Computerized Hand Diagnostic/Rehabilitation System Using a Force Feedback Glove

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Abstract

This paper describes recent results of a unified computerized system for hand diagnosis and rehabilitation. Automatic diagnosis data collection and Virtual Reality rehabilitation exercises are the main characteristics of the system. The diagnosis subsystem includes a tactile sensing glove in addition to standard devices such as electronic dynamometer, pinchmeter and goniometer. Three standard rehabilitation exercises were simulated in a Virtual Reality environment, using the WorldToolKit graphics library. The first two exercises (ball squeezing and DigiKey) allow measurement of finger forces exerted during the rehabilitation routine. The third exercise (Peg board) involves the patient's visual-motor coordination. The rehabilitation subsystem uses a VPL DataGlove retrofitted with Rutgers Master (RM-I) and its interface. The exercises involve manipulation of objects with different stiffnesses and geometry. Grasping forces were modeled and fed back using the Rutgers Master worn on patient's hand. Data is gathered in real time from both diagnosis and rehabilitation subsystems. Finger specific forces recorded during rehabilitation exercises allow better diagnosis of the patient impairment. An ORACLE database is used to store and manipulate patients' records. Proof of concept trials were performed in a clinical environment. Some results of patient records analysis are presented in this paper. A new version of the system using an RM II haptic interface is presently under consideration.

1 Introduction

Reliable clinical evaluation of a patient's hand disability is a very important premise for the rehabilitation process. The hand disability evaluation usually involves measurement of grip and pinch strength as well as the range of motion of the joints of the hand. Standard mechanical hand diagnosis devices (such as the dynamometer, pinchmeter and goniometer) used for these measurements are imprecise and cannot store data on-line. Newer computerized hand diagnosis systems such as EVAL [1], or the Clinical Hand Master [2] have better repeatability and allow faster data gathering. We developed a diagnosis system that includes the electronic versions of the standard diagnosis instruments and a novel tactile sensing glove which measures forces at 16 location in the palm. A previous study performed in our laboratory involving Force Sensitive Resistors, Miniature Strain Gauges and Ultrasonic Force Sensors showed that UFS sensors were better suited for the purpose of measuring grasping forces. Based on the results of this study, a Tactile Glove using UFS sensors mounted on the palmar side of a DataGlove [3] was designed. The glove was interfaced to the graphics workstation using an electronic unit.

Hand rehabilitation is a process requiring repetitive execution of several standard exercises. To increase the finger and palmar strength, finger exercise devices (such as the DigiKey) and rubber balls of different stiffnesses are used. Other devices (Peg Board) enhance the ability to manipulate objects and test the motor-visual coordination. In this paper we propose an innovative approach to the rehabilitation process. A Rutgers Master I [4] is the only hardware device we use to support three rehabilitation exercises running on a graphics workstation. The DataGlove measures the hand gesture and position and maps the user hand movements in the virtual environment. A retrofitted structure in the palm of the glove uses actuators to provide force feedback to four fingers. This way finger/hand and hand/eye coordination exercises can be simulated. The virtual exercises replicate the three rehabilitation routines mentioned above and also provide a record of forces exerted by each finger, which can be used later for the evaluation of patient's progress. Patient's records are stored in a database and manipulated using an Oracle engine. Using different Oracle tools, a Graphical User Interface to access the integrated database was designed. It provides querying options on patient data and can generate and print reports for selected exercises. Thus our integrated system groups together diagnosis, rehabilitation and data storage and manipulation modules, potentially being a powerful clinical tool.

This paper describes the integrated system for hand diagnosis and rehabilitation. Section 2 presents the hardware configuration while section 3 details the various parts of the software simulation: the main simulation program with the GUI, the VR exercises and the database module. Section 4 presents some initial results of clinical experiments involving a small group of patients. Experimental data is analysed in section 5. Future research describing a PC-based system concludes this paper.

2 System Hardware

The simulation is running on a Sun 10 workstation with 64 MB of RAM and a ZX graphics accelerator. The Sun workstation is also equipped with an Analyx [5] data acquisition board having 16 analog inputs and four digital outputs. The board has 12 bit resolution and a conversion rate of 100 kHz. The diagnosis and rehabilitation subsystems communicate with the workstation through the A/D/A board and a serial line as illustrated in Figure 1 [6].

The diagnosis subsystem consists of an electronic dynamometer, an electronic pinchmeter and goniometer [7]. These instruments record grip force, pinch force (key and tip) and range of motion, respectively. The pinchmeter and the dynamometer have adjustable gain. The instruments were recalibrated to output 5V maximum voltage and tests were performed to measure their accuracy and repeatability. It was found that the three instruments have a very good linearity, small hysteresis and excellent repeatability. The devices are interfaced with the workstation via the A/D/A board using channels 9 to 12 (the first eight A/D channels are connected to the Tactile Glove interface mentioned below). The pinchmeter and dynamometer each output a single analog signal, ranging from 0 to 5 V, proportional to the forces applied by the patient. The output of these devices is sampled at a frequency of about 100 Hz. The goniometer outputs an analog signal (bending angle) and a digital one (foot pedal). Another diagnostic tool, developed in our laboratory, is the Tactile Glove [8,9]. It consists of a special designed glove with an electronic interface. The glove has a sensing component - a device similar to a DataGlove - using 16 fiber optic sensors (flex sensors) mounted on the back of a Lycra glove and a tactile component made of 16 ultrasonic force sensors (UFS) [10]. The sensors are mounted on the palmar side of the glove at key locations which experience force during grasping. Unfortunately, sensor noise problems have developed during testing and calibration. Crosscoupling and large noise/signal ratios made calibration extremely difficult.

** Insert Figure 1 here ** Figure 1: The integrated system [6] (The MIT Press. Reprinted by permission

The rehabilitation subsystem uses the Rutgers Master (RM-I) retrofitted on a DataGlove. The sensors consist of optical fibers that run from the sensor interface to the finger joint and back. The more the joint bends, the less light is transmitted. The output of the flex sensor interface is represented by 16 analog signals (0 to 5V). Previous tests [11] showed an overall average error of 5.6 degrees for this type of fiber optic gloves. The DataGlove measures hand gestures and 3-D wrist positions (using a Polhemus sensor) at a rate of about 30 readings/sec and transmits this data to the Sun workstation over a serial line. The Rutgers Master is used for force feedback to the user's fingers. Its compact structure fits in the palm, as shown in Figure 1. The lightness of the feedback structure (about 100 grams) helps reduce patient's fatigue considerably. The force data is output by the workstation through its D/A channels as voltages which are then mapped to the actuators air pressure. The feedback pressure is controlled by analog proportional regulators housed in an interface box. The maximum force experienced by each fingertip is about 4N (for air pressure of 100 psi).

3 Simulation Software

3.1 The Structure of the Simulation Program

The simulation program for the diagnosis/rehabilitation system was written in C++. There are two components of the program, corresponding to the main hardware subsystems: the diagnosis part deals with sampling and recording data from diagnosis tools, and the rehabilitation part consisting of three VR exercises. In addition an Oracle Server manages the patient information recording data from both diagnosis and rehabilitation exercises to the database. A Motif-style [12] GUI provides the user (therapist) with an easy access to the diagnosis and rehabilitation exercises, and performs calls to the Oracle Forms.

Two C++ classes were created to support the input-output devices: the Tactile Glove and RM-I. The Tactile Glove class interacts with the software driver for the UFS providing the application with current sensor data. RM-I class maintains two interactions, with the "Data_Glove" for input and with the RM-I interface for force feedback through the Analyx A/D/A board. Class hierarchy is illustrated in Figure 2.

** Insert Figure 2 here ** Figure 2: The C++ classes hierarchy [6]. (The MIT Press. Reprinted by permission

Drivers for the RM-I subsystem and the Tactile Glove were implemented to support the devices we designed. Experiments were performed with different ways of implementing asynchronous communication via the serial port to see how a protocol affected latencies and the refresh rate of the VR simulation. The first protocol used low level functions to access the serial port. The second protocol was implemented using shared memory (from where it is then accessed by WorldToolKit). Lastly, a driver was implemented using standard WorldToolKit functions for reading the serial port. Using a shared memory protocol and a 200 polygons hand model we achieved a refresh rate of 16 fps. Refresh rates above 15 fps have been shown to be satisfactory for interactive graphics simulations [13].

3.2 VR Exercises

The VR exercises were developed using the WorldToolKit V2.1 graphics library [14]. The WorldToolKit application consists of a main loop in which the universe is initially loaded, rendering parameters are set and various sensor devices are activated. Once the universe is created, the loop continuously executes the following actions: read the sensors, performs universe actions, update objects with sensor input, perform the graphical objects tasks and render the universe. The dynamics of an object are then determined by the sensor it is attached to and the related functions specified in "universe functions". Our graphical objects are stored in "dxf" and "nff" formats. A realistic model of the human right hand was obtained from ViewPoint Datalabs [15]. This complex hand model (over 1500 polygons) was subsequently reduced to a simpler model with less than 200 polygons to increase the graphics refresh rate. Other 3-D objects (DigiKey, Peg board, etc.) were created using Autocad Release 12 [16].

The rehabilitation part starts with a calibration routine. This is necessary to adjust the glove to the patient's hand size and range of motion. During the calibration routine the patient is asked to open and close his/her hand, and the minimum and maximum angles of flexion and extension are then recorded. Subsequently, for each glove configuration a linear mapping between these minimum and maximum angles is used to display the user's hand and to calculate the force feedback.

The first exercise involves squeezing of a virtual rubber ball. At the beginning of the exercise the therapist asks the patient to choose the colored block which corresponds to the required level of exercise difficulty. By choosing one of three colored blocks the user sets the stiffness and the color of the ball. Next, the patient is asked to grasp the bouncing ball. Once the ball is grasped, it deforms according to the movements of the virtual hand. Ball deformation is simulated by vertex level manipulation of the ball object. The computer keeps track of the number of squeezes performed by a patient. The rehabilitation routine terminates when user inputs an exit key or automatically once the desired number of squeezes (specified by the physician) has been performed. The forces experienced by each finger during the routine are recorded in the database and can be visualized at a later time.

** Insert Figure 3 here ** Figure 3: Virtual DigiKey exercise

The second rehabilitation exercise is a virtual version of the commercially available individual finger exerciser, DigiKey [17]. A 3-D model of the DigiKey was created using Autocad. This model was ported into our virtual environment and its dynamics were programmed. The RM-I does not provide force feedback to the pinky, therefore the DigiKey model was modified so that the thumb is exercised instead. The patient has a choice of different levels of force feedback, as illustrated in Figure 3. Five DigiKeys were color coded to match the commercially available models of different levels of maximum force. As in the previous exercise, the patient can select a particular DigiKey with the virtual hand. After grasping the DigiKey, the patient has to perform a required number of squeezes. Again, the forces experienced by each finger during the rehabilitation routine are recorded.

The third exercise implements a peg-in-hole insertion task. A virtual model of a board with nine holes and the corresponding number of pegs was created. The exercise has three levels of difficulty: "Novice," "Intermediate" and "Expert," each level being associated with a different clearance between the peg and hole (smallest for the "Expert" level). The amount of time allowed for the patient to complete the exercise can be set according to results from previous exercises. Visual and auditory clues increase the realism of the simulation. A "click" sound is generated each time a peg is grasped by the virtual hand. A shadow indicates the position of the peg relative to the board. When in position to be released, the peg color changes to white; a correctly placed peg turns blue. At the upper left corner a counter indicates the amount of time left until the end of the exercise (an exercise also ends when all the holes are filled).

A snapshot of a virtual hand executing a Pegboard exercise is shown in Figure 4.

During the exercise, the collisions of pegs with the board are counted. After completing the exercise, the results are stored in the form of number of holes filled, time spent to perform the exercise and number of mistakes made. A mistake corresponds to a missed hole or an attempt to put two pegs in one hole. This data can be later accessed by the therapist.

** Insert Figure 4 here ** Figure 4: Virtual Peg board exercise

3.3 Database Module

Using different Oracle tools [18]- Forms, Reports, Graphics - we designed a system called "Hand Diagnosis and Rehabilitation" (HDR). It allows the user to manipulate patients' data through a user friendly, icon-based, interface. HDR consists of three modules - "Action," "Form" and "Report." The first module, "Action," is responsible for executing all the diagnosis and rehabilitation exercise operations and for storing all the data that is generated by these operations into the database. When selecting an operation, the corresponding routine is activated by the Action module as a procedure specific to the operation. When the operation is completed, the procedure passes all the data on to the database which stores it under the patient's name. The "Form" module provides the graphical interface for data input, query, update, browse or delete the database. It contains two forms, the "patient entry form" and the "HDR data form," designed using the Oracle Forms tool. The "patient entry form" displays a screen with all patient attributes (name, address, etc.) and allows the user to either add a new patient to the database or query data on an existing patient. In addition a "list" button on the form launches a list-of-value dialog box which lists all the patients currently in the database. Before navigating to the next form the therapist has to select the type of exercise he wants to display ("default" button will select all exercises executed by the patient). After the selection is made, pushing the "down" button will pop up the HDR data form. This form contains a list of the operations executed by the patient ordered by date. Figure 5 shows the GUI of both Oracle forms. To see what the graph output of an operation looks like, the therapist can choose the corresponding field and then click on the "graph" button. The form then performs a call to Oracle Graphics to display the required data. Figure 6 shows the four graphs corresponding to the forces exert by a patient during a DigiKey exercise.

By choosing the "report" button, the user activates the "Report" module. This generates an Oracle Report for the current patient and procedure, which may contain some other calls to Oracle Graphics. Using the HDR system a physician can have access to a patient's exercise routine and judge his/her progress without actually having to be present during the exercise itself. After looking at the graphs, the therapist can also judge whether the routine was performed in a satisfactory fashion (i.e. if all the fingers were exercised correctly). A complete report will contain all the data relevant to a particular patient, including all the diagnostic tests he/she has undergone, graphs of exercise routines showing patient progress, comments or observations of the physician, etc.

** Insert Figure 5 here ** Figure 5: Database GUI

** Insert Figure 6 here ** Figure 6: DigiKey exercise graphs

4 Clinical Experiment Results

Using the dynamometer the patients were required to perform a 5 seconds grip test six times, alternating between the left and right hands. After that a three point pinch, lateral pinch and key pinch measurements were performed on each patient. The results of dynamometer and pinchmeter measurements are graphs displaying the recorded values as a function of time. The maximum force and the standard deviation are computed for each test. Finally the bending angles for closing and opening of the fingers of both hands were measured using the goniometer. The output of the procedure is a table with entries for the bending angles. The above-mentioned difficulties with the calibration of the Tactile Glove made impossible testing on patients. Subsequently each patient performed the three rehabilitation routines.

Nine volunteers agreed to participate in the project, eight males and one female. All were screened prior to entry for lack of any hand, wrist, forearm or shoulder pathology or any other upper extremity illness. Their ages ranged from 25 to 65 years. Their occupations are in the clerical, technical and medical fields. No hand therapist was tested. Only right handed individuals could be enrolled since one prototype glove was made available for testing. In addition, this glove is a rather large size which allows for accurate testing of individuals with large extremities and fits best those over 6 feet tall.

Two rounds of clinical test were actually performed. The data from the first clinical trial could not be used due to unreliabilitv of the equipment. The second round of testing was completed rather quickly once the hardware and software problems were solved. Two of the nine volunteers were repeaters.

Volunteers were asked to complete questionnaires regarding their experience with the "glove". Opinions were elicited regarding whether the exercises were purposeful, if the tasks did indeed feel like exercises, the difficulty level of the force given through the glove, where most muscle tension was felt, likes and dislikes regarding the glove and comments. All volunteers found the exercises to be purposeful. Four felt the tasks were like exercises and four felt they were not, with one being equivocal. All found them to be fun and two reported them as difficult. None in the group found it difficult to respond to the force given through the glove. Three patients felt most tension in their hand/forearm muscles during the tasks while three reported it in their shoulder. One person said it was split between the two areas and one person could not tell.

All patients universally liked the device and the most common qualifier was "interesting". Qualities such as biofeedback and watching the virtual hand move on the screen were reasons given regarding the positive impression of the device. The most common dislike was that the glove itself was hard to fit. "Not responsive to digits" and "can't fist" were typical comments. The most difficult task was the peg hole and volunteers found the lack of dexterity or responsiveness of the glove to be a factor in impeding this task.

In addition, the "depth of the computer field did not seem to match real life".

In summary, all enjoyed working with the system and were interested in enrolling in future phases of the project. Comments included "excellent system", "count me in for further trials," "interesting, needs more work," "hand muscles not stressed." Feedback from these trials will be used to incorporate modifications as suggested by the physician and the hand therapist.

With respect to objective data, the system produced graphical output displays for metacarpal-phalangeal joint range of motion for all five digits as well as range of motion for the thumb distal inter-phalangeal joint. The remaining joints could not be assessed because of limitations in the system. Grip and pinch meter readings were also graphically displayed over time. Similar outputs can be generated from other computer systems on the market today. The unique output of this system is the graphical display of the digital forces used during the task completion. Not enough people were tested to make any statistical comments regarding the range and pattern of the oscillations in this current trial.

5 Analysis

From a clinical point of view, the results of this proof of concept trial are encouraging enough to warrant further investigation. Obviously, once gloves are available to size different individuals then a "profile" of graphical displays can be generated and individuals under treatment can be tested and have their display compared to the norm for their size and age. This would be helpful in the clinical assessment of patient compliance and motivation since our current static techniques are unable to do this. The current compensation market for work related injuries in some ways rewards patients for being disabled for longer periods of time and a device that can assess patients effort would be invaluable.

In addition, rehabilitation in complicated cases is lengthy and boring. Having a device that is both more challenging and interesting would help in the rehabilitation process. Also, many insurance agencies in the market-place are awarding contracts based on patient satisfaction surveys and the positive feedback for our device would certainly be a plus in competing for the rehabilitation pool of patients.

When this project was first initiated, the device was envisioned for use in rehabilitation of the hand itself. However, the glove does not yet have the sophistication to replicate complicated hand functions. In its current design, it would be more useful in the latter stages of upper extremity rehabilitation, especially for improving coordination and global use of the limb and for shoulder rehabilitation. Our current physical therapy protocols emphasize exercises rather than goal oriented tasks. This device can put the "exercised" limb back to use and aid in integrating muscle and joint function for a specific goal. Currently, patients are rehabilitated in their exercise regimen, but complain that when they go back to work activity they still have difficulties. Certain work tasks such as assembly line production, keyboard use, use of musical instruments, etc. should be reproducible with the computerized system in our study. This may maximize global endurance and coordination of the upper extremity.

6 Conclusion and Future Work

This paper described an integrated hand diagnosis and rehabilitation system developed at Rutgers University. The diagnosis subsystem uses standard electro-mechanical instruments. The rehabilitation subsystem uses an RM-I force-feedback device composed of a DataGlove and force feedback actuators. The simulation software runs on a SUN workstation interfaced to the subsystems through an A/D/A board and a serial interface. A new approach to hand rehabilitation is represented by the Virtual Reality exercises. While reducing the amount of time spent by the therapist with supervising the rehabilitation routines, the exercises are also interesting and challenging for the patient. Data collected during diagnosis and rehabilitation routines is stored in a database managed by an Oracle

Server. The integrated database allows a close monitoring of progresses made by patients. Results of proof-of-concept trials done with a small group of patients are promising.

Future research will focus on developing a PC based system that will include the main features of the Sun workstation version. The new system will replace the old RM-I interface and the DataGlove by an improved RM-II system [19]. This is a unified position sensing and force feedback structure that makes unnecessary a separate DataGlove. The RS232 standard used by RM-II Interface communication and the robustness of Rutgers Master will allow to build a more reliable system; the PC system will include an Intergraph graphics accelerator board so that rehabilitation exercises design can be enhanced without restrictions related to the simulation refresh rate. Overall performance is expected to improve significantly.

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