

A Benchmarked Automated Progress Measurement System for Haptic Motor Rehabilitation

Ruba Kayyali¹, Shervin Shirmohammadi¹,
Abdulmotaleb El Saddik²

¹ Distributed and Collaborative Virtual Environments Research Laboratory

² Multimedia Communications Research Laboratory

University of Ottawa, Ottawa, Canada

rkayyali@discover.uottawa.ca, shervin@discover.uottawa.ca, abed@mclab.uottawa.ca

Biographical notes:

Ruba Kayyali received her B.A.Sc. in Software Engineering from the School of Information Technology and Engineering, University of Ottawa in Canada. She is currently pursuing her M.A.Sc. in Electrical and Computer Engineering also at the University of Ottawa, Canada. Her current publications include EMBC 07, HAVE 07 and MEMEA 08.

Shervin Shirmohammadi received his Ph.D. in Electrical Engineering in 2000 from the School of Information Technology and Engineering, University of Ottawa, Canada, where he is currently an Associate Professor. His current research interests include Massively Multiuser Online Gaming (MMOG) and Virtual Environments, Application Layer Multicasting and Overlay Networks, and Adaptive P2P Audio/Video Streaming. In addition to his academic publications, which include Best Paper Awards at the IEEE WETICE 2000 workshop and IEEE COPS 2007 workshop, he has over a dozen technology transfers to the private sector and many years of industry experience. He is Editor-in-Chief of the International Journal of Advanced Media and Communications, Associate Editor of the Journal of Multimedia Tools and Applications, Information Director of ACM Transactions on Multimedia Computing, Communications, and Applications (ACM TOMCCAP), and also chairs or serves on the program committee of a number of conferences in multimedia, virtual environments, and distributed simulations. Dr. Shirmohammadi is a University of Ottawa Gold Medalist, a licensed Professional Engineer in Ontario, a Senior Member of the IEEE, and a Professional Member of the ACM.

Abdulmotaleb El Saddik Professor and University Research Chair, SITE, University of Ottawa and recipient of the Friedrich Wilhelm-Bessel Research Award from Germany's Alexander von Humboldt Foundation (2007) the Premier's Research Excellence Award (PREA 2004), Canada Foundation for Innovation (CFI) Award (2004) and the National Capital Institute of Telecommunications (NCIT) New Professorship Incentive Award (2004). He is the director of the Multimedia Communications Research Laboratory (MCRLab) and the director of the ICT-cluster of the Ontario Research Network on E-commerce (ORNEC). He is a Theme co-Leader in the LORNET NSERC Research Network. He is Associate Editor of the ACM Transactions on Multimedia Computing, Communications and Applications (ACM TOMCCAP) and Guest Editor for several IEEE Transactions and Journals. Dr. El Saddik has been serving on several technical program committees of numerous IEEE and ACM events. He has been the General Chair and/or Technical Program Chair of more than 18 international conferences on collaborative haptic-audio-visual environments, multimedia communications and instrumentation and measurement. He is leading researcher in haptics, service-oriented architectures, collaborative environments and ambient interactive media and communications. He has authored and co-authored three books and more than 170 publications. He has received research grants and contracts totalling more than \$6 million and has supervised more than 90 researchers. His research has been selected for the BEST Paper Award at the "Virtual Concepts 2006" and "IEEE COPS 2007". He is an IEEE Distinguished Lecturer. Dr. El Saddik is the founding chair of IEEE workshop on Haptic Audio Visual Environments (HAVE), a yearly workshop on issues related to Haptics (started in 2002) and has been acting as guest editor for 5 special issues on Haptics in the last 4 years.

Abstract: *As Haptic devices become more affordable and economical, research in Haptic-based virtual rehabilitation systems is gaining more interest. In addition to the benefits provided by virtual rehabilitation, Haptics offer force and tactile feedback which can be crucial for much upper and lower extremity rehabilitation. In this paper, we present such a system that provides a rich media environment for motor rehabilitation of*

Author

stroke patients. The system can be used by occupational therapists to measure and monitor the progress of rehab patients.

Keywords: *Haptics, Motor Rehabilitation, Progress Measurement, Virtual Rehabilitation, Occupational Therapy*

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1. INTRODUCTION

There are between 40,000 to 50,000 strokes in Canada each year. Of those, 75% continue to live with some varying degree of severity of impairment. Virtual Rehabilitation was proposed over a decade ago, as an alternative for recovering stroke patients. The conventional rehabilitative systems provided a recovering stroke patient an average of one to two half hour sessions a day with an occupational therapist [1]. This limited time available for stroke patients is not enough to recover at sufficient speed. In order to increase the recovery speed, more frequent and repetitive practice must be made accessible to the patients. This brought about the innovation of coupling Virtual Reality (VR) technology with animated exercises that would allow the patients to practice on practically any computer, even at the convenience of their own home [2-3]. Virtual Rehabilitation has the ability to provide recovering stroke patients with the ability to perform rehabilitation exercises with more frequency and repetitiveness as was previously provided by occupational therapists.

At the same time, the haptic technology or haptics 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. Haptic-based virtual rehabilitation offers the potential to create systematic human testing, training and treatment environments that allow precise control of complex dynamic 3D stimulus presentations, behavioural tracking, performance measurement, data recording, and analysis [4]. Haptic devices are evolving and getting cheaper, more flexible, and more compact in size. Furthermore, the incorporation of haptics in VR-based rehabilitation systems opens up many applications and possibilities, such as haptic guidance and augmented feedback. The Haptic device used for this research is shown in figure 1.

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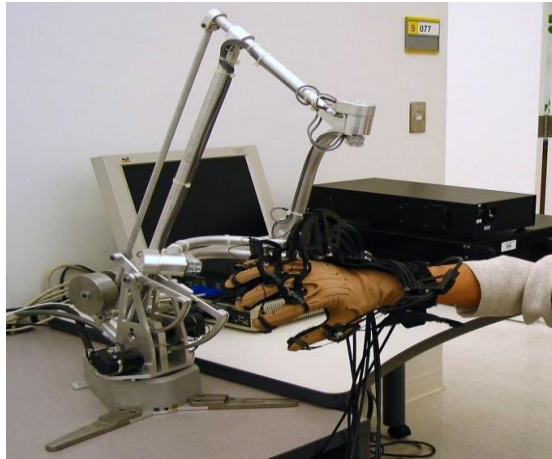


Figure. 1. Immersion's CyberForce® System

There have been several implementations for haptic-based virtual rehabilitation systems. Such systems have managed to incorporate intensive exercises that are designed to target the patient's motor and cognitive skills, in a repetitive and progressive manner. However, there continues to be a gap between the design of these systems and the actual integration of such a system with real rehabilitation patients. The main problem with these designs is the absence of the Occupational Therapist (OT). OTs need to be able to carefully configure the system in order to, for example, select the amount of time delay, angle, zoom, difficulty, and other parameters that will be used as a form of tracking of the patient's progress. This gives the OTs better control of the system, and allows them to determine the progress and improvements of a patient. Measurement of this progress and appropriate consequential actions is the key to the successful recovery of the patients. The proposed system is a Haptic Virtual Rehabilitation system whose goal is to assist patients who suffered from a stroke, acquired brain injury, muscular sclerosis, paraplegia and upper extremity amputees. The system allows patients to perform daily-life exercise that they need to do in real life, such as moving common objects, eating soup with a spoon, and other exercises. The system also provides Occupational Therapists with the ability to configure the weight of the virtual objects in each exercise, and to monitor the progress of each patient, by correlating the results gathered from each exercise with base data gathered against pre-defined criteria. The system uses the CyberForce system from Immersion Corporation, shown in Figure 1. This specific hardware was chosen because it measures the position and orientation of each finger, the wrist, and the hand in general, and simulates objects' weight by exerting downward force. The system's requirements were the result of several consultations with the Rehabilitation Centre of the Ottawa General

Author

Hospital and the Discover Lab at the University of Ottawa. The initial implementation was also placed under the analysis of a group of five occupational therapists that provided thorough feedback and further amendments to the design of the system. As a result of these consultations and trials, the graphical user interface was modified to include further details, tailored for each specific exercise, as well as a new list of exercises derived from common daily activities. The system was then placed under test by 5 volunteers and their data collected and analysed. The final aim of the project is to have the system placed under trial in the Ottawa General Hospital where patients can provide us with feedback and further recommendations for improving the system.

2. RELATED WORK

The use of VR systems has not been restricted to just physical rehabilitation, within the field of medicine, but has encompassed various fields including laparoscopic surgery, and even the psychological aspects of patients. In [5], the authors describe the use of VR-based leisure systems to elevate the self-esteem and independence of adults with cerebral palsy. The introduction of haptics into VR-based systems has lead way to the development of many new applications within the field of medical research. For example, [6] describes the application of haptic technology to create a surgery simulator for training surgeons in the field of minimally invasive surgery.

There exists extensive research and publications in the field of haptic-based virtual rehabilitation. Most of the research relied on preliminary evidence that supported the introduction of haptic technology to virtual rehabilitation. Proving this evidence came about through clinical trials, such as Heidi Sveistrup's work [7] which compared virtual reality-delivered exercise programs to conventional exercise programs for physical rehabilitation. The result of these clinical trials proved the effectiveness of VR-based haptic motor rehabilitative systems over conventional systems. It also helped to emphasise the benefits of using VR within rehabilitative systems, such as the ability to tailor exercises to suit the needs of patients, as well the ability to develop a standard for analysing and assessing the progress of patients [8].

The implementations of haptic-based VR systems have continued to provide more innovative and effective physical rehabilitation systems. In terms of lower extremity, the work reported in [9] and [10] explains how some of the patients' ankle muscles capabilities were improved when introducing haptic effects using the Rutgers Ankle Rehabilitation Interface. The design of the Rutgers Ankle Rehabilitation Interface provides the patient with an at-home rehabilitative system, which allows

Title

for progress monitoring via the internet. As for upper extremity, several attempts have been made to incorporate haptics for arm and wrist motor function rehabilitation [11, 12, 13]. The first of these publications concentrates on the creation of robotic devices that can be deployed in motor rehabilitation systems, and the last paper proposes the use of ER actuators to simulate force feedback. However, there is still no emphasis on the ease of use of the system and its simplicity, from the perspective of the patient.

In our previous work [14, 15], the initial version of a VR system was developed to include a set of exercises that relied on force feedback mechanism. These exercises were obtained by incorporating common tests that OT's have been using, such as the Jebsen Hand [20] and the Box and Block test [21]. The system was then subjected to analysis by a group of five occupational therapists from the Ottawa General Hospital Rehabilitation Centre aged between 20s and 60s, who volunteered their time to assess the effectiveness of the VR system, and the implemented exercises. The aim of the therapists' assessments was to collect as much feedback for the VR system as possible, such that all aspects of the system, including the hardware, software and graphics, were properly scrutinized. The result of the evaluation was a new set of exercises that better represented common daily activities that would appeal more to patients, as well as designs for the automated progress measurement component of the system.

3. THE SYSTEM

The system developed consists of an underlying framework that manages the integration of the haptics device with the virtual environment, and renders the 3D graphics into the virtual environment as well. The system also consists of a user interface that facilitates the user's interaction with the system. The main components are the actual exercises, represented by the 3D graphics. After interviewing several occupational therapists and gathering their feedback [22], new exercises were created that provide the patients with more realistic exercises, inspired by common daily activities. These exercises include the following scenarios:

- Tea pouring and drinking
- Moving common kitchen items onto shelves
- Drinking soup from a bowl with a spoon

More exercises are expected in the future, which will also be taken out of the context of daily activities. We will discuss these exercises shortly, but let us describe the system's functionality by looking at its

Author

user interface first.

3.1 User Interface

The interface allows the OT to interact with the system in a simple and user-friendly manner. It provides the OT with the ability to setup the base data, against which patient data is correlated, and to configure each exercise in accordance with a patient's progress. The following sequence of screenshots represents the user interface, as it would be used by Occupational Therapists, starting with figure 2 below:



Figure 2. Initial Page of the user interface.

An OT must select to either begin the system setup, which includes defining the base data for correlation, or launching the exercise page.

Title

Haptics Occupational Therapy - System Setup

Select exercise to setup:

Select the base data for each level:

Level 1	<input type="text" value="\\al\Users\rkayyal\Desktop\Shelf Results\Shelf_Level1.txt"/>	<input type="button" value="Browse"/>
Level 2	<input type="text"/>	<input type="button" value="Browse"/>
Level 3	<input type="text"/>	<input type="button" value="Browse"/>
Level 4	<input type="text"/>	<input type="button" value="Browse"/>
Level 5	<input type="text"/>	<input type="button" value="Browse"/>

Enter the Acceptable Variance (%)

Figure 3. System Setup Page.

The OT must select each exercise to setup (Figure 3), from the drop-down list, and browse to the data file for each level. The OT would then enter the acceptable degree of variance between the patient's data and the base data.

Author

Haptics Occupational Therapy - Patient Info

Enter Patient Name

Launch Haptics Device Configuration

Select Exercise

Cancel Next

Figure 4. Exercise Page.

The OT enters the patient's name (Figure 4), against which a folder will be created with the patient's name and current date and time. The OT would proceed to configure the haptic device for the patient using the device-specific application. This step would initially require some time to configure the device, but the configuration can be saved into a file and loaded each time.

Title

The screenshot shows a software window titled "Haptics Occupational Therapy - Shelf". The interface includes a dropdown menu for "Select Exercise Level" set to "Level 3". There are two checkboxes: "Angle Control" (unchecked) and "Weight Variation" (checked). Next to "Angle Control" is a field for "Enter Angle Variation". Below "Weight Variation" are seven weight selection dropdowns: "Cup Weight" (200g), "Mug Weight" (350g), "Bowl Weight" (400g), "Plate Weight" (500g), "Pot Weight" (800g), and "Jar Weight" (500g). At the bottom, there are three buttons: "Back", "Start Exercise", and "View Exercise Results".

Figure 5. Exercise Configuration Page.

The OT then selects the level for the exercise, as shown in Figure 5. This provides pre-populated weight variations for certain objects within the exercise. The exercise is then launched, with the required configurations. Once the patient is done, the OT can review the results and analyze them.

Author

Haptics Occupational Therapy - Results Analysis

Browse to Patient's Data: C:\Users\IRK\Documents\data.txt

Analysis of Data

Position of Tracker X: 1.0000000000000002

Position of Tracker Y: 1.0

Position of Tracker Z: 1.0

Time to Complete Exercise: 49453

Number of Collisions: 4

Decision from Analysis: Level 1

Figure 6. Result Analysis Page.

For the analysis, the OT can choose the data against which to compare against. This allows the OT to perform the analysis at a later time. The results are displayed in the lower portion of the page. The correlation of each of positions of each of the Tracker X, Tracker Y and Tracker Z are displayed (Figure 6). The OT can also view a graph populated of the respective tracker's positions against time (Figure 7). The page also displays the final decision of the analysis, which is a determination of which level the patient must proceed to.

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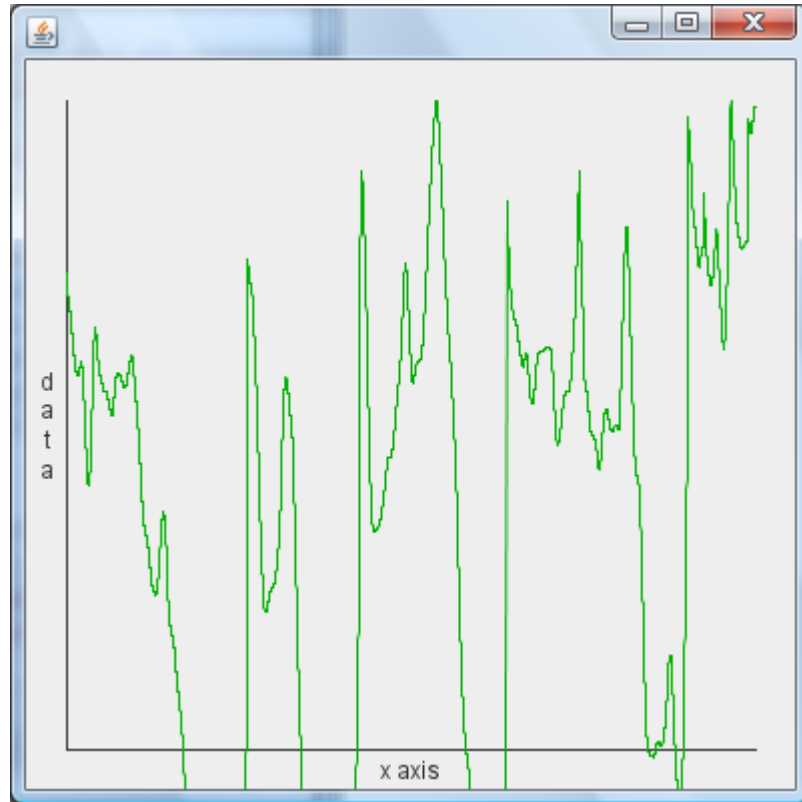


Figure 7. Graph of Tracker X positions vs. Time.

3.2 Maze Exercise

As mentioned earlier in this section, the system offers a number of exercises. The first one is the 3D maze. The 3D Maze exercise essentially consists of a cylindrically shaped object that would be used to traverse a path within a maze from the starting point until the end point. The maze itself is a simple 3D structure, built using mesh cube objects. The following requirements, which were used to tailor exercises, were requested by the OT's:

- Ability to vary the angle of the maze from 45° to -45° the horizontal axes.
- Several levels of complexity.
- Ability to track the speed of patients as they move the stick.
- Ability to alter the weight of the stick being moved through the maze.

Author

The main objective of the 3D-maze exercise is to increase the motion range of patients, along the horizontal and vertical planes. This exercise also allows patients to increase hand's steadiness and eye-to-hand synchronization. The number of collisions between the stick and the maze walls is computed. Speed tracking is another important requirement in measuring a patient's performance. The haptic devices currently employed in the VR system do not provide a means of measuring the speed of the hand as it moves. We addressed this issue by using a spherical ball. The patient starts the exercise but, after a specified time delay, the ball begins to traverse the path of the maze. Once the ball collides with the stick, this means that the patient is moving too slowly and the OT can determine if a longer time delay is needed. Figure 8 shows level 4 of the Maze exercise with Speed Tracking turned off.

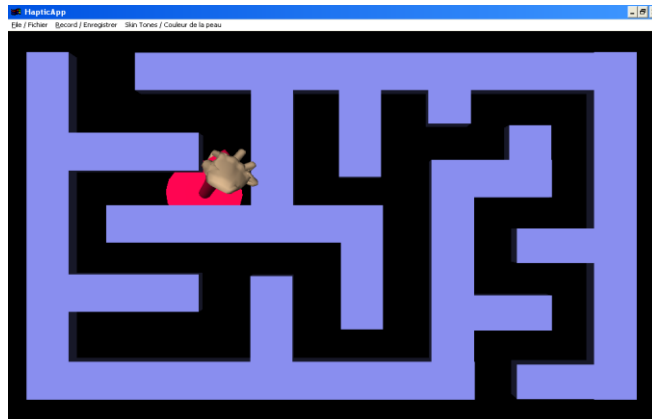


Figure. 8. Maze Exercise Level 4

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3.3 Shelf Exercise

Another exercise is the Shelf Exercise. This essentially consists of two shelves, fixed in place within the virtual environment, and a set of common items that can be found in all kitchens. The purpose of the exercise is to have the patient pick up the items, placed alongside the shelves, and place them on the shelves. The items themselves range in size and weight, and are made distinguishable through the use of appropriate colours. A sample of the exercise can be seen in Figure 9.

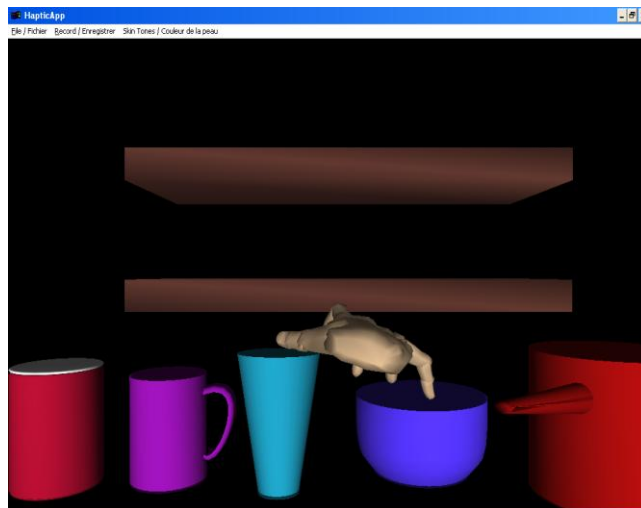


Figure. 9. Shelf Exercise

3.4 Tea Exercise

The Tea exercise includes several levels of difficulty, with each advanced level including a heavier tea pot. The exercise also allows the patient to lift the teacup, separate of the saucer. This also helps the patient learn to perform more delicate tasks which include the use of the thumb and index finger only. The following figure, Figure 10, provides a sample of the exercise.

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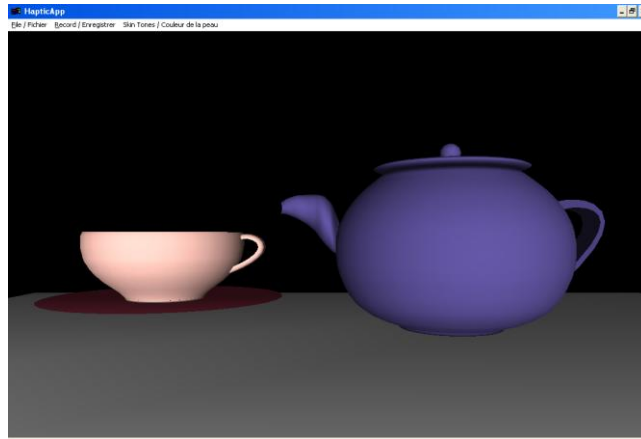


Figure. 10. Tea Exercise

3.5 Soup Exercise

The Soup exercise consists of a bowl of soup and a spoon, which the patient lifts and uses to drink the soup. Again, this sort of exercises allows the patients to practice holding small objects in their hands, and learn to move their arms over a more measured and precise path, to their mouths. A sample of the exercise can be seen in Figure 11.

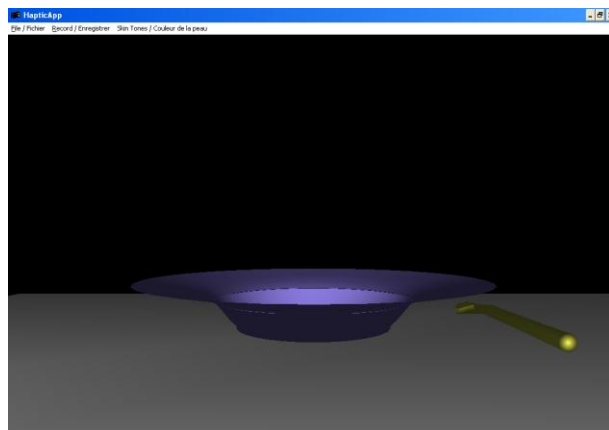


Figure. 11. Soup Exercise

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4. QUALITATIVE RESULTS AND ANALYSIS

In order to determine the effectiveness of the Haptic Virtual Rehabilitation system, trials have been carried out with five volunteers. The volunteers were selected with the following characteristics:

- Volunteer 1: Minimal computer skills
- Volunteer 2: Recently undergone a laparoscopic surgery for shoulder re-alignment
- Volunteer 3: No prior knowledge of the Immersion CyberForce system
- Volunteer 4: Some prior experience with the Immersion CyberForce system
- Volunteer 5: A Haptics expert

The results of these trials were captured and analyzed. The data provided us with a means of following the volunteers' improvement and allowed us to gather feedback from users of the system. The data gathered also proved useful in developing the progress measurement component, when used as a benchmark against future patients' data.

4.1 Trial Procedure

Each of the volunteers went through the same set of steps during the trials. These steps included, wearing the Immersion CyberForce system, configuring the hardware, performing the exercises in the following order: Soup exercise, Tea exercise with 1N (Newton) weight, Tea exercise with 15N weight, Shelf exercise. For each exercise, the required values were gathered in a log file and saved. The same process was carried out five times over a period of three days.

4.2 Results

The trial results were gathered by keeping logs of the haptic data received over the system's framework. The data gathered included:

- Tracker's X, Y and Z coordinates, with respect to each volunteer's configured axes of reference,
- Angles of the five fingers on the right hand with respect to the palm of the hand such that the angle is taken from the joint between the fingers and the palm
- Number of collisions with other objects in the virtual environment
- Time, in milliseconds, for the logged values.

Author

The results for the Soup exercise, as obtained from Volunteer 1, can be seen in Figures 12 and 13, with Figure 12 representing the Tracker Positions (X, Y and Z coordinates) for the first trial, and Figure 13 representing the same data types for the fifth trial. One can see that the values are much more consistent in the last trial, and the range of motion is more stable. This can be determined from the oscillations in position, which appear to be smaller and more consistent in trial 5. Such results can be used by occupational therapists to measure the stability of a patient's arm, and the improvement in controlling the arm and its ability to move along the required path of motion. Similar result patterns were observed for all volunteers, with the less experienced volunteers showing a slightly less significant improvement than those with previous haptic experience.

Other test results have shown more forms of improvement with regards to a volunteer's performance. For example, the task completion time continued to improve, for all volunteers, over the course of the trial period. This can be seen in Figure 14. Volunteer 1 took the longest time to complete the Tea Exercise, which was carried out using a 1N weight for the teapot. This was due to the volunteer's difficulty in trying to visualize the virtual environment as a 3D environment.

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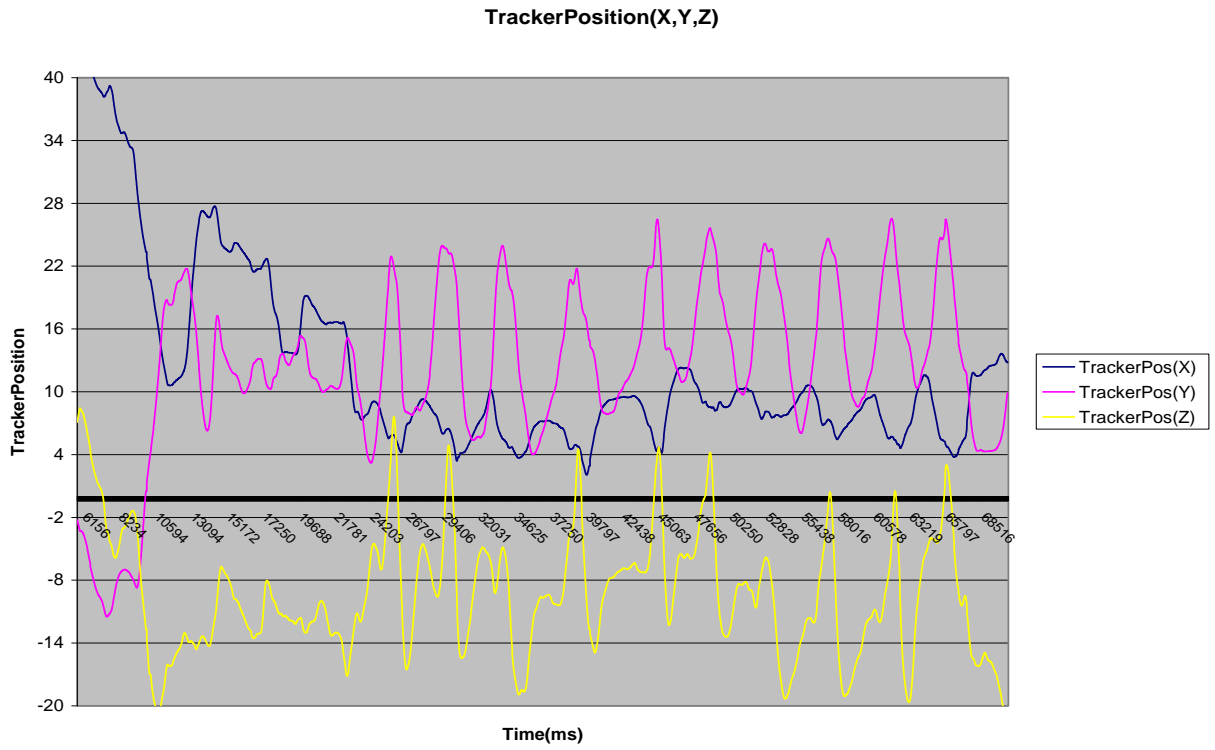


Figure. 12. Soup Exercise Tracker Positions for X,Y,Z Coordinates Trial 1

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TrackerPosition(X,Y,Z)

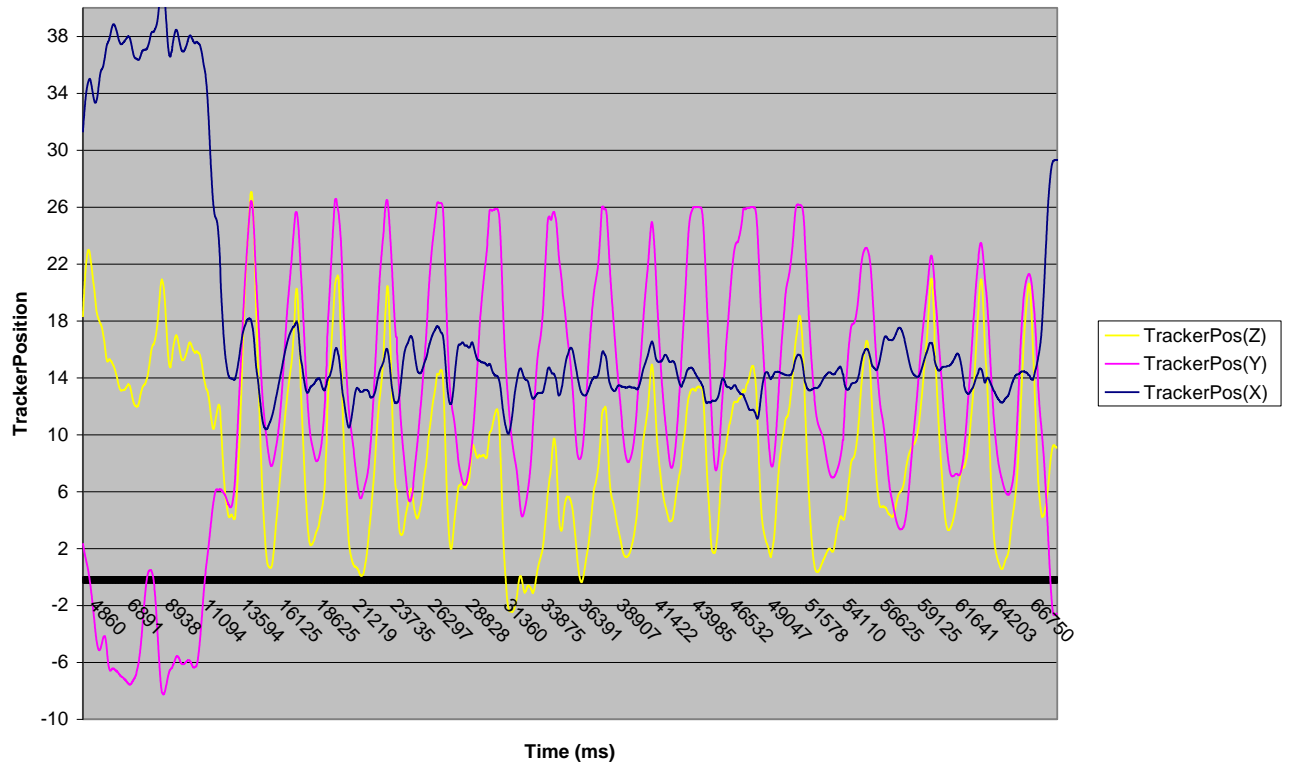


Figure. 13. Soup Exercise Tracker Positions for X,Y,Z Coordinates Trial 5

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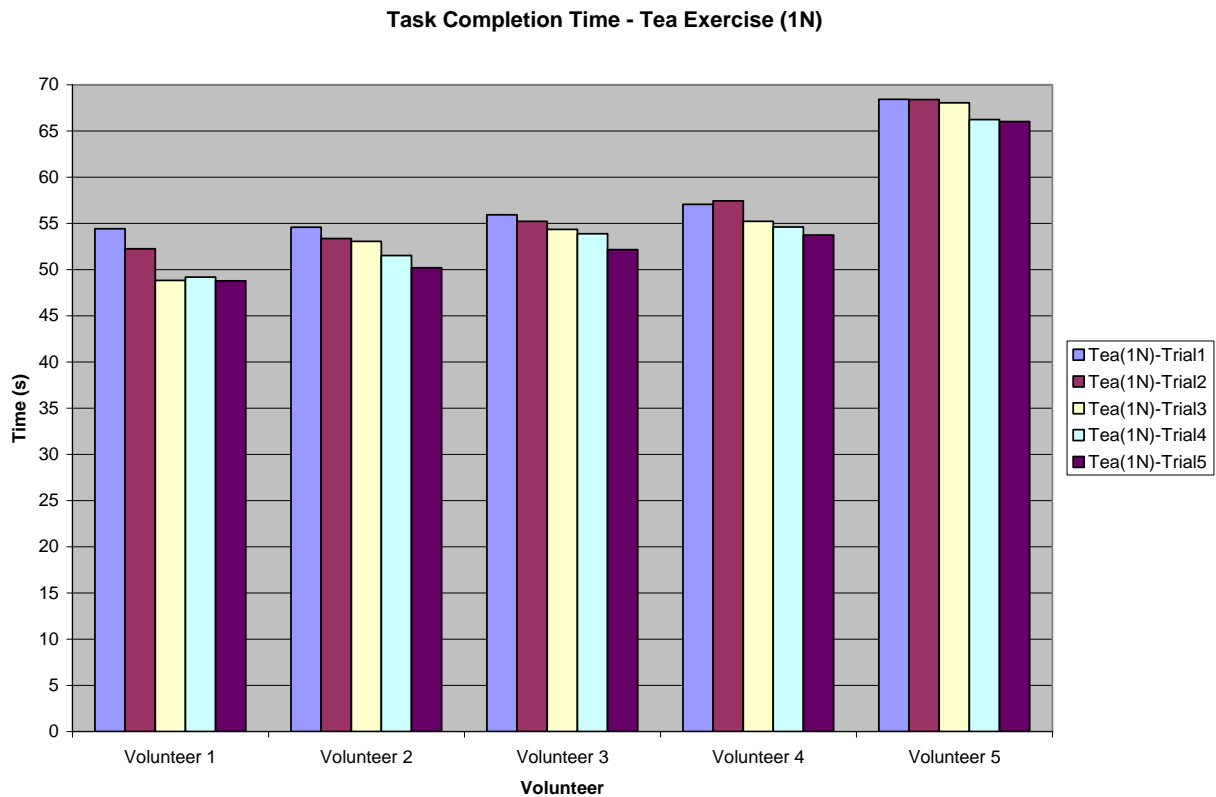


Figure. 14. Tea Exercise (1N) Task Completion Time

4.3 Feedback

Of the feedback received from the volunteers, the most significant issues were related to the hardware used in the system. Most of the volunteers placed emphasis on their inability to view their actions being reflected properly in the virtual environment. This is mainly due to the configuration process and the fact that the CyberForce does not accommodate for different hand sizes. Another problem with the hardware is the restricted workspace available, where the limits are determined by the length of the cables and wires, and by the CyberArm. The workspace limitations caused some of the volunteers to fail at performing the Shelf exercise, and re-configuration of the Immersion CyberForce system was required to adjust the centre of the workspace.

Further issues expressed by some of the volunteers, was their inability to realize the screen rendering of the exercise as a 3D environment. This issue was especially expressed by the volunteers that

Author

had little or no prior experience with haptic devices or virtual environments.

5. PROGRESS MEASUREMENT

5.1 Purpose

The progress measurement component of the system provides the Occupational Therapist with an automated means for monitoring the progress of the patient. The framework of the system gathers and records certain data during an exercise. The data collected is:

- Positions of the X Tracker
- Positions of the Y Tracker
- Positions of the Z Tracker
- Thumb's Proximal in radians
- Index's Proximal in radians
- Middle finger's Proximal in radians
- Ring finger's Proximal in radians
- Pinky finger's Proximal in radians
- Collisions between two or more objects in the virtual environment
- Time, in milliseconds

These values are used to track the motion of the hand within the virtual environment. They also show the strength with which the hand is gripping objects and the angles of the fingers with respect to their knuckles. This indicates whether or not the patient's grip is improving, and if the patient is gaining more strength and control over his/her fingers and arm.

5.2 Design

In order to achieve a complete analysis against all types of benchmarks, we need to gather data for each possible type of healthy users, using each possible exercise at each possible level. With four exercises, five levels and five possible types of users, we have a hundred combinations to gather data against. Potentially, the number of user types can increase to match the new characteristics of the end users. This will drive the number of combinations of exercises, levels and user types even higher. However, this will definitely be the case as more exercises are created, and more levels are designed. In order to avoid this unmanageable exponential growth of combinations, we

Title

needed to curtail the overload of possible base data. After examining the data that was collected over the trial period, we have made the following set of lax conclusions:

- As an end user begins using the system, he/she will be set to level 1. This is indicative of the lack of haptic experience that the end user would have, as it is comparable with the volunteer carrying no computer skills (i.e. volunteer 1).
- As the end user advances over time, he/she will become more of an expert in using the haptics device. This will lead to the end user becoming more and more comparable with the skills of a haptics expert, hence volunteer 5.
- These sets of data are only applicable in the scenario where the system is deployed in a “healthy” environment, such as a research lab. When the system is installed in a rehabilitation centre, the base data will have to be collected from volunteers with different characteristics. These characteristics will be determined at a later stage with the help and knowledge of professional occupational therapists.

Following from these conclusions, we took the decision to simply represent each level by a volunteer with certain characteristics, which we have previously defined in the trial period.

5.3 Implementation

The progress measurement component analyses the data that was collected during an exercise and correlates it with the base data that was provided during the system setup. The base data used in the system was collected during the trial phase of the system. The data collected from the fifth trial of each exercise, for each volunteer, was used for the benchmark data. This was decided as the first couple of trials provided unreliable data since most of the volunteers were not yet accustomed to the system. Each volunteer represents a level in each exercise, with volunteer 1 setting the basis for level 1, volunteer 2 representing level 2, and so on. During the setup phase, these data files are parsed and the required values extracted. The values are then stored in a custom designed data structure that allows for faster runtime analysis.

Analysis of the data is then carried out by the Occupational Therapist at will. The OT simply has to select the data file of the patient to analyze. The correlation is performed based on Pearson’s Correlation Coefficient. The formula used is as follows:

Author

$$r = \frac{n \sum x_i^2 y_i^2 - \sum x_i y_i}{\sqrt{n \sum x_i^2 - (\sum x_i)^2} \sqrt{n \sum y_i^2 - (\sum y_i)^2}}$$

where x_i is an element of the base data and y_i is an element of the patient's data. This provides the coefficient of the correlation between the patient and the base data. The calculation is carried out for every exercise level's set of base data, until an acceptable result is obtained. To determine if a result is acceptable, the following characteristics of the result must be obtained:

- The result is positive in value. This indicates that the two sets of values have a positive correlation. The significance of the positive correlation lies in the linear relationship with the two sets of correlated values, where if one set of values tends to increase, the other set of values also tends to increase. This shows that the values are similar in nature.
- If the result is positive in value, the variance percentage is applied, such that the final decision is based on:

$$\text{Correlation Result} \pm (\text{Variance} / 100)$$

This variance value is what the occupational therapist declares during the setup of the system.

- The correlation result is considered acceptable when the correlation value is between 0.7 and 1.0. We chose to make the correlation a strong positive one as this would guarantee that the patient is strong enough to move onto the next level. Relying on a weak correlation would indicate that the patient could still benefit more from repeating the exercise for a while longer.

At this point, the level for the patient to proceed to next becomes the level for which this acceptable result is obtained. This might be the same level the patient is on, a lower level or a higher one, depending on how the patient is improving or maybe even getting worse.

5.4 Results

In order to properly test the progress measurement component, we had to ensure that the data analysis section worked as expected. Hence, passing in an identical set of data for the patient's results, and setting up the base data also with identical data sets, meant that the correlation results for all of the tracker positions, X, Y and Z, and for the five finger proximals, must all be a value of 1.0. This indicates that the correlation coefficient is 1.0 which is the expected result when the two

Title

items being correlated are identical. It would also mean that the expected level would be the minimum level possible that returns the acceptable correlation coefficient, in this case it would be level 1.

After running the test several times with several different data sets, each set returned the exact correlation coefficient expected, 1.0, and the final decision level was “level 1”. This helped to prove that the data analysis algorithm functioned as designed.

6. FUTURE WORK

The comparison method used, Pearson’s Correlation Coefficient, is one of the few methods that were found suitable to analyze the data that we gathered. However, more research is needed to determine the necessary mathematical analysis that will better suite the dynamic data available. These analytical methods can either be custom-designed mathematical comparison methods that we will develop, or pre-existing comparison methods that we can enhance or re-use. Furthermore, the current implementation would need to undergo more intensive testing to ensure that the most suitable decision is always obtained.

More future work is needed to determine the exact criteria for performing the analysis of the patients’ data. These criteria must include a complete definition for the benchmark data against which the patients’ results will be correlated. The main emphasis falls in balancing the large number of possible combinations of exercises, levels and user types, and developing an effective progress measurement system.

The progress measurement component of the system is still under development, as further research is required to determine the exact measurements required by occupational therapists. Further criteria and analytical methods are needed from assisting occupational therapists to help build an effective progress measurement module.

7. CONCLUSION

In conclusion of the trials carried out, it was apparent that the progress of a patient can be easily measured and monitored throughout the course of his or her therapy. However, further work is needed to implement a precise and effective progress monitor, which allows patients to continue in their therapy with less dependence on occupational therapists. Providing patients with an autonomous progress manager that can determine new exercise requirements for a particular patient, based on quantitative measurements and a pre-defined analytical process, can allow patients to complete their therapy period in

Author

a faster and more efficient manner. This theory is yet to be proven in the future, when the system becomes available for patients to use.

The most important obstacle to the future availability of the system will remain the hardware component. There is continuous emphasis on more reliable and stable haptic devices that can be integrated into a virtual rehabilitation system. The problem remains with creating a form of cooperative association between the haptic industry and occupation therapists to produce such reliable hardware.

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