Expert System-Based Post-Stroke Robotic Rehabilitation for Hemiparetic Arm

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Outline

- Introduction
- Stroke
- Rehabilitation Robotics
- Expert Systems
- Research Methodology
- Clinical Study
- Experimental Results
- Conclusions
- Questions

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Introduction

- Motivation
  - Every 45 seconds someone in the US has a stroke
  - Stroke kills about 163,000 people every year
  - Each year more than 700,000 Americans suffer a stroke (500,000 first time; 200,000 recurrent)
  - Estimated 5.6 million stroke survivors were alive in 2004
  - Loss of arm function affects independence and quality of living of the stroke survivor

  (Statistics from American Stroke Association, 2007)

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Introduction

- Problem Statement
  - Major challenges in stroke rehabilitation
    - ***Repetitiveness of therapy***
    - ***Availability of long-term therapy options***
  - Repetitiveness – solved by robotic therapy
  - Rehabilitation robots need to be programmed, the therapist has to monitor the patient, analyze the data and manually assess the patient's progress
  - Robotic rehabilitation remains uncommon in the medical community

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Stroke

- Stroke (Cerebral Vascular Accident)
  - Occurs when a blood vessel that carries oxygen and nutrients to the brain clots (ischemic stroke, 83%) or bursts (hemorrhagic stroke, 17%) (American Stroke Association, 2007)
  - Brain cells without blood and oxygen start to die
  - Parts of the body controlled by those brain cells are affected
  - Causes paralysis of one side of the body, affect language, vision, memory loss, and behavioral problems

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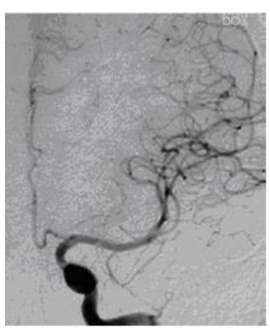
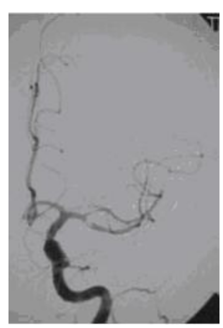
Stroke



Angiogram showing normal blood vessels to the brain

(Higashida, American Stroke Association, 2007)



Many blood vessels are not visible due to hampered blood flow to the brain

(Higashida, American Stroke Association, 2007)

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Stroke

- Stroke Rehabilitation
  - Therapy allows the brain to go through a restructuring process and relearn the movement control with the remaining neurons
  - Motor relearning depends on brain's capacity to reorganize and adapt
  - Training influences the pattern of reorganization even 4-10 years after stroke (Taub *et al.*, 1993)
  - Robotic training is proven to be effective in upper limb motor recovery

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Robotics in Stroke Rehabilitation

- Robotic Rehabilitation
  - The interactive robotic therapist (known as the MIT-MANUS) – developed at MIT in 1992
  - Other rehabilitation robots – MIME, ARM Guide, MULOS, GENTLE/s
  - They lack a comprehensive treatment program
  - Non-availability of analytical and decision tools to help therapists

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MIME Rehabilitation System

(Source: Burgar *et al.*, 2000)

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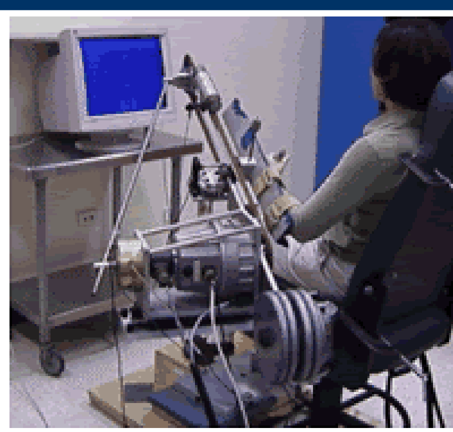
ARM Guide



(Source: Reinkensmeyer *et al.*, 2000)

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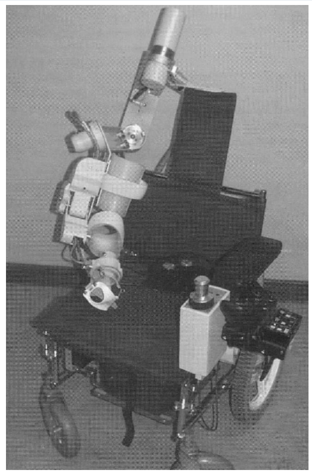
MULOS in a Powered Wheelchair



(Source: Johnson *et al.*, 2001)

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InMotion^2 at the NMR Lab

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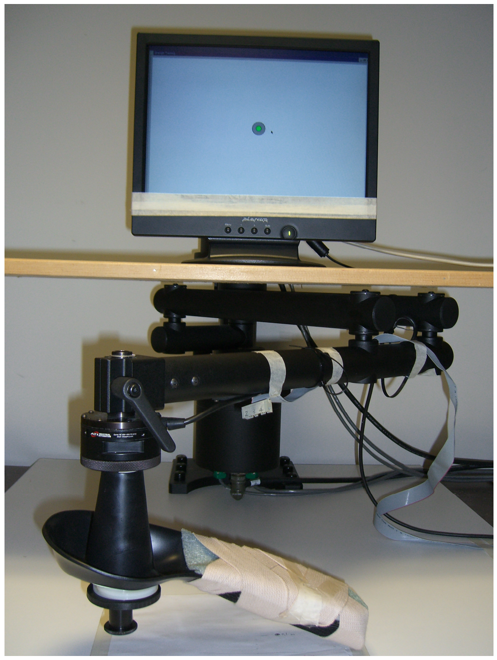

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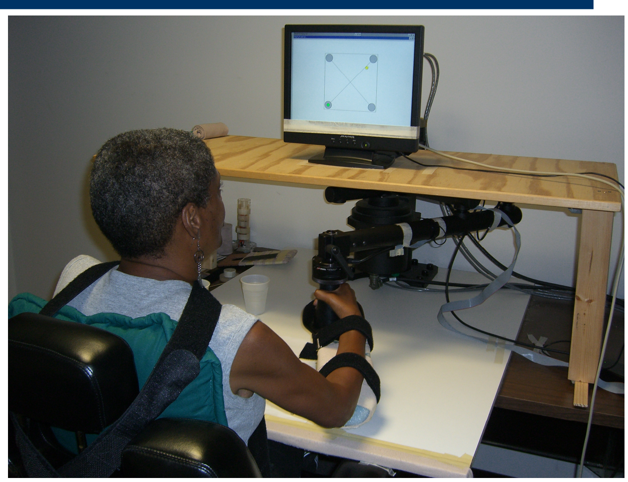
InMotion² being used by a patient



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Expert Systems

- Definition
  - A computer-based decision tool that uses facts and heuristics to make decisions based on knowledge acquired from experts

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Expert Systems

- Expert System Development Process
  - Knowledge acquisition
  - Knowledge representation
  - Tool selection and development
  - Testing, verification and validation
  - Implementation and maintenance

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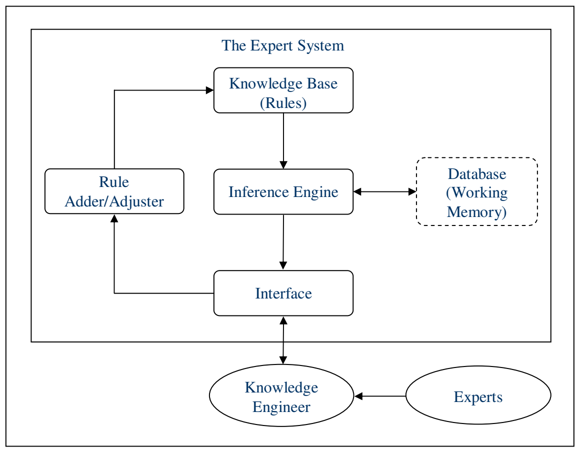
Expert System during Development



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Expert Systems

- Knowledge Acquisition
  - Get the knowledge from the domain experts
  - Refine knowledge to make it formal and precise
  - Identify boundary conditions within which the knowledge is applicable and exceptions for which the knowledge does not apply

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Expert Systems

- Knowledge Representation
  - Knowledge from the experts should be represented in a computer-friendly format such as a *production system*
  - Production system is based on rules

    IF *conditions* THEN *actions*

    alternatively,

    conditions → *actions*

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Expert Systems

- Knowledge Representation
  - Knowledge base will include but not limited to:
    - General principles of therapy
    - Initial conditions of the stroke patient
    - Most effective training exercise patterns and their determinants
    - Methodology by which patient's progress will be assessed

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Expert Systems

- Tool selection
  - InMotion2 controller (Linux kernel module) is developed in C programming language
  - User interface for InMotion2 is created in Tcl/TK
  - Expert system is developed using C Language Integrated Production System (CLIPS)
    - Open source
    - Extensively documented
    - Easy to integrate with Tcl and C

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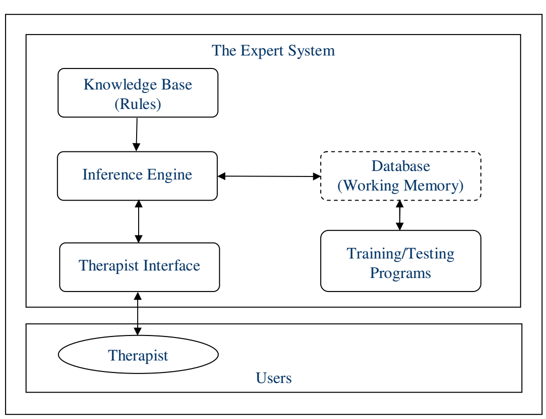
Expert System While in Use



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Expert Systems

- Expert Systems in Robotics
  - Robotics involves simple to complex control systems
  - Intelligent control system consists of decision making at some level
  - Several areas within robotics benefit from expert systems, such as robot vision and image analysis, robotic sensory systems, robot control, etc.

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Expert Systems

- Expert Systems in Health Care
  - Implemented and utilized in major areas – diagnosis and treatment recommendations
  - Complex medical decisions made when stakes are high
  - Given patient conditions/symptoms, expert systems can assist physicians in diagnosis and provide treatment recommendations

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Expert Systems

- How expert systems help in health care?
  - improve accuracy of diagnosis
  - improve reliability of clinical decisions
  - improve cost effectiveness of tests and therapies
  - improve our understanding of medical knowledge and clinical decision-making
- Expert systems to be used in health care only if it improves the quality of care at acceptable cost or maintains the existing standard at reduced cost

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Research Methodology

- Primary Aim of proposed study
  - Design and implement an expert system-based robotic rehabilitation system
  - Evaluate the system by comparing robotic rehabilitation without the expert system
  - Goal of this research is to make robotic rehabilitation easier to use by therapists and reduce the time required for the therapist to treat each patient

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Research Methodology

- Primary Hypothesis
  - ***Stroke patients rehabilitated using an expert system-based robotic rehabilitation system will experience the same improvement as the stroke patients who undergo a rehabilitation program with the same robot but without the expert system***
  - The neuro-motor function of the hemiparetic upper limb will be assessed primarily using Fugl-Meyer Score before and after trainings

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Research Methodology

- Secondary aims
  - Assess the acceptability of the recommended treatment options
  - Compare the two patient groups in motor performance of hemiparetic upper limb in a specific movement pattern

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Research Methodology

- Design Requirements of the proposed system
  - Includes the expertise of many therapists instead of just one (as compared to conventional therapy)
  - Analyzes the result of the training exercises and determines future course of action
  - Enables the therapist to treat more patients efficiently in a shorter time

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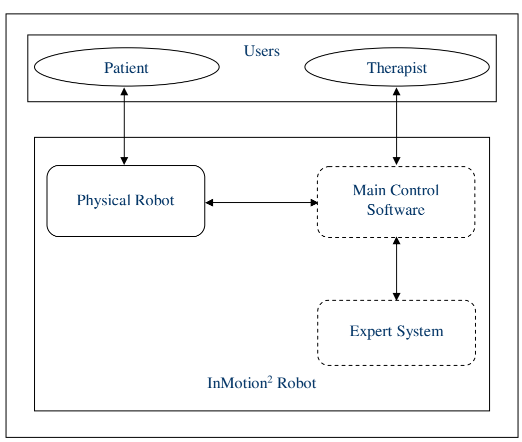
System Architecture



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Research Methodology

- Robotic training without expert system
  - Therapist makes an initial assessment of the patient's motor skills
  - Therapist chooses an exercise and a set of determinants (variable parameters)
  - Visually monitors the patient and/or manually analyzes the data from the robot and assesses the progress of the patient
  - Based on the assessment, reprograms the robot with a new exercise pattern or determinants for the same exercise pattern

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Research Methodology

- Expert system-based robotic training
  - Data from the robot are collected when the patient performs any training exercise
  - The collected data are analyzed and summarized by appropriate software tools
  - Based on the summary, the patient's progress is assessed by the expert system
  - The expert system presents future training parameters and explanation for decisions
  - Upon therapist's approval training will be repeated

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Research Methodology

- Knowledge Base Development
  - Expert knowledge in physical/occupational therapy is complex, subjective, and varies depending on the clinical experiences and educational training of the therapist
  - Interviews, group discussions, and questionnaires were used to obtain the knowledge from the experts and create the knowledge base
- Survey
  - Survey questionnaire is developed with the help of experts

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Research Methodology

- Survey to understand clinical practices in stroke rehabilitation and principles to be applied for robotic rehabilitation
- Questionnaire sent to 320 physical and occupational therapists in Kansas and Missouri
- Received qualified responses from 107 therapists
- Responses from therapists were analyzed and discussed with experts
- The majority responses were used to construct the knowledge base

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Research Methodology

- Knowledge Representation
  - Current literature was referred to refine the knowledge as applicable to robotic therapy
  - Knowledge base encapsulates the expertise of 107 physical and occupational therapists
  - A step-by-step treatment protocol for robotic therapy is developed
  - The treatment protocol is represented as rules for the expert system

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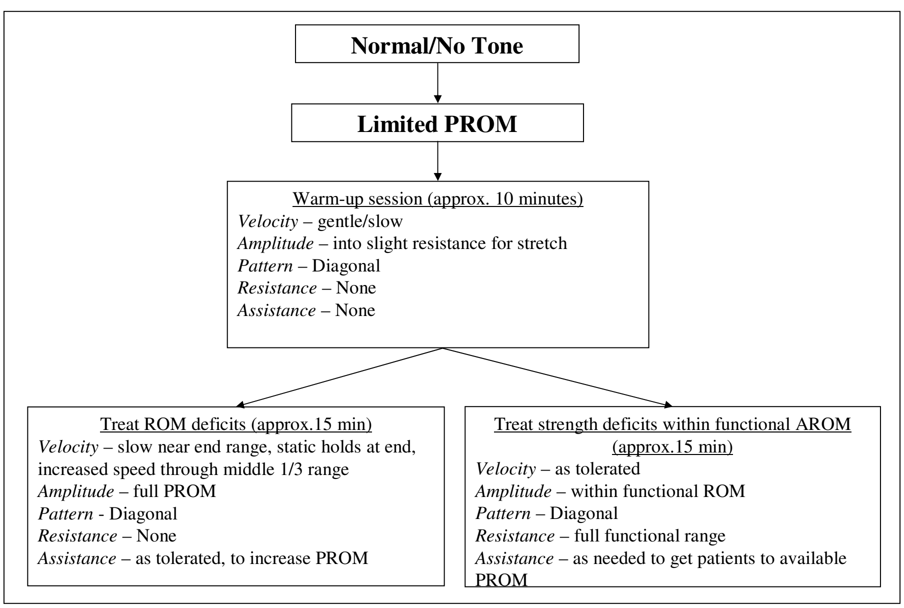
Treatment Plan 1 – Normal Tone & Limited PROM



Treatment Plan 1 – Normal Tone & Diminished Strength & Normal PROM

Normal/No Tone

↓

Diminished strength but PROM normal

↓

Warm-up session (approx. 10 mins)
Velocity – gentle/slow
Amplitude – into slight resistance for stretch
Pattern – Diagonal or pattern which stretches structures most limited
Resistance – None
Assistance – None

↓

Treat strength deficits within functional AROM (approx.15 min)
Velocity – as tolerated
Amplitude – within functional ROM
Pattern – Diagonal or pattern to stretch structures limited
Resistance – full functional range
Assistance – as needed to get patients to available PROM

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Treatment Plan 2 – High Tone & PROM Limitation

High Tone & Limited PROM

↓

MAS grade 1 or greater

Velocity – decrease depending on resistance from patient
Amplitude – increase as tolerated
Pattern – Diagonal
Resistance – increase as tolerated
Assistance – constant force for prolonged stretch

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Sample Rule

- Progress is monitored using accuracy and velocity

Strength training example:

IF (accuracy > 0.90) AND (current velocity > previous velocity) THEN increase resistance by 1

Explanation:

"Since accuracy is better than 90% and velocity is improved, the resistance is increased by 1"

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Research Methodology

- Software Implementation
  - Software is designed for maximum safety of human subjects
  - Provides the human user full control and flexibility for manual override
  - Implemented in Linux platform (same as robot)
  - Software components:
    - Expert system in CLIPS
    - Robot testing and training programs in Tcl/TK
    - Data analysis tool in C

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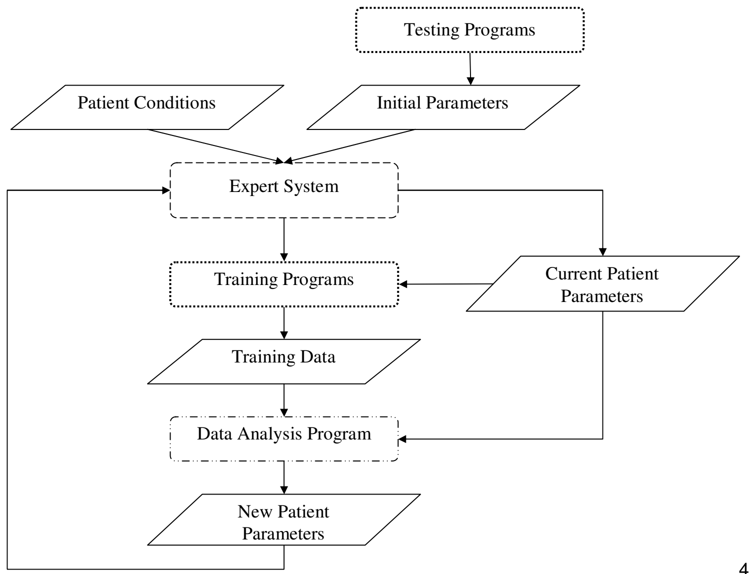
Overview of Software Components



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Research Methodology

- Functional overview of components:
  - Initial patient testing using robot – testing programs
  - Expert system selects training and parameters
  - Patient undergoes robotic therapy – training programs
  - Data recorded during training every 30-40ms – *xy* position, *xy* forces, *xy* velocities, and time
  - After two training sessions data is analyzed – averages of deviation, % accuracy, constant velocity, and maximum resultant velocity
  - Expert system is used to assess progress and changes made to training parameters

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Patient Parameters

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

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Clinical Study

- Institutional Review
  - Human Subjects Committee at KUMC serves as the Institutional Review Board
  - HSC ensures protection of the rights and welfare of human subjects
  - The proposed clinical study was submitted for a full committee review
  - All associated personnel underwent Human Subject Protection training

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Clinical Study

- Study Design
  - One experimental and one control subject
  - Experimental subject underwent training with the expert system-based rehabilitation robot
  - Control group underwent training with the robot but without the expert system
  - Subjects were evaluated for motor functions and compared
  - Acceptability of the expert system is evaluated

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Clinical Study

- Baseline and End-Treatment Evaluations
  - Baseline evaluation – immediately after recruitment
  - End-treatment evaluation – within five days after training ended
  - Primary measure for motor function of the hemiparetic upper limb used Fugl-Meyer score
  - Other assessments – Motor Status Score for shoulder/elbow and wrist/fingers, Modified Ashworth Scale, Motor Activity Log, and quantitative measurements using the InMotion^2 robot

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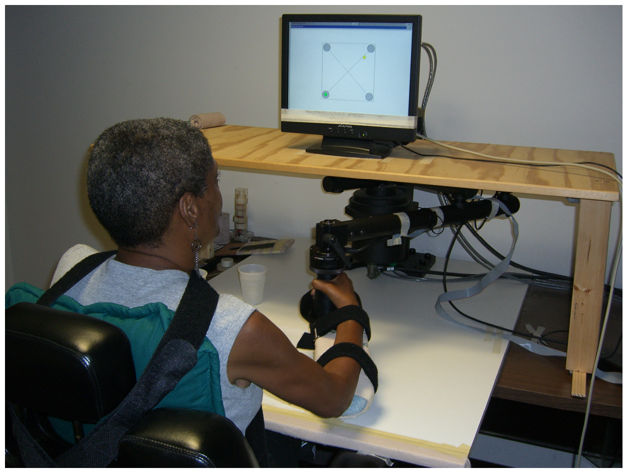
InMotion² being used by a patient



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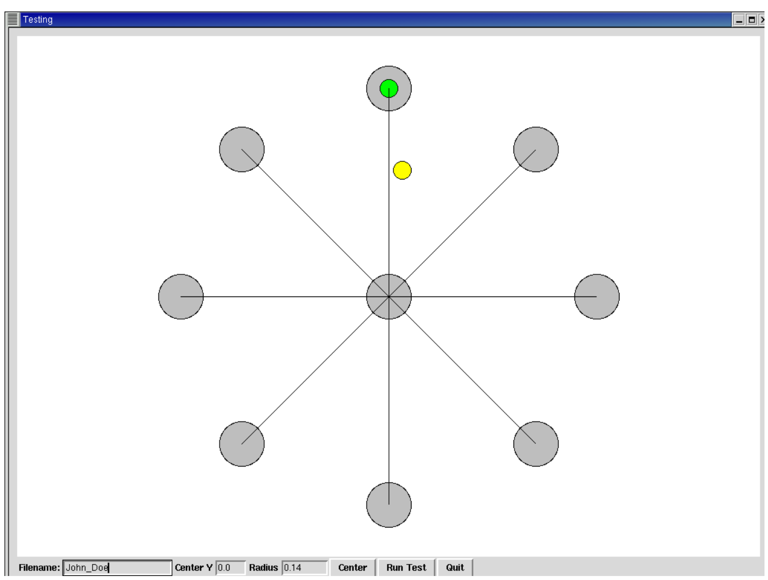
Robot Testing



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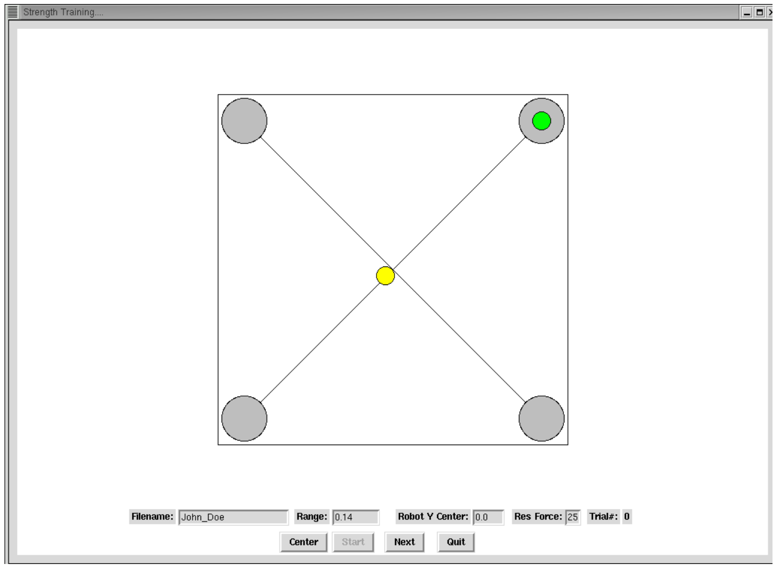
Robot Training



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Experimental Results

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)

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Conclusions

- Summary
  - Objective: Design, develop and evaluate an expert system-based robotic rehabilitation system
  - To understand clinical practices in stroke rehabilitation a survey was conducted
  - Based on the survey responses a comprehensive robotic treatment protocol was developed
  - An expert system and associated software developed to utilize the robotic treatment protocol
  - The proposed system was evaluated in a clinical setting

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Conclusions

- Discussion
  - Therapist agreed with the decisions of the expert system for the experimental subject
  - The data analysis tool makes it possible to quickly summarize training session data
  - Both subjects improved in FMA score, velocity, strength, and accuracy
  - The system eliminates the need for therapist to continuously monitor the patient and/or manually analyze quantitative data
  - Exit survey - subjects enjoyed using the robot

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Experimental Results

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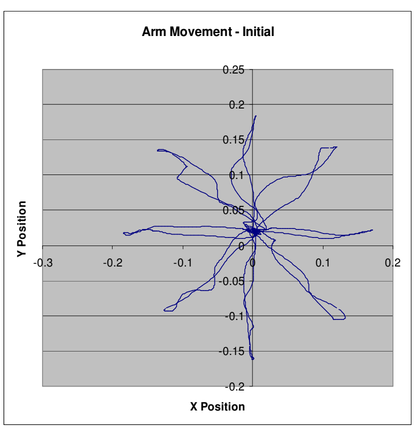
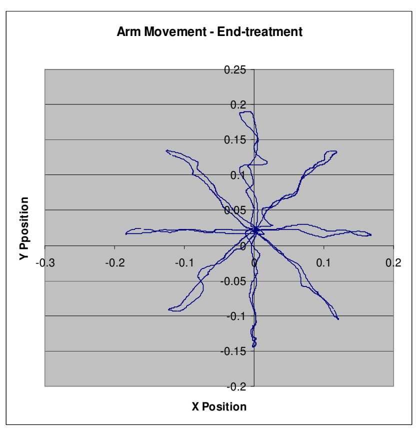
Experimental Subject





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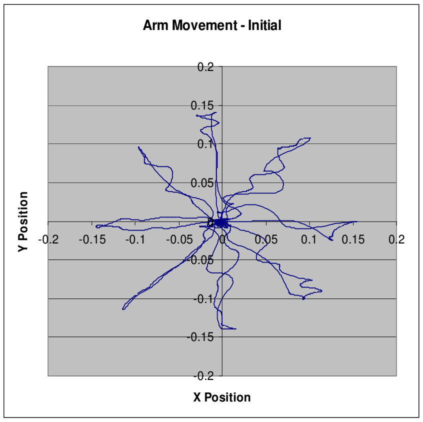
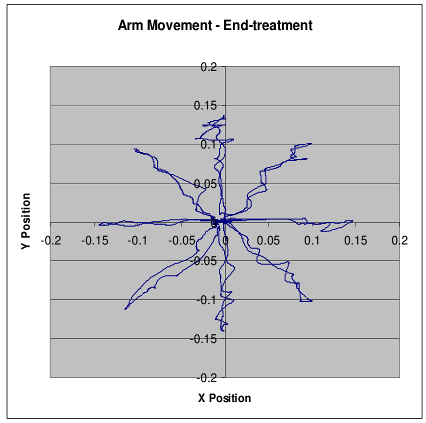
Control Subject





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Exit Survey

No.	Statement	DISAGREE				AGREE			
		0	1	2	3	4	5	6	7
1	Comfortable with the robot therapy								
2	Enjoyed doing therapy with the robot								
3	Believe the therapy was beneficial								
4	Would like to do more robotic therapy								
5	Would have been a better experience if you were working alone with the robot								
6	Would not mind working with the robot alone (on your own) if it was guaranteed by the therapist to be safe								
7	Would make me feel better/safer if a therapist is supervising the robotic therapy								
8	Would rather work with the robot than a therapist								

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Conclusions

- Contributions
  - Gathered stroke rehabilitation knowledge
  - Developed a robotic therapy protocol
  - Designed and developed expert system that will provide valuable suggestions to the therapist
  - Developed robotic testing and training programs
  - Designed and developed software to analyze and summarize data from the InMotion^2 robot
  - Designed a clinical study protocol and conducted a pilot study to evaluate the rehabilitation procedure

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Conclusions

- Limitations
  - Post-stroke therapy is still very subjective varying from therapist to therapist
  - Knowledge gathered is limited to therapists in Kansas and Missouri and it was not specific to robotic rehabilitation
  - Stroke therapy changes as stroke related research progresses
  - Clinical study had only two subjects – serves as a "proof of concept" and statistically insignificant

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Conclusions

- Future Work
  - Conduct a larger study to statistically analyze the effectiveness of the system
  - If beneficial, the expert system can behave as a low-level intelligent robot controller and can be allowed to dynamically modify the training parameters
  - Open source knowledge base for the treatment plan
  - Development of tele-rehabilitation system
  - Incorporate haptic feedback devices and virtual reality based training
  - Development of a stable exoskeleton arm

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Publications & Presentations

- Natarajan P, Oelschlager A, Agah A, Pohl P, Ahmad SA, Liu W (accepted). Current clinical practices in stroke rehabilitation: a regional survey
- Natarajan P, Liu W, Oechslin J, Agah A. A haptic display for robotic rehabilitation of stroke. In *Proceedings of the 11th International Symposium on Robotics and Applications (ISORA 2006), World Automation Congress (WAC 2006)*, Budapest, Hungary, July 24-27, 2006, ISORA-70, 1-6
- Natarajan P, Liu W, Liu H, Agah A. Expert System-Based Post-Stroke Robotic Rehabilitation for Hemiparetic Arm. Poster presentation at the 2006 Information and Telecommunication Technology Center Research Review, University of Kansas, April 7, 2006
- Natarajan P, Liu W, Liu H, Oechslin J, Agah A. Tactile sensory motor training for hemiparetic arm/hand. Poster presentation at the 2005 Information and Telecommunication Technology Center Research Review, University of Kansas, April 7, 2005

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