Block Test (BBT) [26]. The JTHF was developed by Jebsen *et al.* in 1969 and has been continuously used by OTs. This test consists of seven items and was designed to provide a test for evaluating disability and improvement after the training of hand performance used in tasks of daily living.

In this paper, four of the five developed exercises are based on the JTHF and have been collaboratively designed with OTs at Ottawa General Hospital. These exercises are handling a cup, navigating a maze, squeezing a ball, and exercising with a dumbbell. In haptic virtual rehabilitation, some authors have designed a virtual Purdue pegboard exercise to evaluate the manual dexterity in stroke patients [5], [18]. However, this test may have a limited application in acute stroke patients. A simple and traditional test, such as the BBT, is also being used by OTs as a test of manual dexterity. The fifth exercise is "arranging blocks" and is based on this test.

To date, there exists little knowledge about the role of haptic virtual rehabilitation in the assessment of patients. In 2001, a preliminary study with 13 patients suffering from various forms of neurological diseases and three healthy subjects was carried out for upper limb motion analysis [27]. The subjects were asked to navigate a virtual maze by moving a virtual ball attached to the haptic device, and when a collision between the ball and the wall occurred, they received collision force feedback. The results suggested that the proposed haptic virtual system was a potential tool for the objective assessment of upper limb movement deficits, for instance, tremor, movement control, and speed when navigating the maze. In a later research, a simple task was tested for indicating the potential of haptic virtual environments as an assessment method [28]. This task consisted of moving the haptic device from a position to nine other locations. The performance was evaluated by measuring the task completion time (TCT), speed, intertarget distance, and trajectory distance. The averaged measures obtained from seven healthy subjects were used as a reference to assess the results of three patients.

In case of fingers and hand rehabilitation, Jack *et al.* exercised and measured four parameters of hand movement, i.e., range of motion (i.e., finger flexion and extension), speed of motion, fractionation (i.e., a finger flexion while the others are kept open), and strength during a two-week test [9]. In particular, they were focused on measuring motor parameters to show motor recovery during the therapy. However, if VR is planned to be used for remote diagnosis and treatment according to the results, the measured parameters must be consistent, compelling, and clinically meaningful. We present a quantitative study with healthy subjects where different hand and finger parameters were captured and analyzed to define normative measures. The analysis carried out has the potential to be used as a diagnosis tool for OTs.

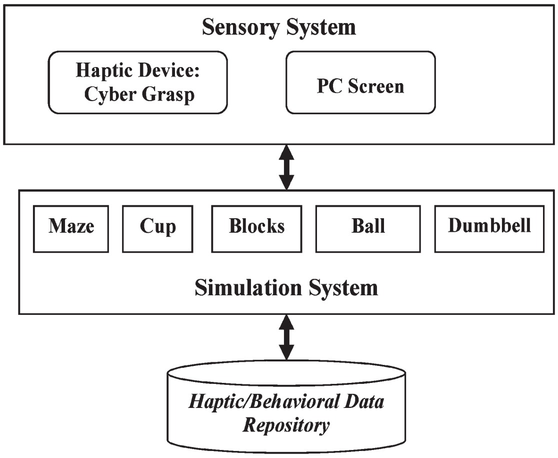

Fig. 1. Proposed framework.

III. SYSTEM COMPONENTS

To develop the five haptic-based exercises, we have designed and implemented a framework that comprises three components, i.e., the sensory system, the simulation system, and the haptic/behavioral data repository (Fig. 1).

The haptic and visual interfaces are embedded within the sensory system. The haptic device used for all the exercises is the CyberGrasp system [29]. This device consists of three pieces of hardware, i.e., the CyberGlove, the CyberGrasp, and the CyberForce armature. The CyberGlove is equipped with sensors to read palm position and the spatial coordinates of individual fingers to construct a realistic avatar of the hand in the virtual environment. The CyberGrasp provides force feedback to the fingers via actuators, whereas the CyberForce is a robotic armature that locates the position of the hand in space and simulates inertia.

The simulation system is responsible for simulating the complex calculations involved in the haptic rendering process loop, maintaining synchronization with graphic rendering and recording haptic behavioral data for further analysis. Likewise, loading and rendering the different exercises are managed by the simulation system.

The haptic/behavioral data repository acts as a collector for the data captured during each subject's exercise session. Data recorded throughout the exercises provide information about the position of the hand on the screen, the angles of the three phalanges, and, finally, a time stamping of the sampled data.

IV. EXERCISE DESCRIPTION

These exercises have been designed to test certain abilities of an individual and include handling a cup, arranging blocks by color, navigating a maze, squeezing a ball, and performing dumbbell training.

The rehabilitation exercises, supervised by OTs, involve applying task-oriented forces to the injured/disabled area to regain its strength and range of motion. On the other hand, it is critically important to help the stroke patient recover hand function abilities through not only easy-to-do but also diverse tasks. The proposed exercises are diverse enough to support a combination of tasks that can be defined by OTs according to each patient's case (with the ability to change task parameters, such as weight, feedback forces, and object geometry).

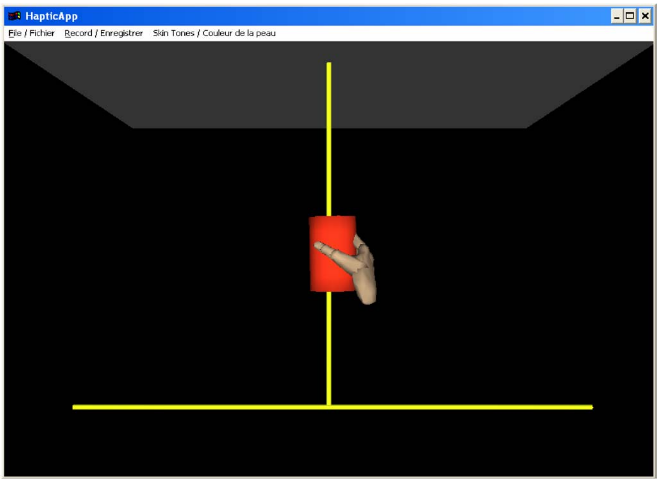

Fig. 2. Handling a cup.

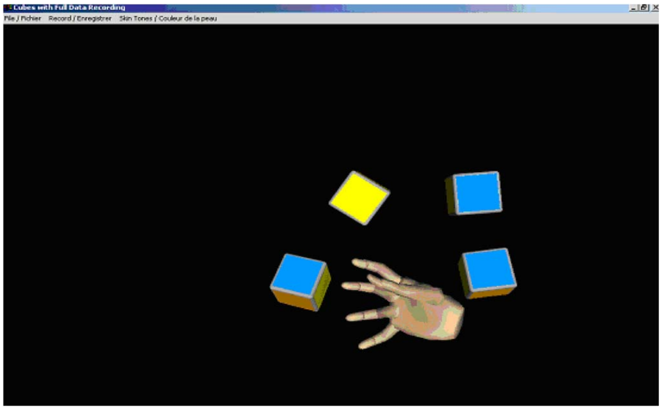

Fig. 3. Arranging blocks.

A. Handling a Cup

This exercise involves handling a virtual cylindrical cup across the virtual space (Fig. 2).

The subject has a view of a cylindrical cup and a virtual hand, which corresponds to his/her hand using the CyberGlove. The user can reach the cup and then grab it. A virtual touchable ceiling has also been added to the scene to limit the subject's hand movement.

B. Arranging Blocks

This is the most difficult exercise to perform. It involves four blocks with each face differently colored (Fig. 3). The four blocks are randomly placed on the right so that the user can practice grasping objects and moving them to the left side.

This exercise tests the subject's perception of patterns and also the dexterity and strength of the hand to grab, move, and arrange the blocks.

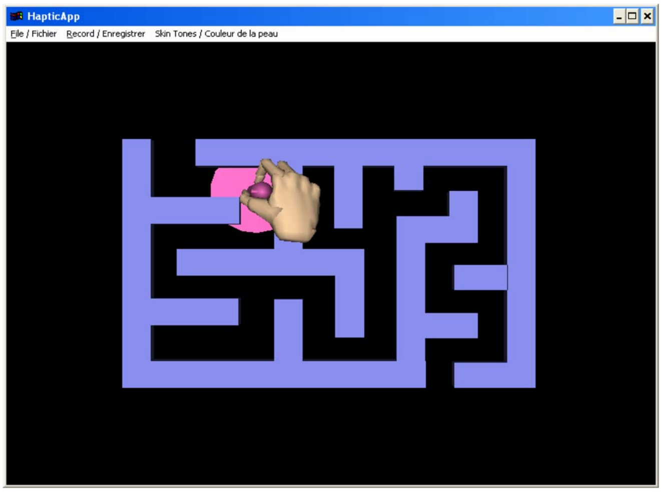

Fig. 4. Navigating a maze.

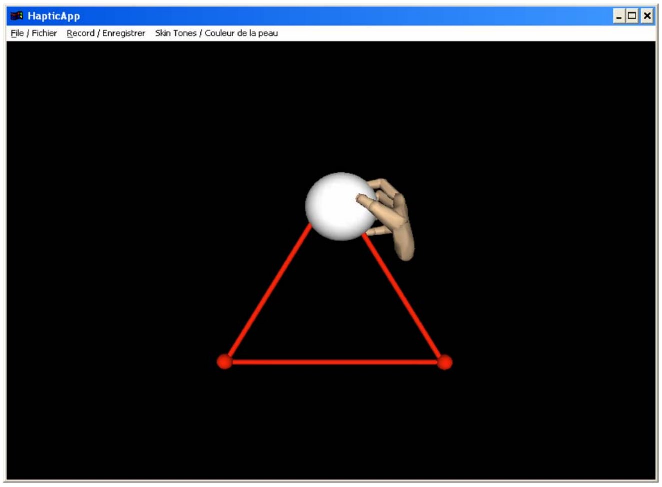

Fig. 5. Handling a stress or soft ball.

C. *Navigating a Maze*

As shown in Fig. 4, a subject sees a maze and a stick with a thin cylindrical-shaped handle. Although there is the task of grabbing the stick, the main task here is to navigate the maze using the stick through the maze's paths to reach the end. The objective of this exercise is to improve the steadiness of the hand movement while performing a task, which also requires eye–hand coordination to avoid colliding with the walls. The size of the maze can be modified to make the exercise easier or more difficult.

D. *Squeezing a Ball*

As shown in Fig. 5, a spongy ball is placed at the center of a triangle so that the subject can easily locate it. The virtual squeezing ball consists of a virtual elastic ball that the patient grasps with a virtual hand, and is designed to strengthen the patient's finger flexion movement. The exercise difficulty is adapted by modifying the hardness of the ball (stiffness and elasticity). This is controlled by the OT by pressing a button.

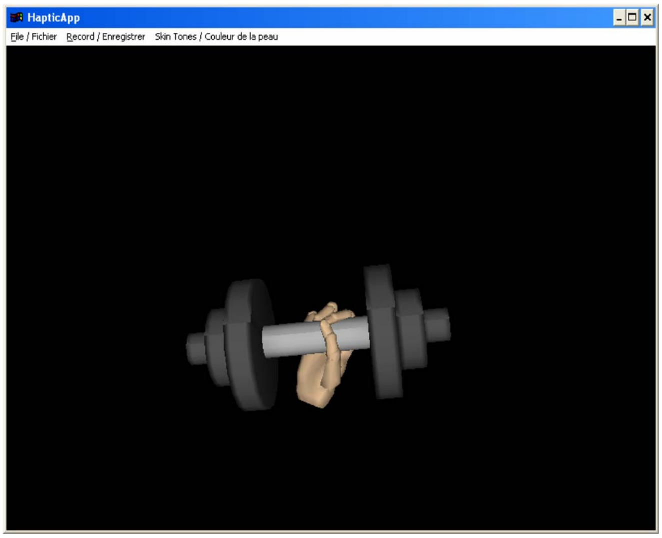

Fig. 6. Working out with a dumbbell.

E. *Dumbbell*

The last exercise aims at fine and gross motor skills and strength. The user sees a weight dumbbell and grasps it in the horizontal direction with the palm oriented upward (as shown in Fig. 6). Generally, this exercise helps in the recovery of the upper-body push–pull muscles, i.e., the shoulders, pectorals, and latissimus dorsi.

V. PERFORMANCE EVALUATION

To prove the effectiveness of this haptic virtual system as a training and assessment tool for OTs, we have designed five hand exercise tasks. In this section, the setup of the tasks is described, and we show how the captured data can be analyzed and used to evaluate the progress of a stroke patient. It is studied how "normal" is the demonstrated behavior of each subject. Ten students (eight males and two females) participated in the experimentation; each repeated the tasks three times over three days. Each trial session consisted of five task blocks, i.e., moving a cup, arranging blocks, navigating a maze, training with a dumbbell, and grasping a spongy ball.

The tasks were designed to examine and measure the spatial and temporal properties of the hand/finger movements. These parameters include the TCT, the range and speed of hand movement, the steadiness of hand movement, the grasping angles, the total energy consumed per every task, among other possibilities. These parameters are derived from the data captured by the CyberGrasp system using its supporting VirtualHand API [30]. The captured data include timestamps, the 3-D coordinates of the subject's palm, the five-finger joint angles (the distal, proximal, and metacarpal joints), and the number of collisions (in the "navigating a maze" task). These data were captured at a high rate of around 170 samples per second.

The first parameter we looked at was the TCT, which is the measure of time it took the subject to successfully complete the task. This parameter examines whether the subject can complete a specific task within a reasonable time interval. The TCTs for the ten subjects while performing the five exercises

TABLE I
TCT FOR TEN SUBJECTS PER THREE TRIALS

	Trials	**Task Completion Time (Seconds)**				
		Cup	**Blocks**	**Maze**	**Dumbbell**	**Ball**
Subject 1	Trial 1	55.00	60.14	31.7	20.02	33.6
	Trial 2	54.64	64.25	42.2	32.37	43.8
	Trial 3	47.19	67.08	34.5	28.81	35.7
Subject 2	Trial 1	54.17	48.14	26.9	111.45	78.7
	Trial 2	49.34	47.56	26.5	26.90	45.1
	Trial 3	45.76	42.16	25.8	26.47	47.6
Subject 3	Trial 1	72.34	63.97	39.8	37.55	56.8
	Trial 2	56.78	116.02	39.1	26.44	43.5
	Trial 3	71.89	55.73	34.5	26.66	34.7
Subject 4	Trial 1	84.39	75.23	30.8	24.66	42.9
	Trial 2	53.42	68.37	27.4	22.87	34.8
	Trial 3	43.90	42.75	33.2	15. 90	26.1
Subject 5	Trial 1	57.55	51.03	44.4	153.22	21.1
	Trial 2	52.06	53.94	41.8	23.53	30.6
	Trial 3	40.06	38.94	33.2	20.70	26.4
Subject 6	Trial 1	49.33	101.58	41.6	15.22	32.4
	Trial 2	29.66	70.37	24.7	20.01	30.4
	Trial 3	45.64	39.12	23.3	14.30	46.4
Subject 7	Trial 1	104.7	84.08	30.7	30.60	50.9
	Trial 2	76.78	57.42	32.1	27.36	32.4
	Trial 3	69.55	93.81	43.8	26.56	32.6
Subject 8	Trial 1	49.52	23.86	17.7	16.73	28.0
	Trial 2	27.30	18.05	10.8	19.33	22.1
	Trial 3	24.23	18.06	9.64	21.70	23.3
Subject 9	Trial 1	85.72	59.25	39.5	25.47	36.5
	Trial 2	69.91	40.37	43.0	27.37	38.1
	Trial 3	57.26	59.72	37.7	32.58	31.4
Subject 10	Trial 1	90.14	127.58	74.5	30.31	60.0
	Trial 2	40.48	54.58	22.6	28.86	42.2
	Trial 3	40.80	61.70	18.0	39.33	28.8

(three trials each) are listed in Table I. It can be noted that for subjects who never used the CyberGrasp before (three subjects), the TCT is clearly high in the case of the first trial of the cup exercise, which was the first exercise carried out. In general, TCTs tend to decrease or remain during the second and third trials. By performing a comprehensive usability study for a larger set of "normal" subjects, a reference TCT per exercise can be estimated and used to test (jointly with other parameters) how close a patient is to full recovery.

A. Handling a Cup

As per the cup exercise, the task was to grasp the cup, lift it in a straight motion along a prescribed path, as shown on the screen (Fig. 2), and release it after five times of getting back to the start-up point. The subjects were asked to move their hands as steady as possible and to avoid moving their hands into or out of the screen. Each exercise was performed three times, setting the weight to the maximum that can be handled by the CyberGrasp cables (25 units). The objective of the exercise was to measure the ability of the user to follow a visual path and test the hand–eye synchronization.

After completing the task, we plotted the XY plane trace of the subject hand movement (Fig. 7). The plot helps in examining the subject's eye–hand synchronization by comparing the prescribed path (the dotted path in Fig. 7) and the path followed by the subject.

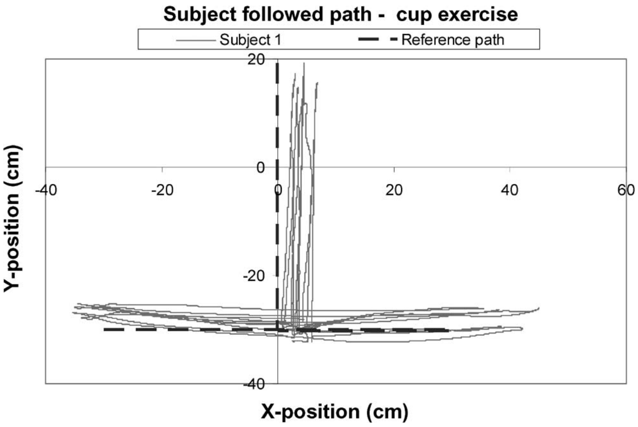

Fig. 7. Position traces of the hand movement in the XY plane.

TABLE II
COMPACTNESS FACTOR FOR THE CUBES EXERCISE

Subjects	**Compactness of cubes exercise (cm)**		
	Trial 1	**Trial 2**	**Trial 3**
Subject 1	28.55	36.23	30.00
Subject 2	36.355	39.69	37.30
Subject 3	25.985	46.42	42.74
Subject 4	31.50	41.91	29.70
Subject 5	61.16	72.78	38.43
Subject 6	37.31	42.60	34.16
Subject 7	53.30	39.80	34.90
Subject 8	36.18	45.70	38.35
Subject 9	35.28	36.14	56.82
Subject 10	35.75	29.92	30.38

B. Arranging Blocks

In the blocks exercise, the simulated task is to move the cubes, one by one, from the right side of the virtual space to the left one and then arrange the blocks to form one big block with its yellow face oriented out of the screen.

In addition to measuring the TCT for each subject, another important factor to be considered in this exercise is the compactness of the task completion. That is, the spatial workspace used by the subject to arrange the cubes. This parameter is determined by finding out the minimum and maximum space coordinates reached by the subject and then computing the distance d between them. Geometrically, the subject movement was completely enclosed in a block with a diagonal equal to d. The compactness factor acts as an indication of the effectiveness of hand movement toward completing a specific task. Table II shows the d factor computed for all the subjects during the three trials.

C. Navigating a Maze

The task in this exercise was simply to navigate the maze. The subjects were asked to grab the stick and navigate the maze using the stick. This test is designed to test and examine the improvement of the steadiness of the hand movement

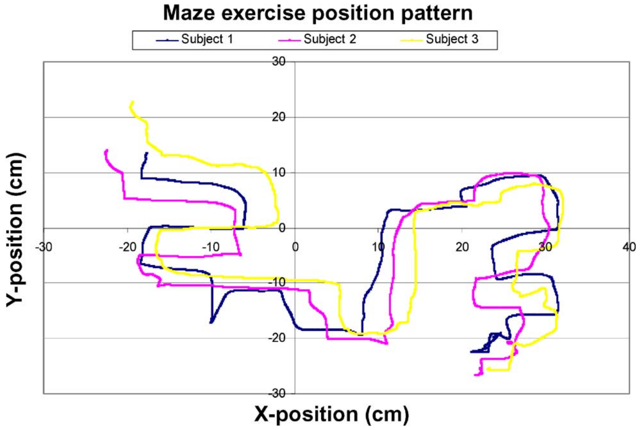

Fig. 8. Position traces of the hand movement in the XY plane for three subjects.

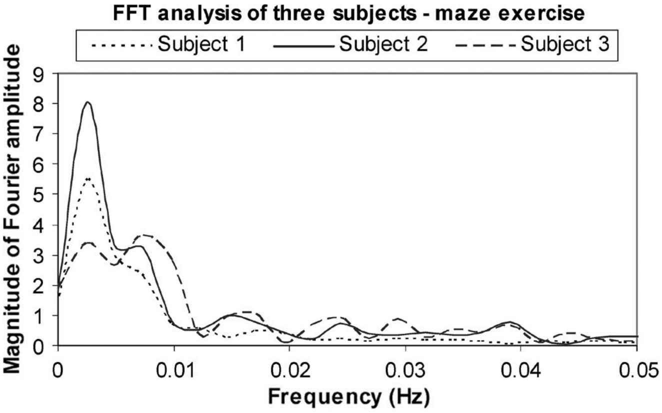

Fig. 9. Frequency spectrum for three subjects (maze exercise).

while performing a task, which requires some concentration. Nonetheless, the challenge here is to complete the maze with the minimum number of collisions with the maze walls.

Plotting the captured position pattern in the same plane as the maze (XY plane in this case) shows the performed trajectory. The XY plane trajectory, as shown in Fig. 8, presents the movement quality. This plot helps therapists to subjectively evaluate the patient's performance and whether she/he was able to complete the maze or if any wrong trajectory was followed.

The steadiness of the hand movement (tremor) can be evaluated by conducting a frequency-domain analysis. High-frequency components contain the tremor information and reflect the ability of the patient to control the haptic device tip during movement. We have used the fast Fourier transform (FFT) to compute the frequency components of the captured position pattern. For a normal subject, the spectrum comprises low-frequency components, whereas for a patient with unstable hand movement, the high-frequency components should be significant. Fig. 9 represents the frequency-domain analysis for three normal subjects, where the absence of high-frequency components indicates a "normal" hand movement. In addition, a usability analysis can be performed to find an average frequency spectrum for normal subjects that can eventually be used to quantitatively evaluate the patient's hand steadiness.

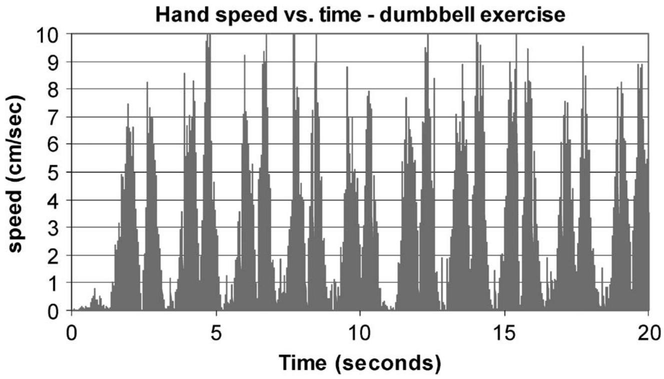

Fig. 10. Speed of hand as a function of time for a subject.

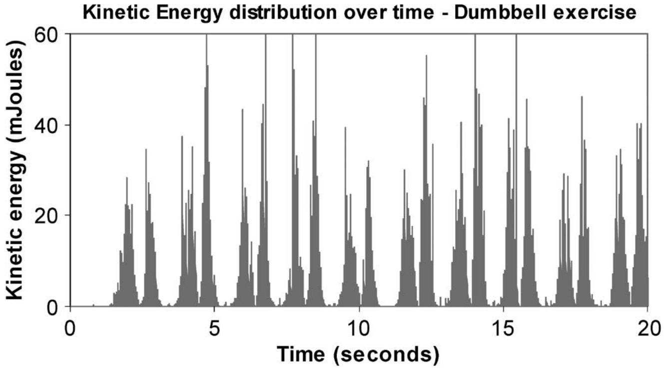

Fig. 11. Kinetic energy distribution over time for a subject.

D. Dumbbell

The subject was initially asked to grasp the dumbbell and maintain his/her hand in the horizontal direction with his/her palm oriented upward. Then, the subject was instructed to slowly lift his/her forearm until it becomes vertically oriented, and then slowly return to the starting position during ten times. The purpose of this exercise is to help in the recovery of the upper-body push–pull muscles, i.e., the shoulders, pectorals, and latissimus dorsi.

To examine the movement of the subject's hand, we measured the speed of hand movement during the exercise. As shown in Fig. 10, the speed distribution reflects the steadiness of the hand movement. In addition, a therapist can use such a curve to evaluate whether a subject was able to perform the ten times exercise with the same level of activeness, which leads to a better understanding of the patient's specific impairment. By comparing the speed of hand distribution curve of a patient with a reference one, therapists can get an insight into the patient's behavior, which, thus, leads to a better diagnosis.

Another important parameter we considered was the total mechanical work performed when moving the hand against the dumbbell. Fig. 11 shows the kinetic energy while performing the task as function of time. The total energy can be computed by adding all the components drawn in Fig. 10. This parameter is important to quantize the effort a patient puts in an exercise, and helps in examining and diagnosing the patient's motor system.

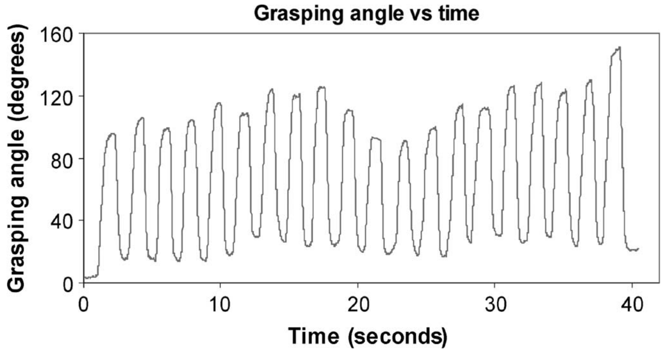

Fig. 12. Grasping angle distribution over time for a subject.

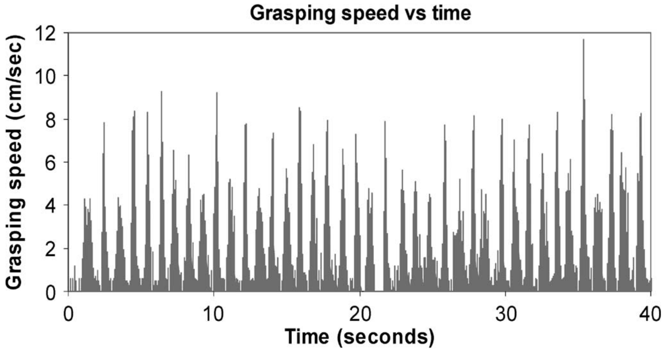

Fig. 13. Grasping speed versus time for a subject.

E. Squeezing a Ball

The task is to grasp the ball and perform 20 uniform grips. The stiffness of the ball remained unchanged through all the trials (at 1 N/kg). This exercise aims at quantizing the griping behavior for normal humans (the range of finger movement) and examines the finger extension capabilities. Therefore, the subjects were instructed to straighten their fingers and make a "complete" grip of the ball.

First of all, we examined the grasping angle variations over time (speed). The grasping angle was defined as follows. We computed the total grasping angle per every finger as the summation of the three angles (metacarpal, proximal, and distal joint angles) and then calculate the average grasping angle for the five fingers. The grasping angle variation over time, for one subject, is shown in Fig. 12. This plot can be used to detect specific finger deficits that might impede the finger movement and thus the proper grasping. We can also plot the grasping angle per finger to examine the behavior of individual fingers. The range of finger movement (grip) for normal hand can also be computed from the same diagram as the difference between the minimum and maximum grasping angle and can be used to evaluate the patient's performance.

Another indication of finger behavior is the measure of the finger speed over time, or finger acceleration, during a grip activity. This plot can demonstrate any abnormal timings, sudden stops, hesitations, or abrupt changes in finger movements before, during, and after squeezing the spongy ball. For instance, Fig. 13 shows the grasping speed distribution as a function of time for one subject. For instance, it can easily be figured out that a sudden change in the finger movement happened during the 18th grip (around 36 s).

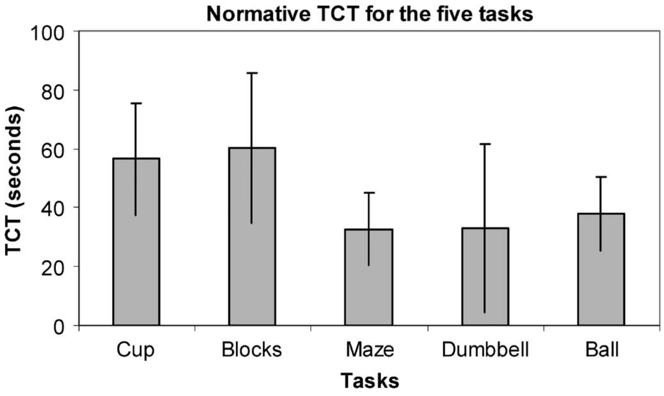

Fig. 14. TCT for the five tasks (mean and standard deviation).

TABLE III
EXCERPT OF NORMATIVE HAND FUNCTION PARAMETERS

	Exercise	Average	Standard Deviation
Kinetic energy (mJoules)	Dumbbell	41.32	21.40
Grasping angle (degrees)	Ball	131.51	21.65
Grasping speed (degrees/sec)	Ball	3.00	0.86

After conducting the five tasks with ten subjects for three trials (altogether 30 trials per task), we derived preliminary normative values that characterize "normal" human hand behavior. Fig. 14 shows the mean and standard deviation of the TCT for the five tasks. Table III lists three vital properties of the hand and finger function, i.e., kinetic energy, grasping angle, and grasping speed. These data, along with the TCT, position traces, and FFT analysis, can be potentials to be used as normative data to assess the patient's performance.

VI. CONCLUSION AND FUTURE WORK

A haptic virtual rehabilitation system with five virtual daily life exercises has been designed and developed for stroke rehabilitation. The system aims at being used as a rehabilitation tool and for diagnosis to quantitatively measure and evaluate the patient's progress and level of recovery. The performance analysis of the proposed exercises has shown the reliability and validation of the proposed framework and its effectiveness as a diagnosis system to analyze the patients' data.

Recently, many research efforts have been put to overcome the current limitations of the haptic hardware technologies for rehabilitation applications [31]–[33]. The envisioned objectives of such improvements include reducing the price of the hardware to make affordable for home use, minimizing the setup and calibration times, and providing a more transparent and stable performance of force rendering. Despite the limitations of state-of-the-art haptic devices, a huge set of interaction data can be captured and analyzed to derive reference "golden" metrics for normal healthy subjects. Consequently, the patient's performance can be tested against the golden metrics, and thus, an objective decision about the patient's progress and level of recovery can be easily made. The long-term objective is to develop a Decision Support System, whereby OTs at clinics can evaluate a patient's performance of exercises carried out at home and accordingly adapt tasks based on the patient's current capacity.

Although this paper shows the feasibility of this system, further research must be done to get clinically meaningful, consistent, and reliable normative data. We plan to test this framework with 50 normal subjects to derive normative data as a reference metrics to evaluate the patient's progress. Eventually, we plan to examine the system with stroke patients and examine the effectiveness of the system as a diagnosis tool.

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