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VR-Based Hand Rehabilitation using a Haptic-Based Framework

Ismail Shakra[1], Mauricio Orozco[1] Abdulmotaleb El Saddik[1]
Shervin Shirmohammadi[1], Edward Lemaire[2]

[1]Multimedia Communications Research Laboratory
[2]Faculty of Medicine, The Rehabilitation Centre
University of Ottawa
{shakra, morozco, abed, shervin}@discover.uottawa.ca, elemaire@ottawahospital.on.ca

Abstract *–Haptic-based hand rehabilitation exercises set in virtual environments have not focused on analyzing the data captured during exercises to draw conclusions that relate to specific aspects of the hand. The framework proposed in this study implemented virtual reality exercises carried out with the use of haptic devices for use in stroke rehabilitation. The exercises were tested with healthy subjects to collect information pertaining to the hand performance; namely movements and grip kinematics. The collected information was extracted from data recorded during the exercise. By analyzing the data, the research effort deduced certain analysis patterns that would provide occupational therapists with a means to continuously evaluate a patient's performance, and hence provide him/her with adaptive recovery courses*

Keywords *– Physical Rehabilitation, Haptic Measurement, Virtual Environments, Human-Computer Interface, Measurement Applications, Intelligent I & M Systems*

I. INTRODUCTION

For humans, physical tasks involve the use of fine sensory-motor skills, such as picking up a glass of water and putting it in a specific location. In the case of stroke patients undergoing rehabilitation, standard exercises administered by occupational therapists and conducted in pre-determined sessions aim to help restore function. In practice, most patients require considerable time to achieve optimum rehabilitation outcomes. This is understandable since rehabilitation exercises must be repeated periodically to fulfill their purpose. In addition, the level of difficulty of each exercise must increase, depending on the patient's progress. In this article, we propose an instrumentation and measurement framework aimed at circumventing the said hurdles in order to provide a safe and fully functional rehabilitation system that is accessible to a recovering stroke patient at all times. Our system uses haptic instruments and virtual reality to measure user interaction and progress, and to simulate rehabilitation activities to a high degree of accuracy in terms of multimodal sensory interaction and guarantees the all important condition of engaging patients fully in the virtual environment. Engaging the user helps to maintain their motivation and increase progress. In addition, the system adapts the difficulty of the rehabilitation tasks according to the user's progress, with the help of an intelligent system at the back end.

II. RELATED WORK

Substantial research that involves Virtual Reality has been carried out in therapy and rehabilitation. McLaughlin et al, for example, developed an immersive motor rehabilitation system with force feedback interaction [8]. Their system is based on a stereoscopic Head Mounted Display (HMD) as a mechanism of visual interaction. As a main objective, a virtual environment (VE) was presented to establish tangible contact between patients and medical staff.

Haptic instruments, which provide the ability of "touching" a simulated shape or textures while also applying a perception of "force" feedback in terms of position and movement of a body part, have also been used in physical rehabilitation. Haptic interfaces include many devices such as force-feedback stylus, instrumented data glove with exoskeleton, or other robotic devices. Examples include applying 3D computer games that provide features to measure and follow the performance of a patient [9], and a PC-based orthopedic rehabilitation system for use at home that allows remote monitoring from the clinic [10]. Most previous efforts involve more or less similar exercises. However, in our framework, we incorporate tests that occupational therapists have been using for a long time, such as the Jebsen Hand [13] and the Box and Block test [14]. Working with seasoned therapists, we worked to overcome technological obstacles such as manipulating small objects (like a spoon for feeding) with the current state of haptic software and hardware. As a result, we have built a system that, in addition to matching existing rehabilitation standards, accommodates future expansions that will be allowed by advances in technology. With our system, user have 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).

III. PROPOSED APPROACH

Fig. 1 depicts our proposed framework which is comprised of four components: A Sensory component, a Haptic/Software Simulation component, the client application featuring the rehabilitation exercises, and a Haptic/Behavioral Data component. First, the sensory component of the system is embedded within the haptic and visual interfaces. Tactile and kinesthetic stimuli are provided by the CyberGrasp system, which consists of CyberGlove, CyberGrasp (exoskeleton based), and the CyberForce instruments. These tools make high-accuracy joint-angle measurements, generate force feedback on the fingers, and make six-degrees-of-freedom measurements of the hand movements, respectively. The CyberForce also creates the feeling of the object weight, thus allowing a patient to feel gravity. The system's software component is responsible for haptics by simulating the complex calculations involved in the haptic rendering process loop, maintaining synchronization with graphic rendering, and recording haptic behavioral data for further analysis. The complex haptic interaction required is handled by the Virtual Hand SDK/Toolkit. This software API offers an object-oriented model with an accompanying C++ library.

A collision detection process handles, both haptically and graphically, the interaction between the virtual hand and the 3D objects in the VE. Collision between objects is measured using a contact patch approach. This collision detection is crucial because it allows the system to provide two implementations of the GJK (Gilbert-Johnson-Keethri) algorithm: the Vclip collision factory [11] and SOLID collision factory [12]. The GJK algorithms are standard methods for collision detection that have direct bearing on the usability of the overall system.

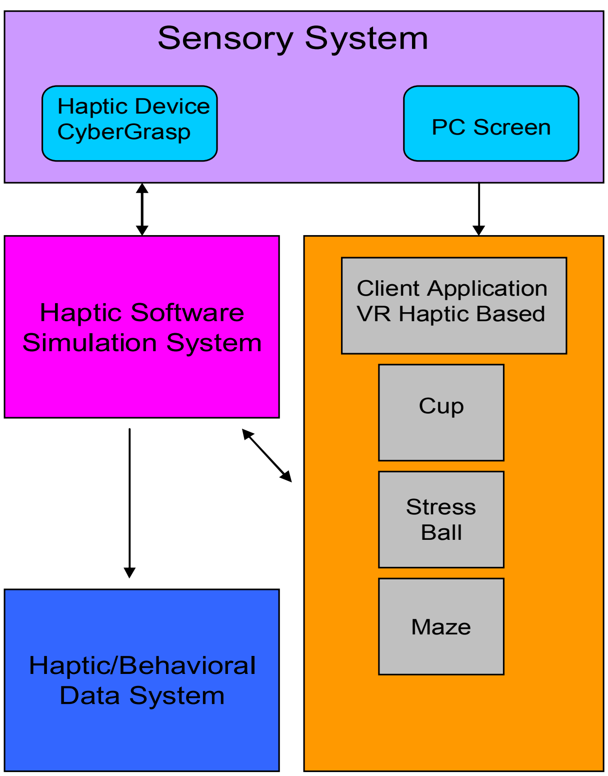

Fig. 1. Proposed Framework

IV. EXPERIMENTS AND RESULTS

We have initially used three different experiments that are being tested with five students from the University of Ottawa. The first one tested patterned motion and involved tilting a cup in a pouring motion after it was lifted vertically and recorded a collision with a virtual ceiling, as shown in fig. 2. This experiment was performed twice by each subject; the second trial involved increasing the weight of the cup by 2.5 times. The second experiment is a simple squeezable ball where the user was asked to squeeze the ball according to a decided pattern of location and repetition. The stiffness of the ball was varied for each student. The last experiment was a virtual maze solving process where the user handles a stick to navigate through the maze paths to reach the end. Haptic instruments provided measurements of the total time for each trial; the 3D world coordinates of the virtual position, and joint angles for middle phalange of each finger. Additional information can be computed such as velocity attained for each trial and the distance covered along each axis by the end of the exercise. This provided the input to obtain valuable information for rehabilitation follow up and user's patterns.

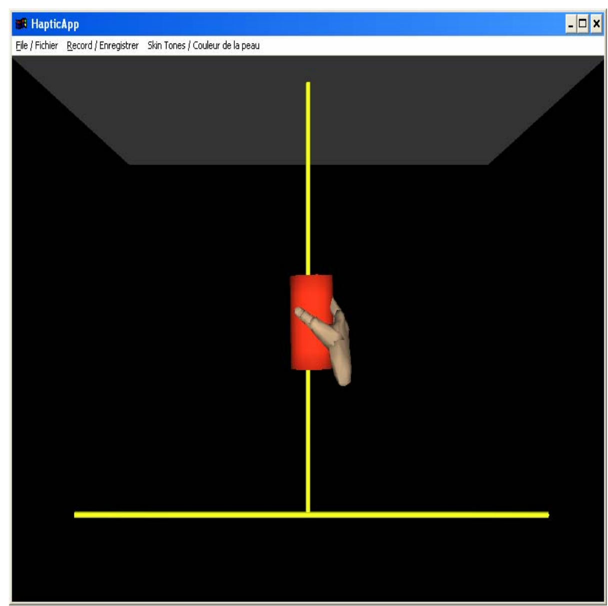

Fig. 2. Moving Cup Vertically to Ceiling

This paper reports the results for the cup exercise. Fig. 3 shows the changes in the middle phalange (proximal) angle of each finger during the exercise for subject 1 with the lower weight for the cup.

By examining the values for distance for the other four subjects, we can compare their performance. The results are summarized in table 1, which shows the total average speed attained by each subject during the two trials for the exercise.

Table I Average Speed Attained by all Subjects during the Exercise (cm per ms)

Subject	1	2	3	4	5
Speed for lower weight	0.089	0.044	0.074	0.047	0.070
Speed for higher weight	0.077	0.041	0.052	0.048	0.066

By comparing the average speeds for all the healthy subjects, it can be seen that the highest value was for subject 1; subjects 3 and 5 showed close values. Subjects 2 and 4, who had the most difficulty adapting to the haptic devices, attained a considerably lower speed. By computing the average speed for all the subjects, a therapist can put a target of about 0.065 cm per ms as a final goal for a patient. This value may vary with the severity of each case.

One more note of interest is the 'Z' distance. This exercise requires movement vertically mainly, and some movement along the X axis, so the distance accumulated across the Z axis can be a measure of hand stability. Table II shows the total 'Z' distance covered along the Z axis for each subject, averaged for both trials of the exercise.

Table II Distance Covered along the Z axis by all Subjects during the Exercise (cm)

Subject	1	2	3	4	5
Average 'Z' Distance for both trials	271	591	436	467	333

Comparing the values obtained, it can be seen that subject 1 covered the lowest distance along the Z axis. This might give an indication that subject 1 has the most stable hand and subject 2 the least. However, this cannot be taken as a sole criterion. A piece of information like this would be most useful to a therapist while treating a patient when combined with other findings from the different exercises. Also, it is interesting to note that subject 4 showed the second highest 'Z' distance of 467 cm behind subject 2. Combining this observation with the prior one about the total average speed being lowest for subjects 2 and 4, a therapist can look at both pieces of data when assessing a patient. A therapist might relate the improvement in speed to a decrease in 'Z' distance (and hence improvement in stability); a patient that exhibits an increase in speed but also an increase in 'Z' distance might be diagnosed to either still be wanting in hand stability or be performing the exercise in a manner that is not correct. In both cases, the therapist can tackle the issue accordingly.

Analyzing the performance of healthy subjects in the manner described can give useful insights into future treatment with patients afflicted with stroke. First, the information that can be extracted from raw data collected from an exercise would provide a therapist with a means of quantifying a patient's level of improvement. This would help in devising more efficient recovery plans by applying some changes on a certain exercise itself or on the way that that exercise should be performed. Finally, comparing analysis of different patient's performances would help a therapist build a solid database that could be used as reference when treating new patients.

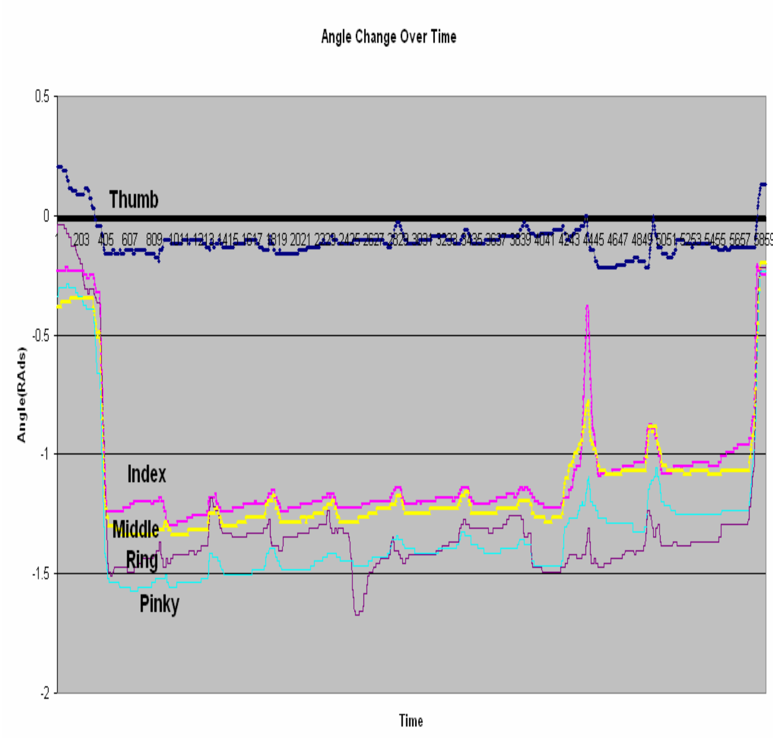

Fig. 3 Angle Change with Time for Lower Cup Weight for Subject 1

V. FUTURE WORK

After analyzing results from other exercises, the next step that comes after this framework will involve testing with stroke patients. Haptic devices must be improved to be less bulky to provide patients with more comfortable settings and provide greater force resistance. Also, believing that home-based systems that would see patients log in to a rehabilitation-based system on their own and perform the exercise is a tremendous achievement in post-stroke rehabilitation, better equipment and more powerful software become a must and not an option.

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