PlayStation 3-based Tele-rehabilitation
for Children with Hemiplegia

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Abstract— The convergence of game technology (software and hardware), the Internet, and rehabilitation science forms the *second-generation* virtual rehabilitation framework. This reduced-cost and patient/therapist familiarity facilitate adoption in clinical practice. This paper presents a PlayStation 3-based hand physical rehabilitation system for children with hemiplegia due to perinatal brain injury (hemiplegic cerebral palsy) or later childhood stroke. Unlike precursor systems aimed at providing hand training for post-stroke adults in a clinical setting, the experimental system described here was developed for in-home tele-rehabilitation on a game console for children and adults with chronic hemiplegia after stroke or other focal brain injury. Significant improvements in Activities of Daily Living function followed three months of training at home on the system. Clinical trials are ongoing at this time.

I. INTRODUCTION

VIRTUAL reality-based physical therapy has a number of recognized advantages over conventional approaches [3, 14]. These include the ability to gradate therapy and adapt automatically to a patient's (limited) functioning level, high patient motivation, transparent data collection and upload, and computerized (objective) measures of progress. Widespread clinical acceptance of virtual rehabilitation is slowed in part by the relatively high cost of current commercially-available systems (such as the $10,000 IREX [9], or the $52,000 Armeo [13]). Other reasons are the lack of sufficient training of physical therapists in the new technology, and lack of large scale clinical data to show medical efficacy, and clinician technophobia.

While commercial technology is lagging, a number of organized and "ad-hoc" research efforts are taking place, looking at game consoles-based rehabilitation. One example is the use of a modified Logitech haptic joystick in order to remotely train the wrist of chronic patients post-stroke [23]. The inability of such patients to maintain grip required Velcro attachment, and their difficulty working against gravity made an elbow support necessary. Another gaming interface that has been adapted for virtual rehabilitation is the PlayStation 2 EyeToy camera [22]. It was used to train a

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small sample of acute and chronic adult post-stroke patients who played the games provided by Sony for the EyeToy. Chronic post-stroke patients were more appreciative of the system than patients in the acute phase, for whom the games proved difficult. This was to be expected, since off-the-shelf games are designed for healthy individuals. Subsequently, Glenrose Rehabilitation Hospital (Canada) pioneered the use of a Nintendo Wii to successfully train a patient with traumatic brain injury [26] and subsequently other patient groups. Their example was followed by numerous clinics and hospitals around the world, with the Nintendo Wii being used to train a number of different patient populations, such as stroke survivors, those with traumatic brain injury, and war veterans [36].

All of the above systems (including the Wii) do not specifically train finger movement. Morrow et al. [19] at Rutgers University adapted an xBox console and low-cost P5 glove for hand rehabilitation [29]. They used custom Java 3D exercises [27], adapted from earlier PC-based simulations developed in WorldToolKit [25], for finger range and speed of movement training. The drawback of this earlier system was the use of the first-generation xBox, with limited computing power, an unreliable sensing glove, and the extensive hardware modifications needed to allow the use of the Linux Operating System.

This paper presents ongoing joint research at Rutgers and Indiana Universities on the development of a PlayStation 3 system for hand tele-rehabilitation of children with hemiplegia. Section 2 presents the targeted patient population as well as the motivation to switch from conventional therapy to virtual rehabilitation for such young individuals. The experiment system hardware used in this project is described in Section 3, while Section 4 describes the custom rehabilitation software. A report on the rehabilitation protocol and current experiments on three case studies is given in Section 5. Section 6 concludes this paper and outlines directions for future research.

II. TARGETED PATIENT POPULATION

Children can develop hemiplegia from a perinatal brain injury or a later brain injury that affects only one side of their brain, or one side far more than the other. To affect movement, the injury must involve motor areas or pathways. The long-term effect of this sort of injury is usually weakness and spasticity of the affected limbs. When the injury causing hemiplegia occurs in the perinatal period or first few years of life, the resulting hemiplegia is known as "hemiplegic cerebral palsy." Causes of perinatal unilateral brain injury

include intraventricular hemorrhage (bleeding in the brain) due to premature birth, and perinatal stroke. Cerebral palsy affects 2.4 out of 1,000 children [12], and the United Cerebral Palsy Research and Educational Foundation [30] estimates there are between 1.5 and 2 million children and adults living with various types of cerebral palsy in the United States. Hemiplegic cerebral palsy accounts for about 30% of those cases [34]. Stroke past the perinatal period is less common and affects between 2.3 [5, 6] and 4.3 [35] children per 100,000 children per year.

Hand dysfunction is probably one of the most disabling aspects of hemiplegia. Most tasks of everyday living use both hands (getting dressed, self-grooming, picking up and handling objects from food to books to toys). Children with hemiplegia struggle with the activities of daily living (ADL) from the time they get up in the morning to the time they go to bed. Constraint-based therapy, which involves constraining the "normal" hand to force use of the plegic hand, has been shown to be effective in the rehabilitation of the plegic hand [2], [4], [28]. However, it is often not well tolerated by children, who resent having one hand constrained (Personal communication, families of pediatric stroke clinic patients to M. Golomb). The novel virtual rehabilitation system presented here is a therapy likely to be better tolerated by children; instead of forcing use of their plegic hand by constraining the other hand, it encourages use of the plegic hand by fitting a sensing glove to the plegic hand to connect to the videogame system. The children are given an enjoyable activity to perform (videogames and videogame-type exercises) with the plegic hand.

Lack of access to ongoing rehabilitative care is another problem faced by these children. In Indiana, the state provides services to children up to three years of age through the "First Steps' program. After that, many children are limited to what they can get through the schools. Our patients have reported going from 3 hours a week or more of in-home therapies from First Steps (which include occupational therapy), down to 30 minutes a month or less of therapy in the school. Many families cannot afford to provide additional therapy, and are further limited by the working schedules of both parents (personal communication, families of stroke clinic patients to M. Golomb). This project provides in-home remotely monitored therapy to children who otherwise would not be able to access it.

III. EXPERIMENTAL SYSTEM HARDWARE

The experimental system described here is built around a PlayStation 3, owing to its ability to run Linux operating system (OS). This OS is needed in the rehabilitation system functional integration and customization. Other reasons to choose the PlayStation 3 are its input/output characteristics, its high performance multi-core computation power and the large existing home base of such consoles. The PlayStation 3 is familiar and easy to be used by children, the targeted age group of the study. Since the purpose of training is hand rehabilitation, a number of commercially-available sensing gloves were considered. The 5DT 5 Ultra (five sensor) glove

was selected due to its lower cost, and the willingness of the manufacturer to build custom child-size gloves [1].

A. The home rehabilitation station

Each home tele-rehabilitation system consists of a PlayStation 3, a right-hand 5DT Ultra glove, computer keyboard, optical mouse, and a flat panel TV monitor (Figure 1*a*). The TV connects through a High Definition Monitor Interface (HDMI) cable to the HDMI port of the PS3. The PS3 has six USB ports, two of which are used to plug a keyboard and a mouse. The 5DT 5 Ultra glove has one fiber optical sensor per finger, thus measuring the "total" flexion or extension of each finger. Each sensor reading represents an integer from 0 to 4095 due to the 12 bit analog/digital converter electronics embedded in the glove wrist unit. A glove calibration is needed to map this range to a % of finger flexion/extension. The 5DT 5 Ultra glove wrist unit has a USB connection, however, the manufacturer has Linux drivers only for serial ports. Thus it became necessary to use the 5DT serial interface kit, which is a USB-to-serial adapter, and a subsequent serial-to-USB adapter, in order to use the glove on the PlayStation 3 operating under Linux.
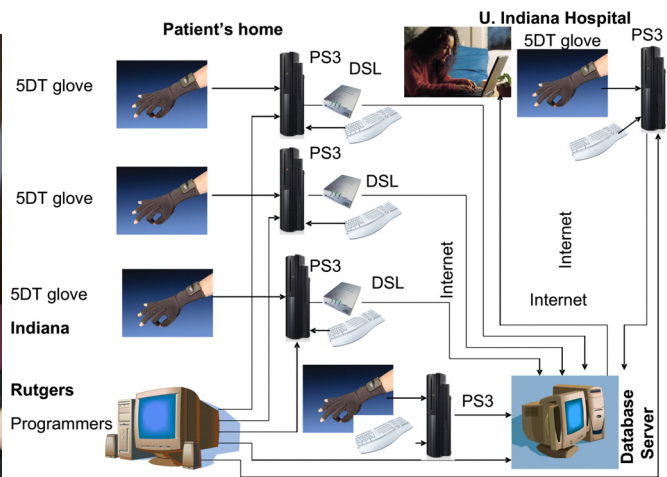
B. Tele-rehabilitation Set up

In order to implement the tele-rehabilitation setting, the PS3 uses a DSL modem/router in the home. The router is connected to the local area network (LAN) port of the PS3 and to the wall phone jack. Three such systems were installed in the subjects' homes in rural Indiana, as illustrated in Figure 1*b*. The members of the research team at the University of Indiana (Indianapolis) have an identical system used for backup, and to test software upgrades prior to loading on the home PS3s. Another PS3 is used in game programming and testing by the research team members at Rutgers University. Under tele-rehabilitation conditions data stored in each home session is uploaded to a clinical database server at Rutgers. This is a Dell quad core workstation with RAID hard drives, uninterruptible power supply and external one TB backup hard drive. A database Oracle module allows the Indiana team to remotely monitor patient progress, as well as compliance with the established therapeutic protocol. This is done using a password-protected web page and graphing environment that allows the clinicians to select variables to be graphed for a specific subject, over the duration of therapy. The infrastructure developed here makes the system a *multiplexed* tele-rehabilitation set up, since a single physician can monitor several patients remotely.

IV. EXPERIMENTAL SYSTEM SOFTWARE

A number of software changes are needed to transform a game console into a rehabilitation station. These include changing the operating system to ensure openness, integration of drivers for peripherals not usually used in standard games (such as sensing gloves), development of customized (and therapy-oriented) games, and implementation of session baselines and schedulers which progress the patient through a sequence of games during a

Fig. 1. The experimental finger training system: a) home station; b) tele-rehabilitation setup.
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given rehabilitation session. If the game console is to be used at home and monitored remotely, as is the case in tele-rehabilitation applications, additional software are needed to allow data upload to a centralized database server, as well as to allow periodic downloads of game upgrades and other changes to the local software settings.

A. PlayStation 3 modified operating system and glove calibration

Operating System Modifications

The powerful PlayStation 3 box is regularly used for local or on-line gaming developed by Sony or third party companies through the commercial Software Development Kit (SDK) provided by Sony. The SDK is proprietary and limits the interaction with the gaming console to standard gaming devices, i.e., joysticks. Furthermore, it does not provide support for custom input devices (such as external sensors and gloves).

The PlayStation 3 has built-in support for third party operating systems that support the IBM Cell Broadband Engine processor. To overcome these limitations and the price of the Sony's SDK ($10,000), the tele-rehabilitation system developed here uses the open source GNU/Linux operating system. While Linux transforms the PlayStation 3 into a general development system, the major performance limitation is that the multi-core and graphics processors hardware are not directly accessible to the Linux operating system. Since the OS cannot directly access the video card for fast rendering (i.e., OpenGL) graphics is currently rendered in software by the PowerPC embedded on the multi-core chip. This in turn limits the complexity and realism of the scenes presented to the patient, in order to maintain the scene refresh rates at accessible levels.

Other customization occurs at the application level. The 5DT Co. does not provide Linux drivers for the USB interface, but instead provides drivers for a serial connection interface. The glove driver only "speaks" the serial protocol, and so the kernel was customized to create a software USB device corresponding to the glove serial-to-USB adapter. A serial-USB kernel module was used on top of this software device to provide the abstraction of a serial software device. The USB software device number/name (USB0, USB1, etc.) assignment is system dependent. It also depends on the external devices already connected to the system (mouse and keyboard). To make the interface for the external glove portable (preserve the same name independent of the devices already connected to the system) a daemon was customized to recognize the glove firmware and always assign to it the same device name ("glove").

The custom games developed as part of this project were written in Java3D. Thus the X server's OpenGL interactions with the hardware were also customized by installing the Mesa library [18], which provides OpenGL rendering functions that Java3D needs to render the 3D virtual scenes. We also installed a PowerPC Java version provided by IBM and an open source implementation of the Java3D specifications (version 1.3). To the best of our knowledge, there were no binary packages available for the OpenGL-drawing native bindings for Java3D, neither Gentoo ebuild [8], nor IBM, Fedora [32], or SUSE [21] builds. Therefore the native sources for Java3D bindings had to be manually downloaded, compiled and installed.

As the game simulation used for rehabilitation is a complete Java application, the simulation codes need to be interfaced with the glove device. A Java wrapper class with a native implementation that uses the Linux glove driver to collect data readings from the glove was used for this purpose. This class extends the Java3D standard interface for external sensors, and the glove could be used for scene interactions as yet another Java3D sensor device.

Glove calibration/Baseline

The calibration method necessary for proper functioning of the glove is handled by the baseline program, which provides a method for both calibrating the glove, as well as storing these values in a log file. This log file will be uploaded to the database at a later point in time to allow correct

interpretation of subsequent game data. Since the glove is calibrated before each session, each game's log file correlates to a specific baseline log file. Due to this correlation, only scaled data are stored in the game's log file and performance is measured by combining the data from both the baseline and games. While running the baseline, the patient is given on-screen cues to open/close their hand or bend/extend their thumb. The program will use the minimum and maximum values obtained in this 90 second baseline application, to create a calibration file used by the rehabilitation games. This calibration file maps the patient's limited range of movement in the affected hand to the full range movement of an on-screen hand avatar. This allows the games to use a percentage of the patient's range as thresholds for completing each trial within the games. These percentages can be modified to allow customization of the games relevant to the patient's progress and individual needs. They also allow for difficulty levels which can be selected by the patient when starting the game in the scheduler (see description below). The thresholds are set accordingly, depending on the selected difficulty level and clinician settings.
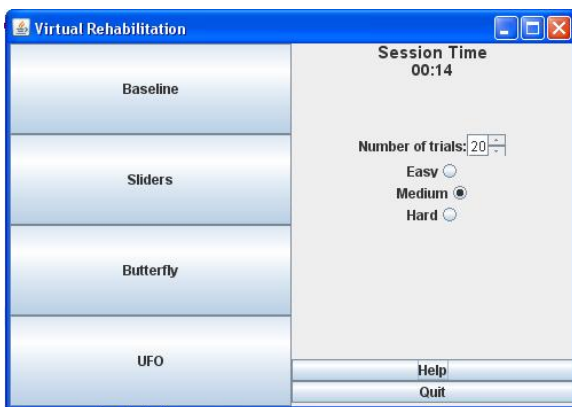

Fig. 2. Session scheduler allowing subjects to select their rehabilitation games and preferred difficulty levels.
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B. Session Scheduler

The session scheduler appears to the patient after starting a session and running the initial baseline. This interface allows the patient to select which game he/she would like to play next, as well as giving the option to choose a difficulty level and number of trials for that game. The total session time is displayed by the scheduler, to show how long the patient has been training thus far on that day. A help screen is also available, which provides answers to any problems with the system that patients might have. The scheduler also allows the patient to run the baseline again, in case the glove had been taken off, or if experiencing any problems with the glove. After playing a game, the scheduler will reappear, allowing the patient to choose what the/she would like to play next. This customized variability helps to further reduce the boredom factor involved in repetitive rehabilitation applications by empowering the patients to choose the games that they like the best, or to focus on

certain tasks that they would like to improve at. The scheduler can also be set to follow a certain set of games if the clinician would like to confine the patient to a set training regimen.

C. The training simulations

Three Java 3D simulation exercises were developed thus far, based on our experience with games authored in earlier studies. Those studies had used more expensive PCs and CyberGlove sensing gloves [15], as well as a proprietary WorldToolKitt language to train elderly post-stroke chronic patients [16, 17]. The use of Java 3D and PlayStation 3 has the advantage of portability and of substantially lower overall system cost. Furthermore, the PlayStaion 3 multi-core architecture opens the door for (future) performance improvements compared to dual-processor PCs used in the past.

Finger Range of Motion Game

The finger range of motion game asks patients to start by making a fist (when extension is trained) or open their hand as much as possible (when flexion is trained). Subsequently, each of the four fingers is mapped to a bar of "dirty" pixels which occlude a pleasant image. Images are randomized, to maintain patient's interest. The task is to clean up the screen, so that the occluded image will eventually be revealed, by either opening or closing the trained hand. The image is uncovered in proportion to each finger motion, providing easily understood performance feedback. The exercise can also be done with the thumb, in which case the whole image is uncovered proportional to the amount of thumb movement. Once a trial completes (a new image is cleaned), points are earned by the patient, and a small version of that image displayed on the side of the current window. Additional performance feedback is provided numerically by the graphical user interface (GUI) 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. Sound is played to add realism and immersion into the game. The sound is similar to that generated during window cleaning, and is produced every time the fingers or the thumb move. Figure 3 shows two instances of the "sliders" game used to train the fingers or the thumb.

Finger Velocity Training Games

First in this category of games is the "butterfly" exercise which asks patients to initially make a fist (if extension is trained) or open their hand as much as possible (if flexion is trained) (see Figure 4). This is similar to the start of the "sliders" game previously described. Subsequently virtual butterflies appear from the side of the screen and need to be "scared away" by moving the fingers or the thumb fast. As long as the patient achieves the set flexion/extension goals before the butterfly reaches the hand avatar, it will fly away, and a virtual flower appears on the screen. If the patient did not move the fingers fast enough, the butterfly comes back and needs to be scared away again. After a number of butterflies have flown away from the hand avatar, a mosquito

attempts to sting it. The patient has to move the fingers fast enough to scare the mosquito away, or else the hand is stung (it flashes red and a corresponding unpleasant sound is produced). The difficulty of the game is increased by making the butterflies or the mosquitoes fly faster. This in turn requires faster reaction time from the patient. The GUI is similar to that of the previous game, with finger specific goals being displayed, as well as total score. Congratulatory text is displayed at the end of the exercise.

A more recent addition to the finger velocity training game category is the UFO game (Figure 5). It borrows a lot from the butterfly game but may be more attractive to play for young boys. Butterflies are replaced by various UFO models (depending on the level of difficulty). In the "bonus" round, the UFO beams a "shrink ray" if the patients had not opened/closed the hand fast enough. The hand avatar then turns green and shrinks. If however, the patient is moving the fingers fast, the UFO flies away and crashes (with corresponding explosion sounds).

Remote clinical database

An integral part of the system is the clinical database. It stores the computerized data generated from the games, and online periodic subjective evaluation surveys. The database module consists of six components. A Java program installed on the PlayStation 3 (in Indiana) uploads the data collected from the different games to a clinical server (located at Rutgers University) using HTTPS (Hypertext Transfer Protocol over Secure Socket Layer). A Java program (designed to accept multiple connections at the same time)
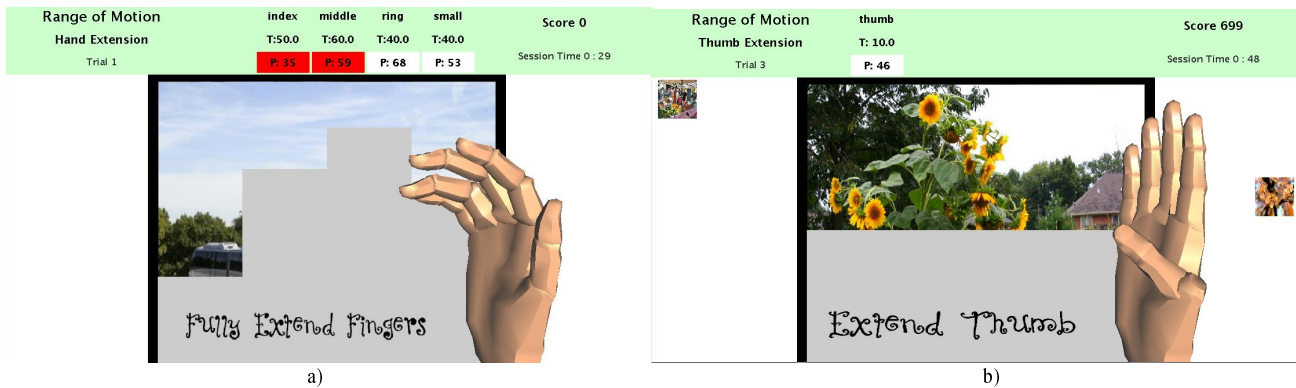

Fig. 3. "Sliders" exercises for finger range of motion: a) finger training; b) thumb movement. © Rutgers University. Reprinted by permission.
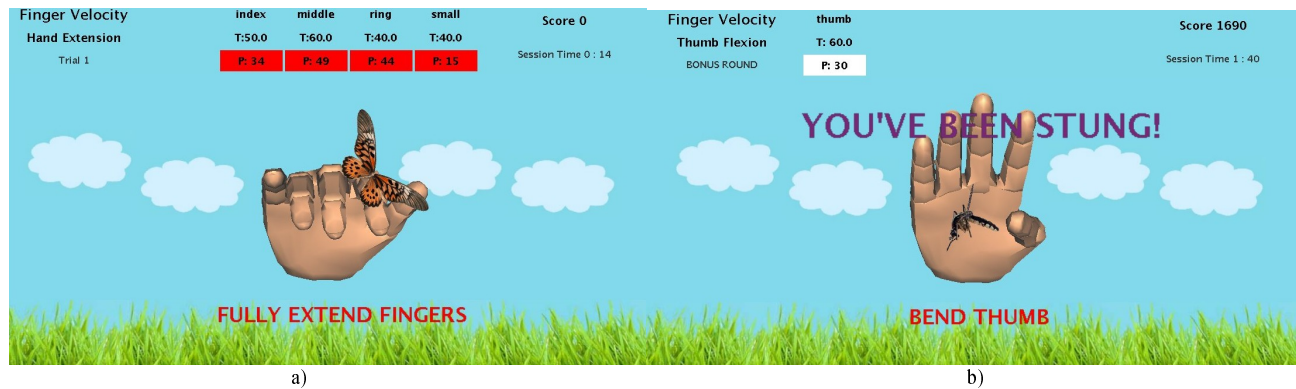

Fig. 4. Java 3D simulation exercises for speed of finger motion. © Rutgers University. Reprinted by permission.
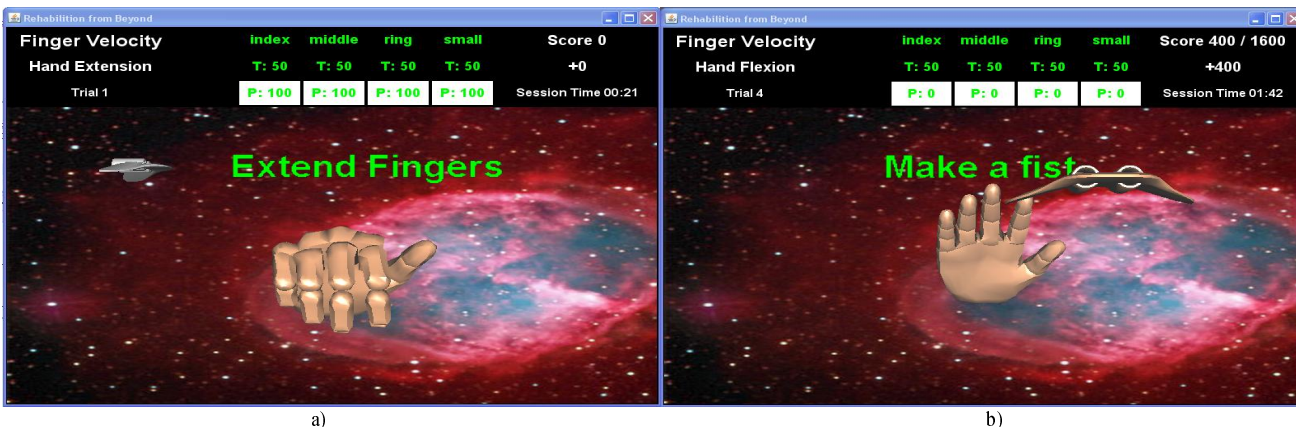

Fig. 5. "UFO" exercises for finger velocity training: a) finger training; b) bonus level. © Rutgers University. Reprinted by permission.

installed on the clinical server then receives these files. Once received another Java program runs to parse these files and extract clinical data and store them on the local database (to ensure security of the data), and saves a copy of the files in an archived folder. The Oracle database module contains the raw data, namely session date and duration, exercise-specific performance, as well as the performance data (averages for finger range of motion and finger velocity). A web portal (also running on the clinical server) allows authorized users to log in, and graph relevant variables showing each patient's progress over the duration of the home therapy. The therapist can upload scanned paper forms directly using the secure web portal. The last component of the clinical database is another Java program installed on the clinical server. This program makes sure that patients practice according to the schedule given by the physical therapist. If they fail to practice on a day they were supposed to, or practiced more than they were supposed to, the program automatically notifies the physical therapist about this discrepancy in practice. An online questionnaire runs on the PlayStation 3 twice a month and allows the patients to evaluate the system. The answers are stored on the database.

Remote game monitoring

The remote capabilities of this system help provide the functionality necessary for full control of the PlayStation 3. Using a cross-platform remote monitoring tool released under the GNU General Public License [10], an authenticated user can visually monitor the PlayStation 3 in real time with full keyboard and mouse control. With servers running on the local and background displays, the system can be used to either watch what is happening on the screen (at home) or to provide a means to make changes, do remote testing, and provide software updates. This functionality was used extensively in the project, as exercise software was continually upgraded, or bugs fixed.

A daemon is running to allow remote shell access as well as secure file transfer, to assist in modifications and updates as well as in data retrieval. A method for notification by e-mail and/or SMS text message to a cell phone has been implemented to notify the clinicians when the patients sign on for their rehabilitation session. If a patient fails to log in for a set number of days, the remote clinician is notified, in order to contact the patient's home.

This array of remote monitoring methods mentioned here allows for multiple ways to determine whether the system is running properly as well as providing a means to tell whether the patient is practicing for the prescribed amount of time, as determined by the clinician. In cases where it is found that the patient is practicing too little or too much, the clinician will be notified immediately and will contact the patient directly to assure that no problems arise. This insures redundancy and consistency, with the database method which notifies the clinician if the patient does not keep up their regular schedule.

V. DISCUSSION

Three children were recruited for this pilot study. They are teenagers with severe hemiplegic cerebral palsy, have difficulty opening and closing their plegic hand, and struggle to pick up objects with that hand. Two of the subjects had perinatal ischemic stroke, the third was born prematurely and had an intra-ventricular hemorrhage. During the study, none of the subjects received other rehabilitation of any kind.

It is necessary to stress that patient selection for the pilot study was extremely important. The three teenage subjects were chosen because they have good cognitive function and the ability to understand that "pilot study means things will go wrong." Due to the sophistication of most videogames on the market, a concern existed that many children would not be willing to practice with a simpler, exercise-based game
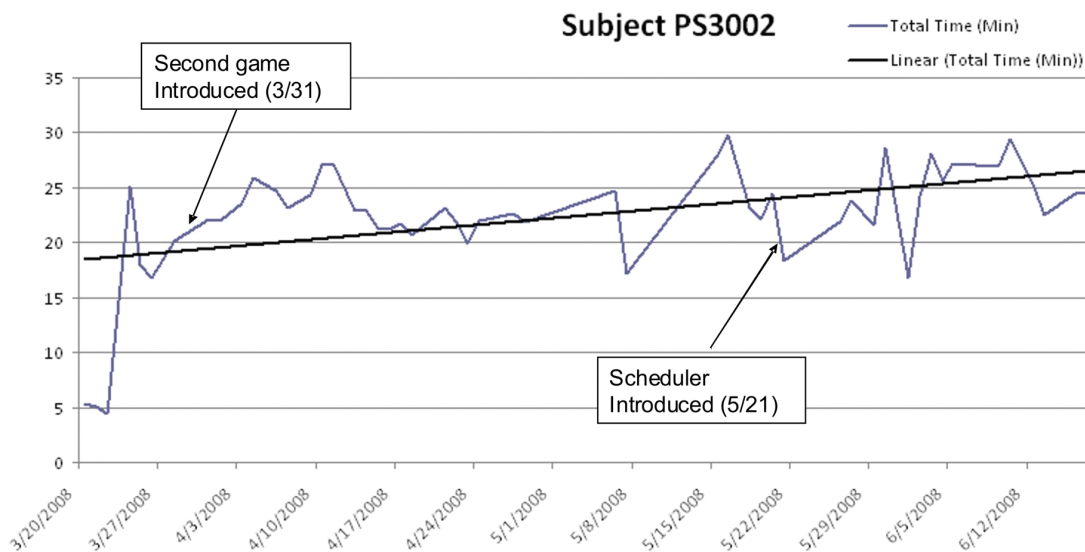

Fig. 6. Subject PS3002 total daily exercise time over three months of training at home in rural Indiana.
Data were uploaded to a clinical database server at Rutgers University (1000 km away).
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that might not work perfectly all the time. Some children with hemiplegic cerebral palsy [11, 31] or later childhood stroke [7, 24] are left with cognitive impairments and tend to have a low tolerance for frustration. The three patients participating in this study are honor students who were initially enthusiastic about this project. Two of the subjects have been very helpful in providing feedback, as well as continuing therapy despite occasional technical problems.

All subjects were told to attempt to practice 30 minutes daily (including rest time between exercises). Figure 6 plots the variation in actual exercise time (exclusive of rest periods) for subject PS3002. Looking at this subject's daily practice over the three months of training is informative of the impact game characteristics and the control patients have on training intensity. At the start of therapy this subject (and the others) had difficulty donning their 5DT Ultra gloves, and practiced less. Once the second game (butterflies) was introduced, the subject's exercise time increased. Subjects were frustrated by the need to do repeated calibrations in a session, and by the fixed number of trials they had to do for each game. These issues were addressed once the scheduler was introduced to them. From then on, they only needed one calibration/baseline per session, and had control on the games they wanted to play. This had the positive effect on addressing boredom, and the subjects continued to exercise more and more. At the time of this writing the UFO game has just been debugged and introduced.

Three months of testing of the three in-home systems have showed that playing therapeutic games on the PlayStation 3 can improve hand function in children with hemiplegia. The combination of patient characteristic limited tolerance for technical problems and varying degree of motivation, have highlighted the importance of remote monitoring.

All three children showed some improvement in hand function (see pre-post changes in ADL in Table I). Detailed clinical testing has just been completed and will be reported when it has been analyzed. Child PS3003 was initially enthusiastic, but then became frustrated with technical issues. As a result he decreased his practicing, while reporting he was still playing. The research team initially wondered if there were technical issues recording his play. However, he would report "no problems" while the other two children continued to report sometimes persistent technical issues. Once subject PS3003 was confronted about the inconsistencies in his claims, he admitted he had stopped training for weeks (while he was supposed to use the system on a daily bases). Possibly because of this, he appears to have had less improvement than the other two children (as seen in Table I).

Further analysis of clinical testing will illustrate the extent of the difference between subject PS3003 and the other two children. Medical noncompliance and false reporting to medical providers are well-known in the literature; many studies of oral medications use electronic pillboxes (Medication Event Monitoring Systems, or MEMS)[20, 33] to look at how many times patients actually open their pillboxes, rather than use their reports of how compliant they are. The initial data in the three months of testing suggest that to achieve maximum efficacy, remote monitoring is an essential component of any in-home virtual reality occupational therapy system.

VI. CONCLUSION AND FUTURE WORK

The system described here is currently undergoing pilot clinical trials in rural Indiana. The next development phase on the technology side will be addition of more exercises, in order to allow longer and more varied rehabilitation sessions. Computerized data from these trials is being collected and a database graphing routine is being designed. The database will also include online subjective evaluations by the subjects, which they will complete every two weeks. Similarly, we will include a subset of the OT (conventional) evaluations, and possibly pre- and post- bone density measurements. Eventually these clinical measures will have to be correlated with the computerized measurements obtained from the PlayStation 3, and with further reports from patients' families on changes in the patients' activities of daily living.

TABLE I
CHANGES IN STUDY SUBJECTS' ABILITY TO PERFORM ACTIVITIES OF DAILY LIVING AFTER THREE MONTHS OF TRAINING
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Subject	Brushing teeth		Carrying Grocery Bag		Put shampoo on hair		Hold spoon		Helper hand dressing		Helper hand sports	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
PS3001	No	No	No	Yes	No	No	No	Yes	No	Yes	No	Yes
PS3002	No*	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
PS3003	No	No	No	Yes	No	No	No	No	No	No	No	No

* Did not try to brush teeth with that hand before training. The children only realized they could perform some of these tasks after being asked to try.

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