ROBOTIC REHABILITATION OF STROKE PATIENTS USING AN EXPERT SYSTEM

Received 2nd June 2010; accepted 7th September 2010.

Pradeep Natarajan, Arvin Agah, Wen Liu

Abstract:

Approximately 50 to 60 percent of the more than five million stroke survivors are moderately or minimally impaired, and may greatly benefit from rehabilitation. There is a strong need for cost-effective, long-term rehabilitation solutions, which require the therapists to provide repetitive movements to the affected limb. This is a suitable task for specialized robotic devices; however, with the few commercially available robots, the therapists are required to spend a considerable amount of time programming the robot, monitoring the patients, analyzing the data from the robot, and assessing the progress of the patients. This paper focuses on the design, development, and clinically testing an expert system-based post-stroke robotic rehabilitation system for hemiparetic arm. The results suggest that it is not necessary for a therapist to continuously monitor a stroke patient during robotic training. Given the proper intelligent tools for a rehabilitation robot, cost-effective long-term therapy can be delivered with minimal supervision.

Keywords: *rehabilitation robots, intelligent systems, human-robot interaction, expert systems, stroke therapy.*

1. Introduction

The goal of this work is to investigate a novel methodology that would enable physical and occupational therapy clinicians to provide long-term robotic rehabilitation of the hemiparetic arm for stroke survivors with minimal supervision. Neither the use of robotics, nor the use of artificial intelligence (AI) techniques is new to the field of medicine. However, the idea of applying robotics to the field of rehabilitation medicine is relatively new. Robotic rehabilitation has yet to attain popularity among the mainstream clinicians. With the increased use of robots in rehabilitation medicine, there are numerous opportunities where AI assisted technologies could play a vital role in assisting the clinicians.

This paper focuses on designing, developing, and clinically evaluating an expert system-based post-stroke robotic rehabilitation system for hemiparetic arm [31]. The system serves as a valuable tool for therapists in analyzing the data collected from the robot when it is used by the patient, helping the therapists to make the right decisions regarding the progress of the stroke patient, and suggesting a future training plan. The system is designed, developed, and evaluated by conducting a clinical study. The effectiveness and the usefulness of such a rehabilitation system are analyzed in this paper. If it can be shown that the proposed expert system-based robotic rehabilitation is effective and useful for the therapists and the patients, this work could pave the way for an affordable, easy to use long-term robotic rehabilitation solution for stroke survivors. Moreover, such a system that requires minimal intervention from the therapist will play a role in making remote stroke therapy a reality.

1.1. Motivation

Stroke is extremely prevalent and its effect is long-lasting; yet the availability of long-term rehabilitation is limited. Every 45 seconds, someone in the United States has a stroke. Stroke is a leading cause of serious, long-term disability in the United States. From the early 1970s to early 1990s, the estimated number of non-institutionalized stroke survivors increased from 1.5 to 2.4 million, and an estimated 5.6 million stroke survivors were alive in 2004 [2]. Approximately 50 to 60 percent of stroke survivors are moderately or minimally impaired, and may greatly benefit from rehabilitation [11], [23].

Loss of voluntary arm function is common after a stroke, and it is perceived as a major problem by the majority of chronic stroke patients, as it greatly affects their independence [4]. In recent years, clinical studies have provided evidence that chronic stroke patients have motor recovery even after 4 to 10 years from the onset of stroke [39], [29]. Given this fact, there has been a strong demand from patients and caregivers to develop effective, long-term treatment methods to improve sensorimotor function of hemiparetic arm and hand for stroke survivors. Even partial recovery of arm and hand sensorimotor function could improve the patients' quality of life, and reduce the socioeconomic impact of this disease-induced disability.

1.2. Problem Statement

The major challenges involved in post-stroke rehabilitation are the repetitiveness of the therapy, and the availability of therapists for long-term treatment. Many rehabilitation techniques involve repetitive mechanical movement of the affected arm by a therapist. The utilization of robots for rehabilitation has assisted the therapists with the repetitive tasks of the therapy. However, the therapists are still required to spend a considerable amount of time in programming the robot, monitoring the patients, analyzing the data from the robot and assessing the progress of the patients. Even the few commercially available robots neither include any tools for analyzing the data, nor do they have any decision making capabilities. The commercial rehabilitation robots do not take full advantage of the available computing power. Hence, this paper focuses on designing an expert system-based robot that contains tools for post-stroke rehabilitation of the upper limb that are easy to use by the therapists.

In order to overcome the repetitiveness of the rehabilitation therapy, the interactive robotic therapist was developed [16], [17]. Since then, even though a number of rehabilitation robotic systems have been developed, they all have one thing in common they lack intelligence, and hence are not easy to use by the therapists. Although most of the systems have the capability to collect different kinds of data during patient training, they still require a therapist (or someone assisting the therapist) to analyze the collected data in order to make the decision regarding the changes in the training program. This makes the system difficult to use and it takes the therapist's time away from the patient.

The hypothesis of this work: Stroke patients rehabilitated using an expert system-based robotic system will experience the same improvement as the stroke patients using the same robot without the expert system. The neuro-motor function of the hemiparetic upper limb will be assessed primarily using Fugl-Meyer and Motor Status scores [1] , [40].

1.3. Approach

Integrating an expert system with the rehabilitation robot allows a new training program to be selected by the robot, based on the data collected during the patient's training. This essentially serves as a feedback loop. The primary aim of this research work is to design and implement an expert system-based robotic rehabilitation system, and evaluate it in a clinical setting. The expert system-based rehabilitation robot will be easy to use by the medical personnel (not requiring any type of programming expertise) and therefore will reduce the therapist's time. Since the expert system is developed using the knowledge acquired from multiple therapists, the decisions made by the expert system are no longer the opinion of one therapist which is the case in conventional therapy. The primary research question addressed by this work is whether or not an expert system-based robotic rehabilitation system, in which the robot will be able to autonomously analyze data, and make suggestions for the future training exercises depending on the progress of the patient, can provide the same or better result than the robotic rehabilitation system without an expert system while making the system easier to use for the therapists.

This paper is organized into eight sections. The next section provides an introduction to stroke and rehabilitation of the upper limb. Section 3 presents an overview of the current state of robotics in upper limb rehabilitation for stroke. Section 4 gives an introduction to expert systems and the steps followed to develop a successful expert system. Section 5 describes how the entire system was developed and the rationale behind the design of various system components. Sections 6, 7 and 8 detail the clinical study, the results and the conclusions.

2. Stroke rehabilitation

A stroke (also known as Cerebral Vascular Accident), occurs when blood flow to any part of the brain stops. When blood supply to a part of the brain is interrupted, it results in depletion of the necessary oxygen and glucose to that area. The functioning of the brain cells (or neurons) that no longer receive oxygen will be immediately stopped or reduced and the oxygen starved neurons will start to die [34], [8]. Brain cells that have died cannot be revived, and the body parts that were receiving signals from those cells for various functions like walking, talking, and thinking may no longer do so. Stroke can cause paralysis, hemiparesis (paralysis of one side of the body), affect speech and vision, and cause other problems [2].

Stroke rehabilitation is the process by which the survivors undergo treatment in order to return to a normal, independent life as much as possible. It is known that most of the motor recovery takes place in the first three to six months after stroke. However, depending on the therapy, minor but measurable improvement in voluntary hand/arm movement occurs even long after the onset of stroke [5]. Some clinical studies have shown that the brain retains the capacity to recover and relearn the motor control even after four years from the stroke onset [39], [29]. Therapy to reestablish the stroke patients' functional movement is a learning process based on the normal adaptive motor programming [3]. The motor relearning of the stroke patients is based on the brain's capacity to reorganize and adapt with the remaining neurons. It has been reported that rehabilitation and intensive repetitive training can influence the pattern of reorganization [20], [35], [28]. Even though many different treatment approaches have been proposed, e.g., [37], physical therapy practice heavily relies on each therapist's training and clinical experience [33].

Studies of robot-aided motor training for stroke patients have demonstrated that it is not only more productive for patient treatment, but it is also more effective in terms of functional improvement of the hemiparetic upper limb compared to conventional physical therapy [6], [24]. The robot-aided motor training could have great potential to evolve into a very effective and efficient clinical treatment.

3. Robotics in Upper Limb Rehabilitation

One of the earliest robots developed for manipulation of the human arm was the interactive robotic therapist [16], [17]. The interactive robotic therapist allows for simultaneous diagnosis and training by therapists through interactions with patients. This system is also used for the quantification of the patients' recovery and progress. Following the successful results of this robotic therapist, several rehabilitation robots were designed, including the Mirror-Image Motion Enabler (MIME) [7], Assisted Rehabilitation and Measurement Guide (ARM Guide) [36], Motorized Upper-Limb Orthotic System (MULOS) [21], and GENTLE/s haptic system [28]. Researchers agree that in general, compared with conventional treatment, robot-assisted treatment definitely has therapeutic benefits [7] , [30]. Robot-assisted treatment has been demonstrated to improve strength and motor function in stroke patients. In one clinical trial even follow up evaluations for up to three years revealed sustained improvements in elbow and shoulder movements for those who were administered robotic therapy [1], [40].

The InMotion2 robot is a commercially available rehabilitation robot [19]. The InMotion2 robot can be programmed to interact with a patient to shape his/her motor skills by guiding the patient's limb through a series of desired exercises with a robotic arm. The patient's limb is brought through a full range of motion along a single horizontal plane to rehabilitate multiple muscle groups [16], [17], [24]. The InMotion2 robot is available in the Neuromuscular Research Laboratory (NRL) at the University of Kansas Medical Center (KUMC) and was used.

4. Expert systems

An expert system is an interactive computer-based decision tool that uses both facts and heuristics to solve difficult decision problems based on the knowledge acquired from human experts. Any application that needs heuristic reasoning based on facts is a good candidate for expert systems. Some of the earliest expert systems were developed to assist in areas such as chemical identification (DENDRAL), speech recognition (HEARSAY I and II), and diagnosis and treatment of blood infections (MYCIN) [18]. The expert system development process consists of four phases - knowledge acquisition, knowledge representation, tool selection and development, and verification and validation [18], [26]. Each phase of the expert system development process is discussed in this section.

Knowledge Acquisition: Knowledge acquisition refers to any technique by which computer systems can gain the knowledge they need to perform some tasks [38]. Knowledge often goes through stages of refinement in which it becomes increasingly formal and precise. Part of this process involves identifying the conditions under which the knowledge is applicable, and any exceptional conditions. In order to design the knowledge base, several discussions with physical and occupational therapists were conducted. In these meetings, the capabilities of the rehabilitation robot were demonstrated to the therapists. Based on the discussions, it was clearly understood that the expert knowledge in the field of physical therapy was very complex, based on practical experience, very subjective to the patient and the type of motor impairment. A pilot survey to better understand the current clinical practices in stroke rehabilitation was conducted among physical and occupational therapists in Kansas and Missouri [33].

Knowledge Representation: The knowledge-based expert system should encapsulate the expertise of the therapists, in order to be an effective tool during rehabilitation therapy. The captured information takes into account factors that are relevant to stroke rehabilitation such as:

- The general principles of therapy.
- The initial conditions of the stroke patient.
- The most effective training exercises, along with the determinants for each exercise.
- The methodology by which therapists assess the patient's progress.

The knowledge gathered from the experts is first refined in a manner such that it is applicable to the InMotion2 robot which is used for stroke rehabilitation of the arm. Next, the refined knowledge is represented using a standard format such as a production system. A production system is a system based on rules. A rule is a unit of knowledge represented in the following form [15], [14]: IF <conditions> THEN <actions>. The expert knowledge represented as a production system is used to make the decisions regarding the selection and/or modification of any training exercise. The expert system is used to monitor the progress of patient's motor learning and modify the training exercises. From the accumulated records of the patient's arm movement data, the progress of the patient can be determined.

Tool Selection and Development: The expert system was developed as high-level intelligence for the InMotion2 robot controller programs. This high-level intelligence monitors the progress of the patient and issues appropriate guidance to the robot for its low-level motion control. One of the most commonly used open-source tools for developing expert systems is C Language Integrated Production System (CLIPS) [14]. Programs for analyzing the raw data collected during the patient training are developed in C. Tcl/Tk is used for the user interface of the robot.

A training exercise is defined as a sequence of tasks or training goals. The rule-based expert system analyzes the symbolic information provided by the system, such as the initial subject conditions, the various movement parameters, the current movement data, and evaluates the subject's progress. As a result of the assessment, the expert system can modify the training exercise. The modification could include selecting a new exercise from the given set of exercises, and/or determining how the determinants of the exercise should be adjusted. In many cases the same exercise could be selected with different determinants (such as the range of motion, velocity of motion, and assistive or resistive forces). Figure 1 shows the architecture of the expert system while it is in use.

Verification and Validation: The expert system is tested at the Neuromuscular Research Laboratory of the Department of Physical Therapy and Rehabilitation Sciences at the University of Kansas Medical Center (KUMC). Next, the expert system was demonstrated to some therapists at KUMC in order to be validated. The experts presented different cases and made sure the expert system satisfies the requirements.

5. Research methodology

This section addresses the design, development, and clinical evaluation of an expert system-based robotic rehabilitation system using the InMotion2 robot. The first step in developing this system is to understand the current stroke rehabilitation practices. Based on interviews with therapists, literature review, and a survey among clinicians in Kansas and Missouri, a list of patient conditions and corresponding treatment protocols were formulated. These protocols were fine-tuned to suit robotic therapy with the help of therapists. This became the knowledge base (also known as rule base) for the expert system. After the knowledge base was finalized, the protocol for the clinical study was developed. Based on the requirements of the clinical study, the software components of the system were developed and implemented. The system was tested and the clinical study was conducted upon approval from the Institutional Review Board at KUMC.

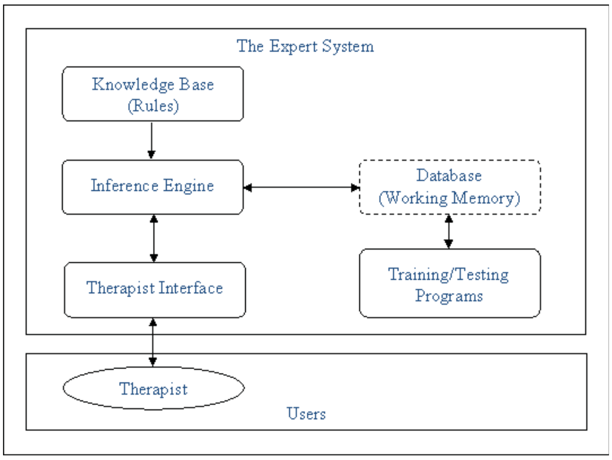

Fig. 1. Expert System while in use.

5.1. Design Requirements

In the conventional rehabilitation, the therapist performs an initial assessment of the stroke patient's sensorimotor skills. Many standard tests such as Fugl-Meyer, and Motor Status Assessment are widely accepted as quantitative tests. Based on the initial assessment, the therapist chooses one or more exercises for the patient and starts the rehabilitation process. This cycle of assessing the patient and administering therapeutic exercises is repeated as long as it is feasible. Several studies have shown that robotic post-stroke therapy can be effective but there is no published literature that outlines a comprehensive and generic treatment procedure. In most of the reported studies, a therapist makes an initial assessment of the patient, then chooses one or more exercises with suitable determinants (the variable parameters for each exercise), and then begins the robotic rehabilitation. When the patient undergoes therapy with the robot, the therapist visually observes the various motor skills of the patient and assesses the progress of the patient. In some cases the therapist manually analyzes the data collected from the training programs and makes a decision regarding the patient's progress. Depending on the therapist's assessment, once again one or more training exercises with suitable parameters are chosen for the patient and this process is repeated.

In the expert system-based rehabilitation system, instead of the therapist continuously monitoring the patient and providing the robot with the training exercise and the parameters, the expert system makes the necessary decisions. The system undertakes the usually time-consuming task of analyzing voluminous training data in order to evaluate the patient's progress without the intervention of the therapist. The expert system then presents the future training exercise and the parameters along with the explanation for the decisions. The therapist reviews the decisions and the explanation. Once the therapist approves, the robotic training is repeated. This allows the therapist to supervise the entire process for multiple patients within a short amount of time. For the therapist, it is not necessary to monitor each patient continuously.

The determinants or the variable parameters of each robotic training exercise include the single plane movement patterns, the number of repetitions or desired time duration, velocity of the training motion, assistive forces, resistive forces, and range of motion. These parameters need to be selected and modified by the expert system after taking into consideration the various patient conditions. The entire decision tree for the expert system is presented as the treatment protocols.

5.2. Knowledge Base Development

Understanding the current practices is imperative for the development of an expert system-based robotic stroke rehabilitation system. Given the broad range of therapy approaches, it is important to obtain data on what stroke rehabilitation methods are actually being used by clinicians. The pilot survey was aimed at understanding the current stroke rehabilitation practices of physical and occupational therapists who were providing care in two Midwest states: Kansas and Missouri. More than 100 clinicians participated in the survey. The knowledge collected from clinical experts enabled the development of the treatment protocols which serve as the rehabilitation system's knowledge base.

The stroke rehabilitation methods adopted by therapists vary widely and they seem to combine principles from different approaches in their current practice. This may be an indication of a need for an optimal approach to be developed through more research. The majority responses from the clinicians were used to construct the knowledge base of the expert system for robotic rehabilitation. The self-reported background information of the clinicians correlates with the dated treatment choices reported in sections of the questionnaire. The uncertainty among clinicians revealed in some sections of the survey shows that more evidence of clinical approaches is needed to ensure efficacious treatments [33].

5.3. Knowledge Representation

The knowledge gathered is implemented as rules for the expert system. These rules are used by the expert system to determine the appropriate robotic training for the patients during the clinical study. A step-by-step treatment protocol has been developed in conjunction with the knowledge gathered from the experts and the current literature. This protocol is given in a diagrammatic format in this section.

When a stroke patient begins the robotic therapy, the therapist makes an initial assessment which includes all the base-line evaluations. During the initial assessment three main conditions of the patient are determined - tone, strength, and Passive Range of Motion (PROM). For each patient, tone can be normal or high, strength can be diminished, and PROM can be limited or normal. Figure 2 shows the treatment plan that has to be followed if the patient's tone is normal and the PROM is limited.

Similar to treatment plan 1, two more treatment protocols were developed one for treating diminished strength, and the other for high tone and limited PROM. Definitions of acronyms used in the treatment plan are:

- ROM - Range of Motion of the patient
- PROM - Passive ROM, the range in which the patient is unable to actively contract the muscles to perform the movement on his/her own.
- AROM - Active ROM, the range in which the patient is

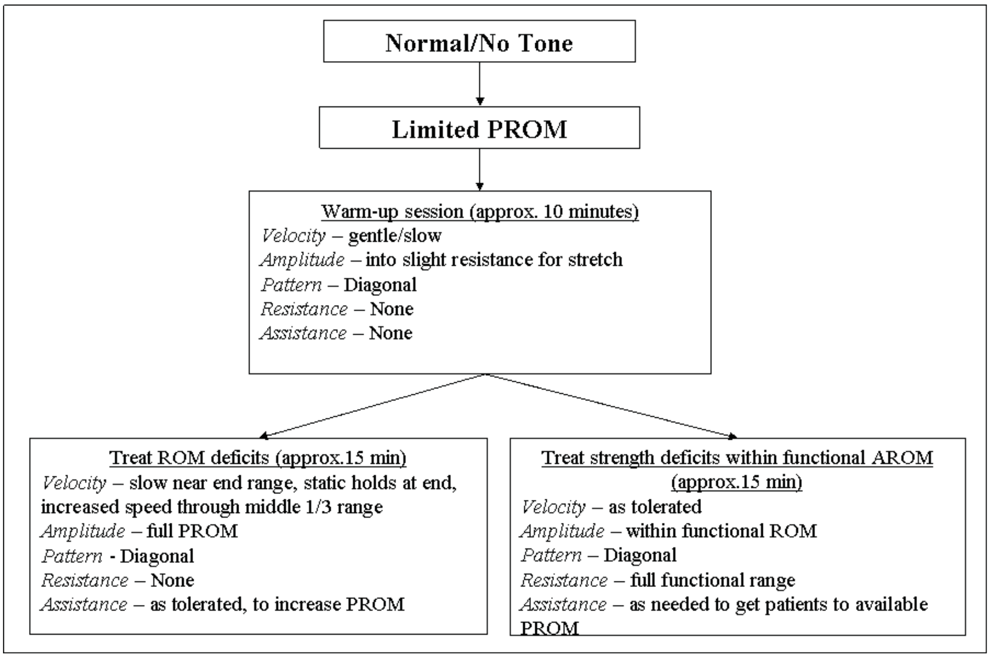

Fig. 2. Treatment Plan 1 - normal tone and limited PROM.

able to actively contract the muscles to perform the movement on his/her own.

Patient's progress during the stretching treatment is monitored primarily using the range of motion. Subsequent training exercise parameters are modified as follows:

- Increase amplitude as tolerated to increase ROM.

Patient's progress during the strength treatment is monitored primarily using the accuracy. Subsequent training exercise parameters are modified according to the following:

- Accuracy of 90% or better over a given number of repetitions, number of trials, or time.
  Progress resistance for patients functioning with AROM.
- If applicable, wean patients off assistance as tolerated.
- Adjust time demand.
- Modify target constraints to make the task more difficult.

5.4. Software Implementation

The software components in this research were developed according to the needs of the clinical study. The design provides the human user full control and maximum flexibility for manual override at any point during the clinical study. Figure 3 gives an overview of the software architecture as well as the flow of data through the system. The components can be grouped into three categories:

(1) The expert system developed using CLIPS.
(2) The robot testing and training programs in Tcl/TK
(3) The analysis program developed using C.

The functioning of the overall system can be explained in a step by step manner as follows:

- In the patient's first visit, initial testing with the robot is done. During this test various arm movement parameters and the patient's conditions regarding tone, strength, and PROM are recorded and saved in the parameters and conditions data file, respectively. The list of parameters is given in Table 1.
- The expert system takes the data files as input and selects an appropriate treatment regimen for the patient. In addition to selecting the training exercises, the expert system also makes the necessary modifications to the parameters data file.
- The robot training program takes the parameters data file as input and provides the appropriate exercise to the patient.

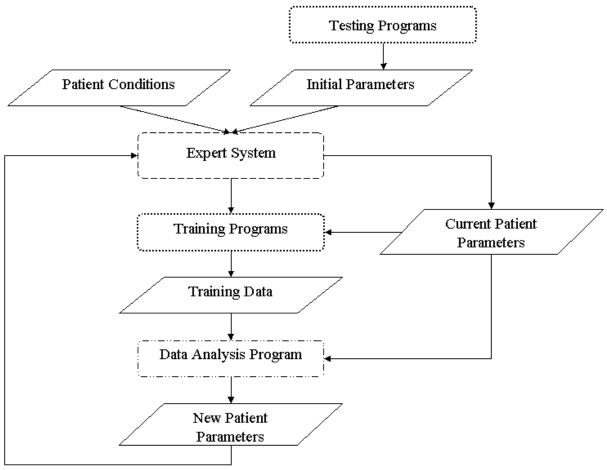

Fig. 3. Overview of the software components.

- During the training, the program records the data relevant to the patient's movement at 30 milliseconds interval. The data includes the x and y position, the x and y forces, the x and y velocities, and the time at every data point.
- The data from the training sessions is analyzed by the analysis program. This program calculates the average deviation, the percentage accuracy, the average velocity, and the average of the peak resultant velocity. The analysis program stores the calculated values back in the para-meters data file.

- The parameters data file is the input to the expert system. The expert system checks if the new parameters are different from the old parameters in terms of accuracy, range or motion, velocity, etc., as shown in the treatment plan. If they are different, the conditions for progress are checked and subsequently any applicable changes are made to the parameters data file.
- This new parameters data file is used as input by the training program and the training cycle repeats.

The list of parameters in file is given in Table 1, and how the parameters are represented in the InMotion2 robotic training is explained.

Center of y-axis - The center position (origin) of y-axis can vary from patient to patient due to reasons such as the position of the chair in front of the robot, the length of the patient's arm, etc.

ROM - The range of motion is represented as the radius of a circle. This implies that the range is not direction specific. For example, if a patient has AROM of 0.14m then it can be understood that the patient can actively move the arm under his/her own power to any point within the circle of radius 0.14m from the center (the origin) position.

Table 1. Patient Parameters in Data File.

PARAMETER	SHORT DESCRIPTION
AROM	Active Range of Motion (m)
PROM	Passive Range of Motion (m)
resist_force	Maximum tolerable resistance (N/m)
assist_force	Minimum required assistance (N/m)
center_y	Center position, origin of y-axis (± m)
deviation	Average deviation from straight line path (m)
accuracy	Average % accuracy with respect to length of motion segment
velocity	Average velocity calculated from time taken (m/s)
max_res_vel	Average of the peak resultant velocity (m/s)

Resistance - In the InMotion2 robot, any force is a function of a parameter called stiffness. This is similar to that of the stiffness of a spring called the spring constant. The robot uses back-drivable electric servo motors to implement a spring-like feel. The stiffness is measured in Newtons per meter. For a spring, it is the amount of force required to stretch the spring by one meter, and it can be represented as:

$$F = -kx$$

where k is the spring constant, x is the displacement of the spring. When the robot arm is set to be stationary at a point and if one tries to move the arm, one will be moving against the resistance of the arm. This resistance will be felt like the stiffness of a spring and the force experienced will increase as the arm is moved farther away from the set position. This method is used in the strength training exercises.

Assistance - The assistive forces applied to a patient's arm by the robot arm is also manipulated as a function of the stiffness. When the patient does not need any assistance from the robot, the stiffness can be set to 0, i.e., no force from the robot. As the stiffness is increased and the robot arm is programmed to move along a specified path, then it will exert assistive force on the patient's arm. Higher stiffness means that the robot arm follows the programmed path more closely and provides increased assistance to the patient's arm.

Deviation - During training, the robot is programmed to record the position data about every 30 milliseconds. The data file also stores the information about the desired straight line path in the form of starting point and ending point. If the starting point is given as (x_1, y_1) and the ending point is (x_2, y_2) then the equation of the straight line can be given as:

$$Ax + By + C = 0 \quad \text{where}$$
$$A = y_2\ y_1, \quad B = x_1\ x_2, \quad \text{and} \quad C = (x_2.y_1)\ (x_1.y_2)$$

Using this equation of the line, the perpendicular distance to the line from any given point, (x_p, y_p), can be calculated as follows:

$$d = \left| \frac{x_p.A + y_p.B + C}{\sqrt{A^2 + B^2}} \right|$$

The calculated distance is given as the deviation from the desired straight line path at any given instant.

Accuracy - The calculated accuracy is an extension of the deviation. The average deviation is represented as a fraction of the length of the motion segment. For example, more than 96% accuracy means that the average deviation is less than 4% of the length of the motion segment.

Velocity - The velocity is calculated from the time taken to complete a motion segment. Although the instantaneous velocity is recorded every 30 ms, this velocity is not constant. Therefore, in order to calculate the average velocity of the patient's arm, the time taken to complete each motion segment is noted. Based on the time and the distance of the motion segment, the average velocity is determined.

Resultant Velocity - The velocity recorded in the data file from the robot controller is the instantaneous x and y velocity vectors. The magnitude of the resultant is calculated using the formula,

$$R_{vel} = \sqrt{(x_{vel})^2 + (y_{vel})^2}$$

6. Clinical study

The aim of this clinical study is to test various aspects of the newly developed expert system-based stroke rehabilitation system in a clinical setting. The results of the clinical study will serve as "proof of concept" for a possible full-scale study.

Two chronic stroke patients were recruited for this study with the help of the Kansas Stroke Registry, established at the University of Kansas Medical Center. Subjects in this study were adults, greater than 21 years of age, who are diagnosed patients with symptoms of mild to moderate stroke. One subject assigned to the experimental group underwent robotic training with the expert system the other subject assigned to the control group underwent robotic training without the expert system. A step-by-step overview:

STEP 1. Base-line (initial) testing should be done for all subjects by a therapist. This will be used for post-training comparisons. The therapist should also find out the patient conditions regarding Passive Range of Motion (PROM - limited/normal), and tone in the passive range (normal/ MAS1/ MAS1+/MAS2).

STEP 2. Initial testing using the robot - should be done for all subjects. The various parameters of arm movement for the subject are measured using the appropriate robotic testing programs. The parameters measured are listed in Table 1.

(Steps 3, 4, 6 and 7 are for the experimental group. For the control group only step 5 is given; however the parameters for step 5 are manually calculated and verified by the therapist.)

STEP 3. Use the recorded data file from the testing program and run the analysis program on it. This program calculates the average deviation, accuracy, average velocity and peak resultant velocity, and stores the results.

STEP 4. Run the expert system to determine the steps in training.

STEP 5. Subject training - run the training programs as suggested by the expert system (or by the therapist for control group) after the parameters are verified by the therapist.

The warm-up programs stretch the ROM and slowly increase the velocity. There are five trials each with two repetitions on the diagonal pattern. Resistance and assistance is minimal.

The train_ROM and train_strength programs are used for stretching the range and for strengthening the affected arm respectively. There will be 10 trials each with two repetitions.

STEP 6. After every two sessions (i.e., one week of training with the same parameters) use the recorded data file from the training sessions and run the analysis program on it. This program calculates the average deviation, accuracy, average velocity, and peak resultant velocity, and stores the results.

STEP 7. Run the expert system to determine the progress and the future training steps.

Repeat steps 5, 6 and 7 for four weeks (two sessions/ week).

STEP 8. Repeat step 1 to collect all the end-treatment data.

7. Experimental results

As explained in the study protocol two human subjects were recruited for this study. One of the subjects was assigned to the experimental group and one to the control group.

7.1. Baseline Evaluations

A baseline evaluation was conducted for each subject to assess the sensorimotor function. Primary measure for the motor function are the Motor Status Score for shoulder and elbow (MS1) and Fugl-Meyer Assessment (FMA) score for upper extremity. A quantitative assessment of motor function of hemiparetic upper limb was also conducted using the robot. Other neuromotor functional assessment techniques which were used include: Motor Status Score for wrist and fingers (MS2), and Modified Ashworth Scale (MAS).

Motor Status Score [12] - MS1 consists of a sum of scores given to 12 shoulder movements and five elbow/forearm movements (maximum score = 40). MS1 uses a six-point ordinal (unequal intervals) grading scale (0, 1-, 1, 1+, 2-, and 2), ranging from no volitional movement to faultless movement. The MS1 is capable of detecting a significant advantage of robot therapy for shoulder and elbow [1], [40].

Fugl-Meyer Assessment [13] - FMA scale is applied to measure the ability to move the hemiparetic arm outside the synergistic pattern on a three-point scale (maximum score of 66 points). The FMA scale is also widely used in evaluating the effectiveness of robot-aided therapy [7], [30].

Modified Ashworth Scale - MAS is a six-point rating scale that is used to measure muscle tone.

Quantitative assessment of motor function - During initial testing, the program displays a circular pattern with eight different targets along the circumference and the subjects are asked to move the robot arm from the center of the circle to each of the targets sequentially. During this movement the velocity of the motion, the active and passive range of motion, the accuracy of movement, and the required assistive/resistive forces are measured and recorded. These values provide a quantitative assessment of the subject's upper limb motor function.

7.2. Subject Training

The therapist and the subjects were unaware of the subjects' group assignment. The therapist's opinion was sought regarding the best robot-aided treatment option for both subjects. The therapist opined that since the subjects do not have PROM limitation (i.e., within the applicable range of robot therapy), they should be trained for improving strength and accuracy.

Experimental Subject Training: For the experimental subject, the expert system is used to determine the treatment plan. Since the subject does not have PROM limitation, the expert system chose strength training treatment. For the robot training, the parameter values are chosen from the initial testing data. However for the AROM, if the subject's AROM is greater than 14cm, then it is automatically capped at 14cm [10].

In the strength training exercise, the robot arm is positioned at the center of a square and the targets are placed at the four corners. A screenshot of this program is shown in Figure 4, and a subject using the program is shown in Figure 5. The subject is asked to reach the targets moving along the diagonal of the square. The robot arm resists any movement away from the center position. The maximum tolerable resistance measured during the testing session is used by the training program. The training session consists of 10 trials in which the subject is required to reach the targets twice, i.e., two repetitions in each trial. The training program also keeps track of the number of targets missed by the subject. Each target has a maximum timeout period of about two minutes after which the target expires and moves to the next position.

The analysis program is used on the experimental subject's training data to measure the average deviation, percentage accuracy, and velocity of movement. To allow for day to day variations in the motor functions, analysis is done after two training sessions instead of every session. Following the analysis, the expert system is used to determine the progress made by the subject. According to the expert system, perceivable progress is made only if these conditions are all satisfied:

- At least 95% of the targets are reached,
- Measured accuracy is better than 90%, and
- Velocity has improved compared to the previous result.

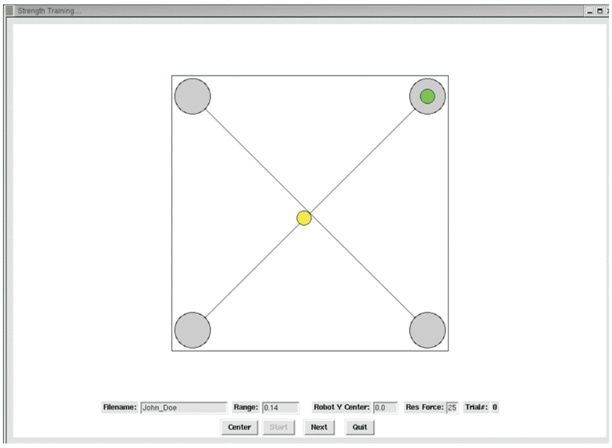

Fig. 4. Screenshot of the strength training program.

For the experimental subject, only once during the four week training did the expert system detect progress and subsequently increased the resistance value for future training. This change in resistance was approved by the therapist.

Control Subject Training: As mentioned earlier, the therapist determined that strength training would be appropriate for the control subject as well. The same strength training program is used under the supervision of the therapist. The main difference in the treatment for the control subject is that the performance of the subject during training was visually monitored and manually noted if any targets were missed by the subject. Based on this observation therapist determined whether the subject has made enough progress to warrant any increase in resistance.

7.3. End-Treatment Evaluations

The end-treatment evaluation was conducted within five days after the completion of the training. The same tests that were used during the baseline evaluation were used again to assess the neuromotor functions of the subjects. The results of the end-treatment evaluations of the two subjects are given in Table 2. In addition, the table also shows the change in scores compared to the baseline values.

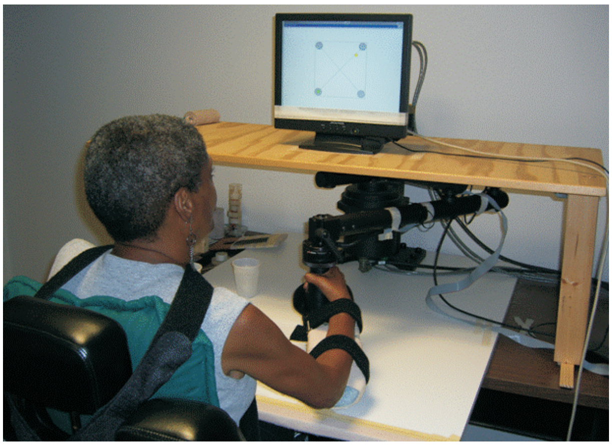

Fig. 5. A subject using the strength training program.

Table 2. Comparison of Subjects.

Characteristics	Experimental Subject		Control Subject	
	Baseline	End-treatment	Baseline	End-treatment
Years post stroke	7		34	
FMA Score - Sensory	3	5 (+2)	6	6
FMA Score - Motor	32	34 (+2)	30	33 (+3)
MSS shoulder/elbow (MS1)	28.8	26.8 (-2)	22.8	19.8 (-3)
Modified Ashworth Scale (MAS)	2	2	2	2
AROM	0.17m	0.17m	0.17m	0.17m
Velocity	0.05961 m/s	0.0787 m/s	0.02371 m/s	0.02672 m/s
Resistance	43 N/m	46 N/m (+3)	22 N/m	28 N/m (+6)
Accuracy	86.1%	86.6% (+0.5)	93.3%	95.3% (+2)

7.4. Effectiveness of the Rehabilitation System

After the initial testing, the expert system was used to determine a treatment plan for the experimental subject. The expert system arrived at the conclusion that strength training should be carried out because the subject had no PROM limitation within the range of the robot. The therapist agreed with this decision of the expert system and the subject went through strength training for four weeks. During the four weeks, the expert system was used to monitor the progress. Only once during this period did the expert system detect progress and increased the resistance. After reviewing the data, the therapist agreed with that decision as well.

For the control subject, after the initial assessment, the therapist determined that strength training would be most suitable. After the the decision, the control subject's initial conditions were input to the expert system and it arrived at the same conclusion as the therapist. After the first two sessions of strength training, according to the therapist's observation the subject had made progress and so decided to increase the resistance. The therapist's decision was checked against the expert system but it did not detect enough progress with the subject because the velocity had not improved. The therapist was very pleased with the analysis program. The data collected during a training session typically contains close to 115,000 data points (one data entry for every 30ms). The analysis program makes it possible to quickly analyze and summarize the data from an entire training session.

8. Conclusions

The objective of this work is to design, develop, and evaluate an expert system based post-stroke robotic rehabilitation system [31]. The new rehabilitation system can be a valuable tool for therapists in analyzing the data from the robot, helping them make the right decisions regarding the progress of the stroke patient, suggesting future training exercises, and delivering robotic therapy. To understand the current stroke rehabilitation practices, a survey was conducted among clinicians in Kansas and Missouri. The majority responses from the clinicians were used to construct a treatment plan for robotic rehabilitation. The treatment plan was implemented as the rule base of the expert system. The delivery of robotic rehabilitation required the development of certain testing programs and training programs, and a data analysis program that can analyze the voluminous training data and summarize it to the expert system. These associated components were developed as part of a new robotic rehabilitation system. The rehabilitation system was evaluated in a clinical setting with two human subjects. The clinical study is intended to verify the effectiveness of expert system-based robotic rehabilitation. The effectiveness of the expert system, the testing and training programs, and the analysis program was evident from the fact that the therapist agreed with the analysis and the decisions made by the system.

The expert system-based rehabilitation was studied both for its correctness and usefulness. The correctness of the expert system was evaluated based on how close its decisions are to that of the therapist. Twice the expert system made decisions regarding the treatment plan and regarding the progress of the subject in the experimental group. Both times the therapist agreed with the decisions and was satisfied by the explanation provided by the expert system. For the control subject the therapist made the decisions about the treatment plan and the progress. When the expert system was used to test the therapist's decision, it produced the same treatment plan but not the same decision about the subject's progress. The one time in which the expert system produced a different result can be attributed to the fact that the therapist made the decision about the subject's progress based mainly on visual observation. The therapist did not use any tools to analyze the quantitative data. The therapist followed the procedure that clinicians follow in everyday practice.

The training programs record data at an interval of about 30 milliseconds. The data file produced by the training programs on average consists of about 115,000 data points. Manual analysis of one of the data files using a spreadsheet program could take an average computer user anywhere from one to two hours. A therapist using the robot does not have the time to quantitatively analyze all of the patient's data. The data analysis program developed as part of this rehabilitation system can analyze the data file and produce summaries within a few seconds. It produces information such as the average deviation of the subject's arm from the targeted straight line path, calculates the percentage accuracy as a fraction of the length of the path, calculates the average time taken to reach the targets and thereby the velocity, the average x and y directional forces, and the mean peak resultant velocity. Having this information immediately after a training session would enable the therapist to make sound decisions based on quantitative data. The ability to summarize a training session also means that the therapist does not have to observe the patient continuously. The therapist can simply look at the summarized results at the end of a training session and make decisions.

The results also show that a subject trained with the robot tends to show improvement in his/her motor functions. This result is consistent with many other studies that have shown that robot therapy improves motor function in hemiparetic arm of stroke patients [1], [30]. Figure 6 shows the move-ment of the affected arm of the experimental subject before and after robot-aided strength training. It can also be seen that the accuracy has improved marginally. The mean deviation before the therapy was

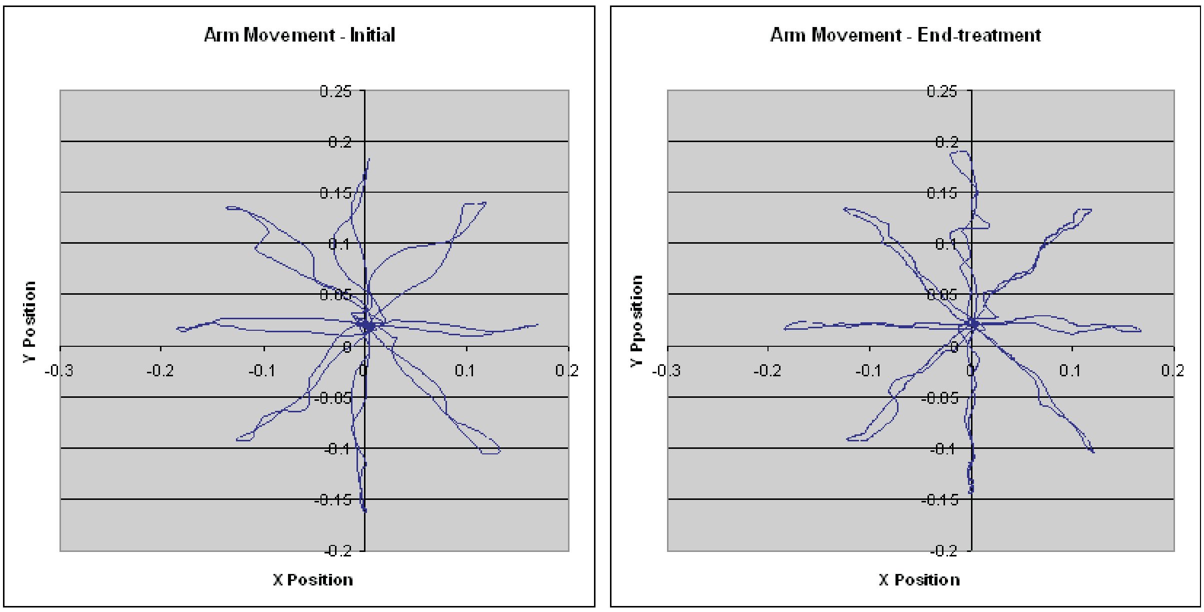

Fig. 6. Movement of the experimental subject's arm along the x-y plane, before and after treatment. The graph on the left shows the data from the initial testing and the graph on the right shows the data from the end-treatment testing.

0.0139m and after the therapy it was 0.0134m.

The results of this clinical study presented in Table 2 also show that the experimental subject's FMA for both sensory and motor scores improved by two. Similarly for the control subject, the FMA motor score has improved by three. The end-treatment testing with the robot also revealed that the experimental subject had a marked improvement (32%) in the velocity of the affected arm. There is also a slight increase in arm strength of both subjects as measured using the robot. At the end of the clinical study, both subjects were asked to fill out an exit survey. Their feedback showed that the subjects were comfortable and enjoyed using the robot. This illustrates that robotic therapy in addition to being effective, can be entertaining and enjoyable for stroke patients as well. The results presented in Table 2 show that both the control subject and the experimental subject benefited from robotic therapy. The improvement in motor performance was similar for both subjects. This proves that the quality of care provided by the expert system-based rehabilitation system is comparable to the care provided by a therapist using existing robotic treatment methods.

The main limitation of this rehabilitation system is that stroke therapy is highly subjective, varying from therapist to therapist and also from patient to patient. Currently, there is no consensus among the therapists regarding the best treatment options. It is still possible that a therapist might reach a conclusion different from that of the one suggested by the expert system based on his/her beliefs and clinical experience. Since the clinical study conducted to evaluate the rehabilitation system is limited to only two stroke patients, it should be construed as a "proof of concept" as the results are not statistically significant.

One area of immediate focus following this research could be modifying the expert system to behave as a low-level intelligent controller for the robot producing a real-time adaptive system. Another area directly related to this research is tele-rehabilitation [9], [22]. The results from this research prove that minimally supervised therapy is possible. A rehabilitation robot can be made available at a com-munity clinic and a therapist from a remote location can periodically review the suggestions made by the expert system in order to approve or modify it. The delivery of robotic rehabilitation and its effectiveness could be augmented by incorporating virtual reality and haptic feedback devices [32], [27] or by a portable exoskeleton arm [25].

AUTHORS

Pradeep Natarajan - IBM Corporation, Lenexa, KS 66219 USA. E-mail: pnatara@us.ibm.com.
Arvin Agah* - Department of Electrical Engineering and Computer Science, University of Kansas, Lawrence, KS 66045 USA. E-mail: agah@ku.edu.
Wen Liu - Department of Physical Therapy and Rehabilitation Sciences, University of Kansas Medical Center, Kansas City, KS 66160 USA. E-mail: wliu@kumc.edu.
* Corresponding author

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