PC-based Telerehabilitation System with Force Feedback

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Abstract

A PC-based orthopedic rehabilitation system was developed for use at home, while allowing for remote monitoring from the clinic. The home rehabilitation station has a Pentium II PC with graphics accelerator, Polhemus tracker, and a novel Multipurpose Haptic Control Interface with its own Pentium board. This interface is used to sample patient's hand positions and to provide resistive forces using the Rutgers Master II (RMII) glove. A library of virtual rehabilitation routines was developed using WorldToolKit software. At the present time, it consists of two physical therapy exercises (DigiKey and Ball) and two functional rehabilitation exercises (Peg Board test and Ball game). All VR exercises allow automatic and transparent patient data collection into an Oracle database. A remote Pentium II PC is connected with the home-based PC over the Internet and an additional video-conferencing connection. The remote computer running Oracle server is used to maintain the patient database, monitor progress and change exercise level of difficulty. This allows for timely patient progress monitoring and repeat evaluations over time from the Clinic. The system will soon start clinical trails at Stanford Medical School, with progress being monitored remotely from Rutgers University. Other rehabilitation haptic interfaces under development include devices for elbow, and knee rehabilitation connected to the Multipurpose Haptic Control Interface.

1. Introduction

Timeliness and duration of rehabilitative therapy are problematic for remote rural locations or depressed urban areas. In such instances there are no clinics in the vicinity of the patient's home. Avoiding travel to the clinic altogether would mean that adequate therapeutic intervention can be done at home. However, therapists may not be able to travel to the patient's home, or may be unwilling to do so.

The leading cause of activity limitations for Americans are orthopedic impairments. Such patients typically follow a regimen of combined clinic and home rehabilitation. Home exercises are done on simple mechanical systems that are loaned to the patient. Since these mechanical devices are not networked, there is no way a therapist can monitor a patient's progress at a distance. There is also no way to verify that indeed the patient has done the prescribed home rehabilitation exercises. There is a need for a telerehabilitation system that will record data from patient rehabilitation routine and will allow therapist to remotely monitor patient's progress.

Historically, computer-based biomechanical evaluation tools were first used for monitoring the rehabilitation process. Greenleaf Medical developed “Eval” and “Orca” systems for orthopedic evaluations [1], [2]. The systems offer easy data collection and storage and tools for analyzing the patient’s information. Other companies (Lafayette Instrument Company, Electronic Healthcare Systems, Inc.) are offering software for patient monitoring and evaluation [3, 4]. Data is stored in custom databases and patient reports can be displayed.

The systems described above were designed to be used in the clinic so that they don't include a rehabilitation component. No forces are applied on the patient by these devices. Prototype systems that do provide forces for manual therapy have been developed by Hogan at MIT [5], Luecke at Iowa State University [6] and Takeda and Tsutsul at Nagasaki Institute Applied Science [7]. All these are for upper arm impairments, and are rather complex, making them difficult for use at home.

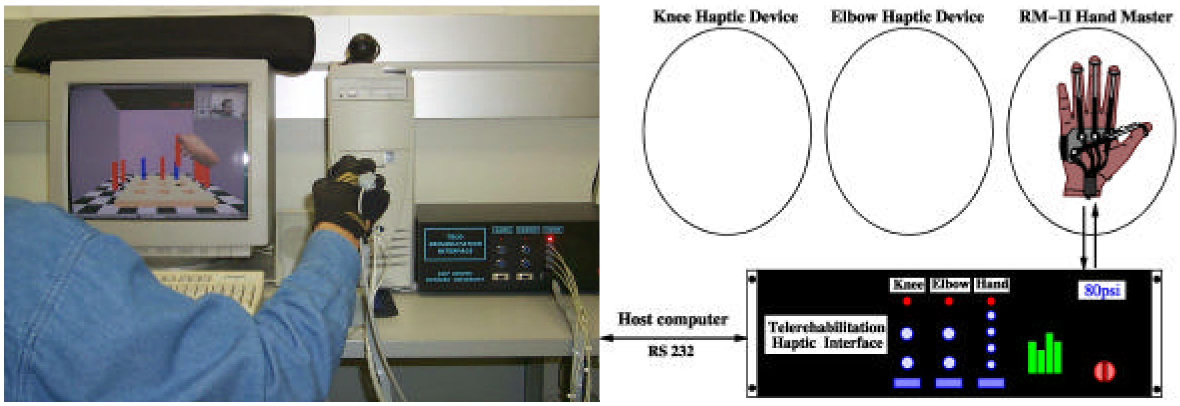
A VR-based system for hand rehabilitation was also developed by Burdea and colleagues [8, 9]. The system differs from the other prototypes mentioned above as it includes a diagnosis module, a rehabilitation module using VR simulations and the Rutgers Master I haptic glove [10]. Proof-of-concept trials were promising especially for the subjective evaluation of the system by the patients. Problems remained due to the DataGlove technology used for hand reading, and the slow graphics workstation used.

The systems described above contain no networking component, and the diagnosis and rehabilitation are done at the clinic. This paper describes another Client/Server telemedicine application in orthopedic rehabilitation. This *tele*rehabilitation system contains has PC workstations, a novel Multipurpose Haptic Control Interface, the Rutgers Master II (RMII) force feedback glove, a microphone array for hands-free voice input and videoconferencing hardware. The system will start clinical trials at Stanford Medical School in November 1998 (client site), with rehabilitation progress being monitored remotely from Rutgers University (Server site). Section 2 describes the telerehabilitation system hardware. Section 3 presents the Virtual Reality rehabilitation library of exercises. The database for patient therapy and presents the Client/Server architecture and networking setup are presented in Section 4. Section 5 concludes this paper.

2. System Hardware

The prototype of the home rehabilitation system is shown in Figure 1-a. It contains a Powerdigm Pentium II PC equipped with an InsideTrack 3D tracker [11], a FireGL 4000 graphics accelerator, a custom microphone array, and a net camera. The Pentium PC is connected to the novel Multipurpose Haptic Control Interface (MHCI) which can drive several rehabilitation haptic interfaces (for the hand, elbow and knee). The MHCI is a redesigned version of the RM-II system, with a new haptic control loop, an upgraded imbedded PC and multiplexing capabilities. It can switch between the hand, elbow and knee haptic devices seamlessly, as required by the VR exercise routine to be executed. The system is self reconfigurable, depending on the patient's needs, without any hardware changes (connect, disconnect, etc).

Currently the system is used with the Rutgers Master II haptic glove while the elbow and the knee units are under development. As shown in Figure 1-b, the RMII glove is an exoskeletal structure that provides forces at the patient's fingertips and contains its own non-contact position sensors [12]. Thus, the system is simplified (no need for a separate sensing glove) and light (about 100 grams). The actuators we are using have glass/graphite structures with very small static friction. The combination of high, sustained, feedback forces (16 N at each fingertip), and low friction provides high dynamic range (300). This makes it capable of high sensitivity and resolution of the feedback forces. We used an InsideTrak to measure the patient's wrist position 60 times/second, while the RMII provides 75 finger position updates/second.



a) b)

Figure 1. Telerehabilitation workstation: a) prototype developed at Rutgers;
b) The Rutgers Master II connected to the Multipurpose Haptic Control Interface

The microphone array [13] provides hands free voice input by focusing on the patient's head siting approximately 3 feet in front of the monitor. The net camera connected to the PC parallel port is able to provide up to 15 fps QCIF images when running on a local machine.

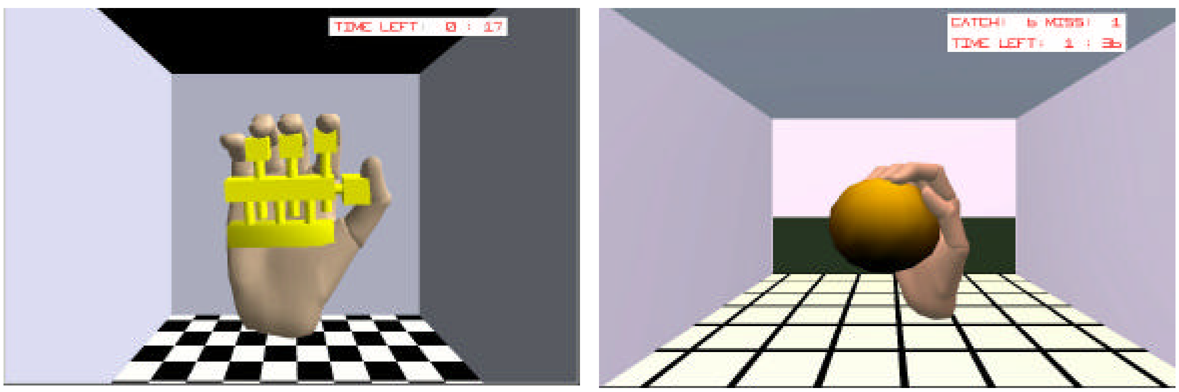
3. Virtual Reality Rehabilitation Exercise Library

The VR exercises were developed using the WorldToolKit graphics library [14]. The Virtual Environment was made simple in order to keep the patient focused on the rehabilitation procedures. All exercises contain a high-resolution virtual hand [15] and several objects (DigiKey, Peg board, rubber ball, etc.) created with AutoCAD [16], or WTK Modeler. Several hand gestures allow patients to interact with the virtual objects: whole hand grasping, two finger grasping (lateral pinch), selecting and releasing. Contact detection is checked between hand segments and the objects, with intersection between hand segments and objects triggering a grasping gesture. Objects stay attached until a release gesture is executed. The select gesture is executed with the index finger touching a virtual object. This gesture is used only at the beginning of each exercise to interactively set the rehabilitation routine level of difficulty, and virtual object stiffness.

We broadly classified the rehabilitation routines in two categories: physical therapy (PT) and functional rehabilitation. Physical therapy exercises use force feedback to improve patient's motor skills (exercise muscles and joints). Functional rehabilitation exercises have much greater diversity because they aim at regaining lost skills (activities of daily living or job related skills). Therefore the output depends on each exercise design, but the essential feature of these exercises is patient's interactivity with VE. Each therapy exercise has several levels of difficulty corresponding to the maximum force that can be applied, the time allowed, the skill level or other parameters.

The first PT exercise models a rubber ball squeezing routine. The ball stiffness is color-coded and can be selected by the patient at the beginning of the exercise. Ball dynamics simulate gravity and Newtonian laws. Once it is grasped, the ball deforms in contact with the virtual hand while force feedback is displayed to the patient and recorded in the database. The exercise terminates when either the patient presses an exit key or the allowed time was exhausted.

The second PT exercise implements a virtual version of the DigiKey [17], which is an individual finger exerciser, illustrated in Figure 2-a ([8]). The model was modified to include the thumb instead of the pinky due to RM-II configuration. The DigiKey maximum force levels were color coded to match the commercially available set. After grasping the selected DigiKey, contact detection is checked between fingers and the corresponding cylinder ends; while in contact, the virtual cylinders are driven by the patient's finger movements. Forces proportional to the displacement of the DigiKey cylinders are fed back to the patient and stored transparently and simultaneously in the database.



a) b)

Figure 2: Virtual rehabilitation exercises: a) virtual DigiKey (adapted from [8]); b) Ball Game exercise.

The first functional rehabilitation exercise is a peg board insertion task. The simulation uses a virtual peg board with nine holes and corresponding number of pegs. The exercise has three levels of difficulty: “Novice,” “Intermediate” and “Expert,” each with a different clearance between the peg and hole (smallest for the “Expert” level). The amount of time allowed to complete the exercise is set by the therapist. Visual and auditory cues increase the simulation realism and help the patient overcome visual distortions. Pegs are grasped with a lateral pinch gesture and change color when in a correct insertion position. Exercise results are stored in the form of number of holes filled, time spent to perform the exercise, and number of errors made (missed hole or an attempt to put two pegs in one hole).

The second functional rehabilitation exercise is the racket Ball Game shown in Figure 2-b. The patient has to throw the ball so that it hits the target wall above a marked area; after the ball bounces back the patient has to catch it after at most one bounce off the ground. The ball speed (“fast” or “slow” ball) is selected at the beginning of the exercise. Any correct catch increases the patient’s “catch” counter while any miss will increase the “miss” counter. The ball deforms when caught by the patient and loses energy while bouncing. This exercise is useful to train feedforward ballistic type movements and hand-eye coordination. Throwing and catching movements help improve accuracy and speed control.

4. Clinical database and Client/Server architecture

Patient data is stored during the therapeutic exercises and organized in several tables: patient table (personal data), index table (exercise index, type and date), and exercise tables. The database Graphical User Interface (GUI) was designed using Oracle Forms, Reports, and tools ([18]). The patient entry form provides the graphical interface for data input, query, update, browse or delete of records. The exercise form displays a listing of sessions of specified type performed by the patient. "Raw data" corresponding to the forces exerted by the patient's fingers is displayed when pressing the "show" button. Finger forces "raw data" is however of little use to the clinician. This data is therefore processed in order to extract meaningful information for patient assessment. The finger force mean, standard deviation and force integral (effort) for each session are computed and displayed. A time history of these parameters over several rehabilitation sessions is subsequently created. The graph also shows a target (goal) parameter which the patient has to achieve over a specified number of sessions. This goal can be remotely modified by the clinician or therapist after assessing patient progress.

The database is stored at the server side (clinic), as illustrated in Figure 3. The therapist has remote access to the patient's exercise routines without having to travel to the patient's home. After looking at the graphs, the therapist can also judge whether the routine was performed in a satisfactory fashion or not. A Client-Server networking component has a menu-style GUI developed on a WinNT platform. The database update module written using ProC transfers data from VR rehabilitation exercises into the clinic database. The asynchronous transfer uses a TCP/IP connection and transfers data stored as local files subsequent to each exercise routine. The data file transferred contains exercise type, patient ID, execution time and exercise raw data.

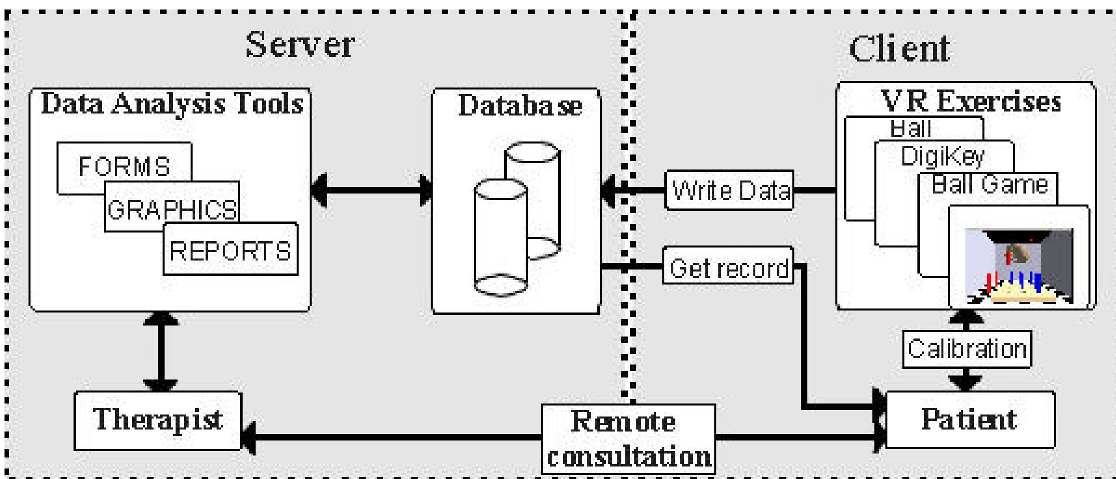


Figure 3. Telerehabilitation system software architecture

The Client site (patient home) is running real-time VR exercises. While wearing the rehabilitation haptic devices, the patient controls the system using voice commands. The speech interface uses a Microsoft speech recognition engine ([19]), with a small grammar implemented for our application. Care has to be taken when programming all software components to share a single processor machine. The VR exercises thus run with higher priority to allow maximum graphics frame rate. The server site (clinic) stores the database, and provides patient data analysis tools. Videoconferencing tools installed at the server site use CuSeeMe videoconferencing software ([20]). The graphical interface thus allows a patient to start VR exercises and open a video channel for consultation with the therapist; it also includes documentation in the form of qeuriable help and tutorial movies (mpeg or avi format) for correct execution of the rehabilitation routines. We expect to get low video frame rates while connecting the Rutgers and Stanford sites over the Internet. Once Internet2 becomes available for the project real-time video performance is expected.

Quality of network services is very important for the system reliability and performance. We identified several parameters that affect the network services: datafile size, time to transfer and failure rate. The amount of data collected from the exercise depends on its type and duration. For physical therapy exercises we are recording patient applied forces at a sampling rate of four reads/second. For a one-minute exercise that means about 7 Kb of data. Functional rehabilitation exercises need only tens of bytes to be transferred to the database. Transfer time and failure rates need to be measured experimentally. Networking data will subsequently be collected for statistical purposes from the Internet experiment involving Stanford University (client site) and Rutgers University (server site).

5. Conclusion and Future Research

A PC-based telerehabilitation system using Virtual Reality and force feedback interface was developed for home use. The haptic hardware used to display forces on the patient's body includes a novel Multipurpose Haptic Control Interface and the RM-II glove. A library of VR exercises was modeled after standard rehabilitation routines. This contains both physical therapy and functional rehabilitation routines. Data collected during the exercises is stored remotely at the server site (clinic) using the Internet. Here the therapist can analyze it, evaluate patient progress and modify VR exercise parameters over the network. Remote consultation is supported using a videoconferencing system.

Developing new haptic devices for rehabilitation is an ongoing research effort in our laboratory. Elbow and knee interfaces are currently being designed for control by the same Multipurpose Haptic Control Interface hardware. Clinical trials with the telerehabilitation system will start soon at Stanford Medical School.

The system will be extended in the future to include several Client sites (patient homes with rehabilitation workstations) and a central clinic Server. This configuration, called *multiplex* telerehabilitation, should allow the testing of the full potential of telerehabilitation technology. Additional issues of patient identification, data security and remote consultation multiplexing have to be addressed. A new Web-based distributed architecture for the multiplexed telerehabilitation system was proposed recently [21]. This innovative design assumes fast speed networks (Internet2) and takes advantage of newly developed Internet technologies (Java3D) to create a distributed system (database, multimedia, VR) which resides entirely on the Web.

Acknowledgments

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