Low-cost Virtual Rehabilitation of the Hand for Patients Post-Stroke

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***Abstract*— We are witnessing the convergence of game technology (both software and hardware) with rehabilitation science to form a second-generation virtual rehabilitation framework. This is fortunate in view of the need to reduce system costs and thus facilitate adoption in clinical practice. This paper presents an Xbox-based physical rehabilitation system currently under development at Rutgers University. Unlike its high-end precursor aimed at hand training for patients post-stroke, the experimental system described here uses an inexpensive P5 game glove and Java 3D simulations. This results in significant cost savings, albeit with some tradeoff in functionality.**

I. Introduction

THE advantages brought by virtual reality to physical therapy [1] have been recognized by the engineering and rehabilitation science communities (see Holden for a recent review [2]). However, widespread clinical acceptance of virtual rehabilitation is slow in coming, partly due to the lack of sufficient statistical data on efficacy and safety. Just as important, the cost of systems such as IREX [3], or SenseGraphics 3D-LIW is prohibitive for many outpatient clinics where such high-end computerized systems belong. There is therefore a need for low-cost (off-the-shelf) systems that are easy to install and use, either at an outpatient clinic, or (in the future) at home.

One component of Virtual Reality-based rehabilitation is the computer running the simulation exercises, typically a PC (single or multi-processor). The increased computational performance of game consoles, such as Sony's PlayStation 2 [4], makes them a natural candidate to replace the more expensive PC. An example is the just-announced CatEye GameBike [5], which transforms an exercise bicycle into a video game controller when connecting it to a PlayStation 2. The patient can then exercise while playing a variety of games against the computer (car racing, speedboats, motorcycle racing, etc.). Game consoles will be even faster in the future, with the PlayStation 3 being the computational equivalent of 8 processors [6], and vastly surpassing the graphics performance of even the fastest PC on the market today.

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Another part of a low-cost computerized physical rehabilitation system is the user interface device, which mediates the patient's interaction with the simulation. Reikenmeyer [7] integrated a modified Logitech haptic joystick in order to train the wrist of chronic patients post-stroke. The inability of such patients to maintain grip required Velcro attachments, and their difficulty working against gravity made necessary an elbow support. With these modifications the system allowed patients to play video games and improve their wrist function in their home, while being evaluated remotely through tele-rehabilitation. Another gaming interface that has been adapted for virtual rehabilitation is the PlayStation 2 EyeToy camera. It was used successfully by Rand et al, [8] to train a small sample of acute and chronic post-stroke patients who plaid the games provided by Sony for the EyeToy. Brooks and Peterson [9] used the EyeToy in mirror therapy with children, using a projector and large screen to allow children to view their full-size image in the game. The Microsoft force feedback steering wheel, originally developed for racing games has been used in driving simulators for re-training patients with traumatic brain injury or patients post-stroke [10].

In order to keep the cost of virtual rehabilitation low, one also needs low-cost authoring and runt-time software. These VR toolkits are used to create and run the simulation exercises on which the patients train. Game software engines, once costing in the hundreds of thousands of dollars, now can be purchased for about $500 (such as 3D Game Studio developed in Germany [11]). Alternately one can write code in Java 3D [12], which is free, and performs just as well as expensive authoring toolkits in terms of scene refresh rate and latency [13, 14].

Our group has done pioneering research on the use of virtual reality for the upper-extremity impairment training of patients post-stroke [15-17]. Finger range of motion, fractionation and speed of flexion exercises utilized a CyberGlove [18] which costs about $10,000 and were programmed in WorldToolKit [19], licensed for $6,000. While trials performed at the University of Medicine and Dentistry of New Jersey were very encouraging, it was clear that the system was too costly. This paper presents initial work on a follow-up low-cost system currently under development at Rutgers University. Section 2 presents the experiment system hardware, while Section 3 describes the software used. A cost and functionality comparison between the two systems is given in Section 4 together with directions for future research.

II. Experimental System Hardware

The low-cost rehabilitation system that is being developed for hand rehabilitation post-stroke is shown in Figure 1. It consists of a modified Xbox that runs the training exercises, a P5-glove which measures the flexion of all fingers as well as the wrist 3D position, a graphics display (in our case a color monitor), and Internet connection to a laptop used in software development. The reasons for choosing the Xbox as computing platform are cost, large number of existing systems in patients' homes and the possibility to modify its hardware as required for use as a rehabilitation platform.

The Xbox is a sixth-generation gaming system made by Microsoft. It contains a Pentium III CPU (733Hz), an Nvidia Graphics Processing Unit (GPU) chip, a 10 GB hard drive, a 1-GB front side bus, unified memory architecture, USB ports, NVidia audio processor, and a network interface [20]. The Xbox used in our experimental system was version 1.4 containing a Conexant video encoder, a 1.00.5101.01 kernel version, and a 1.00.5960.01 version dashboard.

The modifications made to the original Xbox are highlighted in Figure 2:

- A Xodus Xenium mod-chip [21] was installed on the Low Pin Count Interface (LPC) debugging port of the Xbox. This was done in order to bypass the original BIOS of the Xbox when connecting to its CPU. This allowed the use of Cromwell BIOS instead of the original BIOS of the Xbox. The added Xenium has a hard-drive copying and upgrading utilities, an ftp server, and 1 MB of space for additional BIOS that are used for booting.
- An additional CD-Rom drive was installed in order to increase the readability of media of the system.
- An Xbox-to-USB Adapter was added to attach USB 1.1 compliant peripherals, namely a keyboard, a mouse and the P5glove.
- To give the patient a better view of the exercises the TV normally used by the Xbox was replaced by a CRT monitor. This in turn required an NTSC-to-RGB adapter (model Video Game Jockey).

A P5 glove (made by Essential Reality) is connected to the Xbox USB adapter. The P5 glove measures the flexion of all fingers as well as the wrist position vs. a "base station" tower [22]. It has an ergonomic design, with the sensing structure weighing only 4.5 oz (128 grams) and being placed on the back of the hand. Each finger sensing structure has one resistive bend sensor, which measures the global bending with a 3.0-degree maximum resolution over a range of 0 to 90 degrees. The wrist 3D movement (translations and rotations) is tracked optically using infrared LED mounted on the backhand connector. This allows wrist measurements to be done 60 times every second, while the hand is kept at up to 4 feet (1.2 meters) from the base station. The base station in turn is connected to the Xbox over the USB adapter, transmitting the patient's hand gestures. In our experiments only the finger flexion data were used, as described in Section 3.

Fig. 1: Overall view of the experimental low-cost finger training system. © Rutgers University.

III. Experimental System Software

A. *Xbox modified operating system*

The Xbox hard drive has the **Fat-x** special file system designed by Microsoft that works only with the Xbox kernel. For this reason there are some limitations on the file systems that can be installed on the Xbox hard drive. The Linux distribution installed on the Xbox is **Xebian**, a special distribution based on Debian specially tuned for the Xbox. The Xebian operating system was installed as it has kernel support for an open source implementation for the **Fat-x** file system. This allowed the installation of the **GNU/Linux** operating system on an image file on top of **Fat-x** file system. Thus to the Xbox original operating system, **GNU/Linux** looks like a normal file on the disk. This installation method has the advantage that it preserves the original Xbox software, while allowing us to run a custom operating system that transforms the Xbox in a machine suited for virtual rehabilitation exercise development.

The P5 glove used in the present system is supported on **Linux**, yet manual modifications on the kernel side for the glove were needed for the glove to work properly. The default kernel had to be patched and recompiled, and the communication to the Xbox through USB driver that the glove producer provides was implemented in user space, using the **libusb-0.1.8** library. As our intention was to make the glove data available in Java, and the driver was written natively in C, we had to implement a JNI interface that passes the natively read data from the glove to the **Java Virtual Machine**. Implementing a **JNI** interface requires that the native library be a shared library that can be dynamically loaded at runtime. We used a "server" program that is provided by the glove manufacturer as a proxy to get the data for us. Communication between the server program and our JNI native implementation is done using a shared memory block and a synchronization mechanism.

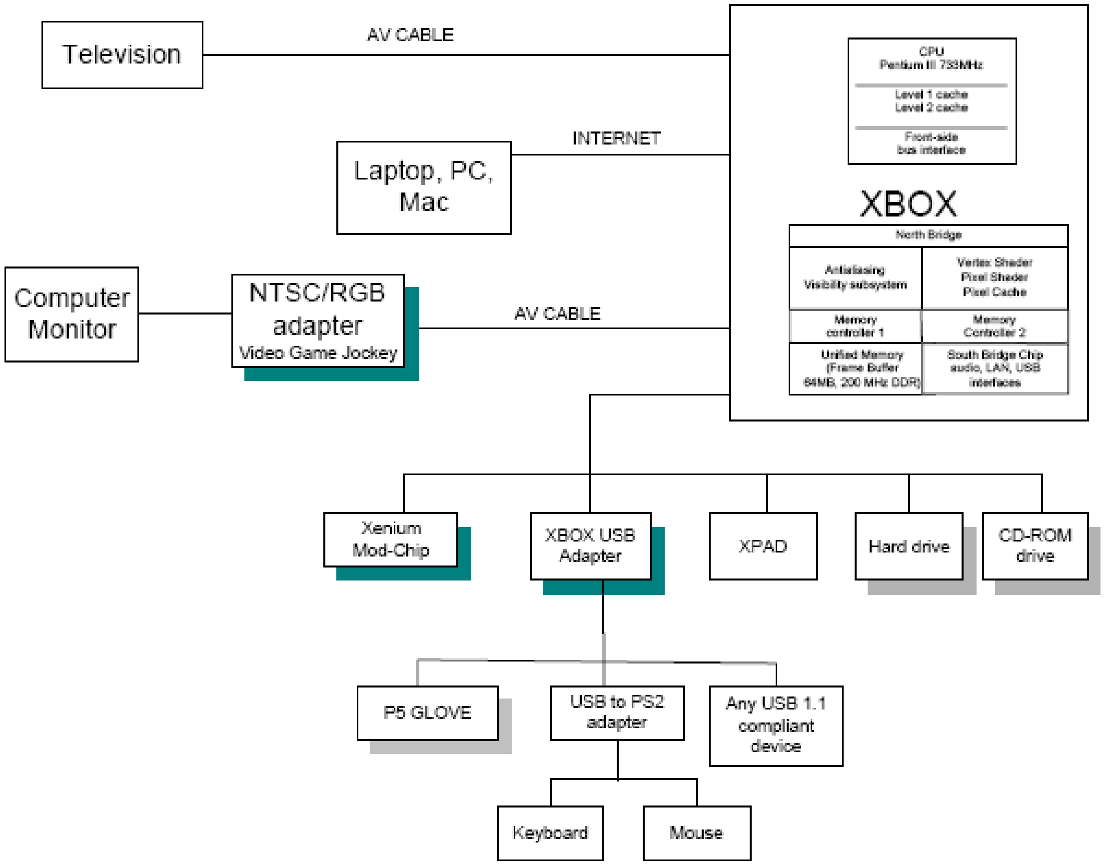


Fig. 2: System hardware block diagram (modifications to the original xBox architecture are shaded). © Rutgers University.

The latest Java Virtual Machine 1.5 (Sun's implementation) and Java3D were installed on the Xbox. The Java3D implementation for Linux platforms uses an OpenGL library to render its graphics. The Xbox NVidia GPU is a game console dedicated chipset, and does not have Linux support for hardware-accelerated rendering. The graphics driver that comes with Xebian distribution is a generic open-source driver for NVidia chipsets, that is slightly modified to output vertical refresh rates that are compliant with a NTSC TV frequency. Given these restrictions, we could not use the hardware OpenGL implementation of the graphics card. Instead we chose the **Mesa-6.4** OpenGL software implementation library.

B. The Training Simulations

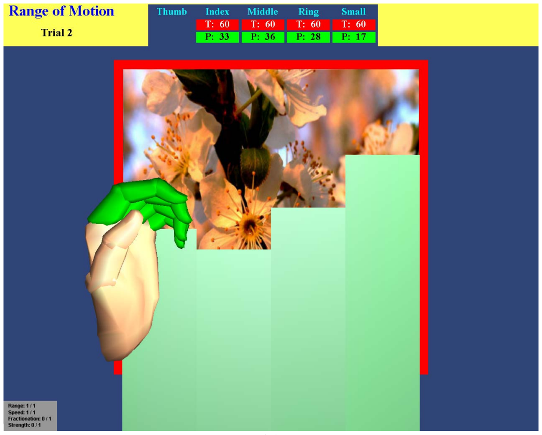
The Java 3D simulations were chosen to emulate a subset of two of the four WorldToolKit exercises that were the basis of the 2002 study on hand training for post-stroke chronic patients [23]. The use of Java3D had the advantage of portability. Exercises were first developed and tested on a laptop, then downloaded to the Xbox. Thus the same exercises would run on both platforms, as long as Linux (and not Windows) was used.

The glove driver outputs only "raw" values from the glove finger sensors, thus a calibration is needed after the patient puts on the P5 glove. After calibration, in order to produce valid bending information, a linear interpolation between the calibrated data and the maximum raw value is performed. Averaging of several readings is used to reduce the "noise" in the data, and prevent the virtual hand from shaking on the screen.

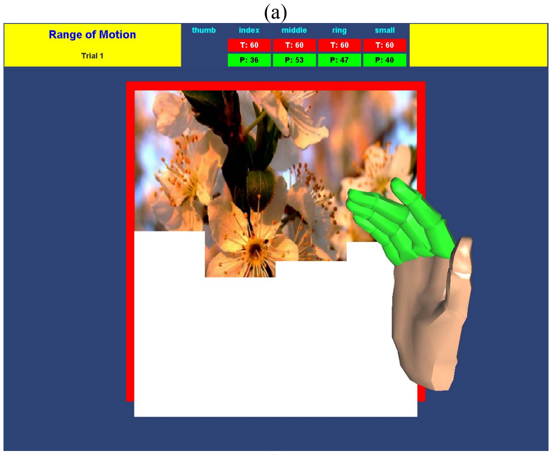
Following calibration, the patients are baselined, in order to determine their range and speed of motion for a particular session (day). Then the starting values of the exercises are based on the baseline, past results, and the recovery plan for the patient.

FINGER RANGE OF MOTION GAME

The finger range of motion game asks the patient to start with the hand in the neutral (flat) position. Each of the four fingers is mapped to a bar of "dirty" pixels which occludes a pleasant image. The task is to clean up the screen, such that the occluded image will be seen. The image is uncovered in proportion to each finger flexing motion, such that the patient receives feedback on his/her performance in real time. Additional performance feedback is provided numerically by the graphical user interface top portion of the screen. At the start of the exercise each finger is given a goal, and actual finger bending is displayed in real time. As the goal is reached for a particular finger, its numbers change color and start flashing. At the end of the trail, additional congratulatory images (fireworks) and sounds (applause) are plaid on successful completion, in order to keep the patient motivated. Figure 3 can be used to compare the screen shots from the original game (programmed in WTK) and the new one (Java 3D). The latter was captured on the laptop running Linux with



(a)



(b)

Fig. 3: Virtual Reality simulation exercises for finger range of motion: a) WorldToolKit; b) Java3D. © Rutgers University

the P5glove attached, since the Xbox does not have screen capturing software installed. Furthermore, the Xbox system has a 16-bit color map instead on the 32-bit used by the laptop. Thus on an Xbox the screen will appear less colorful, and with lower resolution.

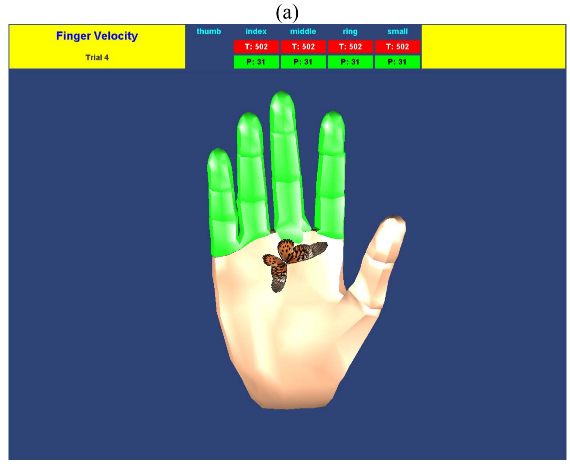
FINGER VELOCITY TRAINING GAME

The Finger Velocity exercise consists of the patient flexing their fingers from the flat position to a fist as fast as they can while their individual finger velocity of motion is measured. At the start of the exercise a virtual butterfly circles in the palm, and subsequently it is flying away if the velocity goal is met or exceeded. The patient can perform the same motion repeatedly, until either the butterfly flies away or the maximum time is exceeded. The same feedback mechanism is implemented, with finger-specific numerical values displayed by the GUI and congratulations offered at trial completion.

IV. DISCUSSION

Table I is a cost comparison between the experimental hand physical therapy system presented here and its precursor, which used a PC, a CyberGlove and exercises programmed in WorldToolKit. It can be seen that the new system compares favorably in terms of total cost ($549 vs. $17,600). In this analysis we considered a Java Research License for

(a)



(b)

Fig. 4: Virtual Reality simulation exercises for speed of finger motion: a) WorldToolKit; b) Java3D. © Rutgers University

non-commercial use which makes it free for this project. When such technology translates to commercial clinical use, the software will no longer be free. Conversely, the cost of the high-end system would have been even higher if its use of the Rutgers Master II haptic glove were considered.

Another important aspect to consider when comparing the two systems is their functionality. There is no question that the low-end system also has lower functionality. The P5 glove cannot measure the individual joints of each finger, unlike the CyberGlove. Furthermore, the P5 glove has less accuracy and resolution, compared with the more expensive CyberGlove. Unlike the Rutgers Master II haptic glove used in 2002 to train finger force exertion, the P5 glove does not provide force feedback.

It is unclear at this time how a glove such as the P5, which is designed for normal hand anatomy, will function when worn on the affected hand of patients post-stroke. It is possible that force feedback could be added to the library of exercises we developed thus far, through the use of actual prop objects grasped by the patients. Finally, pilot data with patients exercising on the new system are needed, in order to fine-tune its software, improve its usability and begin to gauge its medical efficacy. Tests on post-stroke patients are being planned at this time. If such a system is proven useful to retrain the hand in post-stroke populations, it will open the door for more training at home, under tele-rehabilitation settings. It also needs to be pointed out that both the Xbox and the P5 are no longer being produced (although they are still being sold on the Internet). The PlayStation 3 and a (yet-to-be-sold) low cost glove will replace the system being tested here.

TABLE I

COST COMPARISON BETWEEN THE HIGH-END AND LOW-COST FINGER TRAINING SYSTEMS

Variable	**Low-end system**	**High-end system**
Computing platform	Xbox $175	PC $1,500
Glove	P5 $13	CyberGlove $10,000
Programming toolkit	Java 3D 0(free)	WorldToolKit $6000
Monitor or TV	$300	$300
Extra Components	$61	none
Total cost	$549	$17,800

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