Robotic Techniques for Upper Limb Rehabilitation and Evaluation

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Abstract: - In this paper we discuss the development of a therapeutic robotic system using an industrial manipulator, off-the-shelf hardware and in-house developed software. The development work starts with the analysis and the establishment of the requirements for a rehabilitation robotic system (RRS) and describes the proposed prototype and its operation. The developed system incorporates the necessary hardware and software modules to permit its use in safe and effective rehabilitation exercises. Tests were conducted on healthy individual and showed a correct behaviour of the system. The developed biomechanical model of the patient's arm and the rehabilitation exercise collected data simulate the dynamic behaviour of the arm and allow for the extraction of forces at the joint level. This information with other indicators will be used for the evaluation of the recovery process

Key-Words: - Rehabilitation Robotics, Therapy Robot, Neuronrehabilitation, Biomechatronics, Stroke

1 Introduction

Partial or full loss of motor function can be caused by Cerebrovascular accident (stroke), spinal cord injuries, and occupational and sports injuries. Early intensive rehabilitation is effective in the treatment of impaired limbs [1], but the process is slow and lengthy. This type of treatment becomes costly and is a major burden on the healthcare system. A major issue is the need for a human attendant and/or caregiver to work with these patients. In addition, the current conventional physical and occupational therapy in treatment centres are subjective, labour intensive and often require one or more therapists to work with one patient. It will be beneficial to investigate a more cost effective system that can take part of the job, perform some of the repetitive tasks and reduce the need for a human attendant.

People worldwide require physical therapy due to the loss of motor function because of injury and disease. Aging of population can aggravate these injuries. The literature revealed that in the studies of the upper extremity, repetitive movement practice improved mobility of the hand and arm after stroke [1-4]. Moreover, rehabilitative therapy is found effective in improving walking ability for a number of spinal cord-injured patients [5-6]. Physical rehabilitation is an area where robotics can contribute significantly and provide a considerable opportunity to improve the quality of life for people with limb disability or impairments. This type of rehabilitation robot is recently become known as the Therapeutic Robot.

A robotic system that has controllable movement, velocity, and is supported by intelligent real-time sensing capability can be a vital assistant in today's physical therapy centres. The historical data of patients' performance should also be recorded in real-time, which will help therapists and physicians to monitor and evaluate patients' progress. Coupled with traditional methods of evaluation, EMG can provide an excellent measure of how well a patient has responded or is responding to a treatment.

There has been a recent increase in research of rehabilitation robots focusing on the issues dealing with the control system design [7, 8]. These papers have presented techniques for controlling various robots for rehabilitation applications, including powered robot arms for disabled people, wheelchair mounted robots, and robotic workstations for neuro-rehabilitation. References [9, 10] are among several that describe this work. However, these systems have not yet made their way to the practical field in rehabilitation centres mainly due to their prohibitive cost or to the necessity of more research and development. On the other hand, there are very few studies which addressed the quantitative evaluation of the patient recovery during the course of a treatment using these developed devices. An example of such a study is presented in [11]

This paper describes some aspects of the RRS developed at the School of Engineering at the University of Guelph. It explains how the different software and hardware modules are interconnected and contribute in the process of rehabilitation. Next section presents the general requirements of a Robotic Rehabilitation System and the following explains the characteristics of the developed system and how it incorporates arm modelling to be used for the purpose of evaluation. To the best knowledge of the authors existing RRS systems do include such a model. Initial experimental results are presented in the forth section and the paper is closed by conclusions.

2 Requirements of Rehabilitation Robotic Systems (RRS)

An RRS is a balanced combination consisting of a robotic system, computer technology, sensory devices and software. It should be primarily designed to assist the therapist in providing safe and effective rehabilitation exercises and offer a quantitative measure of the recovery of the affected limbs. Therefore an RRS should have all the necessary elements to provide the intended design benefits. The system should be easy to operate, easy to attach and detach the patient limb and reliable. The most important requirement is safety, because in contrast to an industrial manipulator, the process requires continuous contact and interaction between the robot and humans. From the treatment point of view, the system should be able to monitor and record all information from the robot and all other sensors of the system to permit a thorough analysis when required. The required components of RRS include:

1) A robotic mechanisms (manipulator) able to cover the intended work volume, with a controller which allows real time access to joint values and velocities. The robot and its controller should allow full back-drivability as it is required in therapy exercises, and equipped with force sensing capability to record the interaction forces of the patient limb at any moment.
2) Monitoring and control software for the different parts of the system.
3) User friendly graphical interface, which permits easy and simple operation and monitoring of the therapy process.
4) Software and sensory system for the acquisitions of therapy trajectories from manual therapist driven exercises.
5) A real time measurement system of the patient's spatial limb configuration during therapy is desirable for recovery evaluation.

With these requirements incorporated an RRS will be able to perform effective therapy exercises in active, passive and combined modes, and provide information fit for quantitative evaluation of the recovery progress.

3 The developed RRS

Taking in consideration all characteristics and functional requirements an RRS has been designed and its components developed and integrated to form an operative system. Given the resources and adequacy we opted for using an existing manipulator and off the shelf equipment. Adaptation of the hardware and the development of the software were all performed in the laboratory facilities. A schematic representation of the architecture of the system and the flow of information is shown in fig. 1. The rest of this section describes the most relevant modules of the developed system.

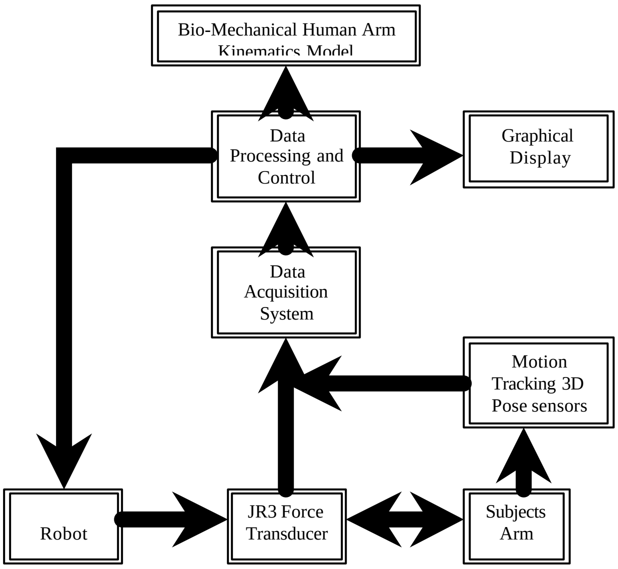

Fig 1. RRS component diagram

3.1 Hardware

The manipulator used in the development of our RRS was a CRS-255, a small industrial robot capable of 5-DOF movement. A 6-DOF JR3 Force transducer mounted at the end effector of the manipulator provides force feedback to the system, the force is read through a USB data acquisition card (USBDAQ-9100MS) which samples at 100 Hz. A modified medical wrist brace was used as the mechanical link between the human arm and the force transducer. The brace's firm structure keeps the wrist and forearm securely attached to the manipulator, while the Velcro strapping allows for easy removal of the splint from the force transducer and/or the human limb from the brace. For security reasons the link between the subject and the robot should have a physical breaking point to allow the release of the brace during excess loading on the limb. In our case the mechanical limitations of the manipulator will not allow it to produce harmful forces. The Spatial orientation of the upper limb is tracked through the use of a Polhemus Patriot pose sensor attached to the brace casing and the elbow joint of the limb (fig. 2). Each sensor is capable of measuring its location and orientation in 3D-space and can be sampled at 60 Hz. A computer (PC) is used to process and store the inputs and outputs to the system.

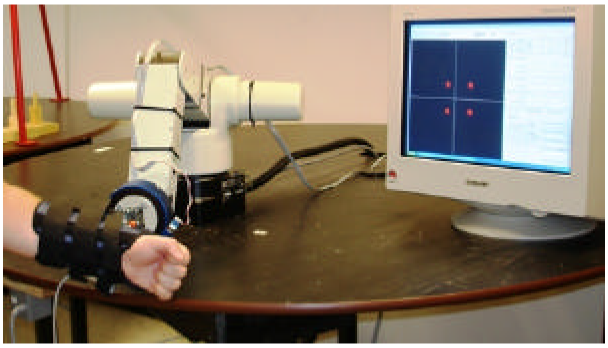

Fig 2. Actual RRS developed with display

3.2 Software

The software for the RRS was developed in visual basic and uses CRS' Active Robot functions to control the manipulator. Graphical feedback is available to the therapist/user through an OpenGL window, which can display different views of the exercise progress. One view shows the movement of the limb as well as the path that the wrist has taken on the screen in real-time using the data collected from the pose sensors. The interface can also display recorded trajectories that have been taught to the system using the "Teach and Repeat" method allowing the therapist to check recorded exercises visually before running them. When a patient is going through an exercise the graphical display is switched to show key points that patient is required to travel through to complete an exercise. The key points are represented as spheres on the screen, the goal point to be travelled to is represented in green while the remaining points are represented in red. Once the patient reaches the goal point the next key point in the exercise turns green and the previous goal point becomes red. The interface also displays a score during the each exercise that is derived from a simple scoring method based on subject's proximity to the desired exercise path during the exercise run. The score is intended as motivation for the subject to improve while completing multiple repetitions of an exercise.

The software records all the data acquired by the system during each exercise allowing extensive post processing to be done on the data later. This gives the ability to compare how well a patient performed an exercise during successive therapy sessions. Part of the collected data is stored in a format suitable for dynamic analysis using the biomechanical model of the human arm developed as part of the project.

3.3 Biomechanical Model

A key benefit of using an RRS to assist in rehabilitation is that quantitative data can be recorded and used to monitor patient performance during therapy. As part of our system a biomechanical model of the human arm presented extensively in [12], was developed to isolate which part of the limb is generating the forces measured at the mechanical link between the subject and the manipulator. When modelling the whole human arm it is important to consider the limitation of patients requiring post stroke rehabilitation. The modelling of the shoulder (socket joint) can be overly complex when dealing with the simple motions that patients are required to relearn to be functionally capable of performing daily life activities (DLA). Acquiring information about the range of motion and joint strength to assure the patient's capability to accomplish DLA and monitor performance is the goal of this model. Therefore, it is not required to model all limb's DOF as they are not involved in all type of arm movement, and hence, the reason for reducing the calculated DOF of the model. Using robotic kinematics, the human arm was modelled as a 5-DOF manipulator, with 3-DOF representing the shoulder joint and 2-DOF representing the elbow joint as shown in fig 3. The wrist joint was not modelled as it is does not move in the brace that attaches the limb to the manipulator. Using the inverse dynamics theory, iterative Newton-Euler dynamics algorithm presented in [13], and the biofeedback collected from the force and pose sensors the forces and torques at each DOF of the arm model can be approximated. This attaches a quantitative measurement to the performance of each set of muscles responsible to the modelled joint movements. With this information it can be determined which muscle group is responsible for the forces generated at the end effector. This along with orientation data can show if the patient is gaining more control over their motions or if they are adjusting their arm positioning to use muscle groups that are functioning better to compensate for weaker areas.

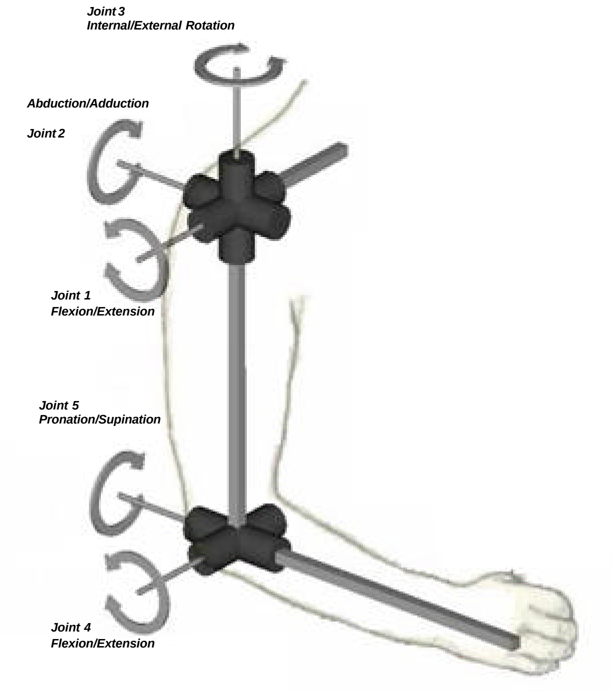

Fig 3. Kinematics scheme of the biomechanical model

3.4 Exercise Acquisition

The robotic can be taught exercises by the operator through a “Teach and Repeat” method. With the pose sensors attached to the patient’s arm the therapist can manoeuvre the limb through an exercise while the system tracks and learns the movement in 3D space. The robot is then capable of assisting the patient’s movement through the patient specific exercises developed by the therapist/operator. This unique function of “Teach and Repeat” learning allows a therapist to teach the therapeutic robot exercises in a manner that is natural to their training. The robotic system is capable of off-line learning of any therapy exercise (trajectory, velocity and orientation), within the robot’s work space. The therapist can move the arm through the recommended exercise and the system can capture and record automatically all the exercise information. To reduce the number of data points that are saved and converted into the final exercise a linear simplification technique is used to reduce redundant points and smooth out the exercise. The technique used in this case is the Douglas-Peucker algorithm [14].

In the Douglas-Peucker algorithm data points are selected based on their proximity to paths established between points that are already included in a filtered data set. The algorithm is initiated by adding the start point and end point of the original data set to a filtered set. A path is then established between all points in the filtered set and all remaining data points are evaluated for their closeness to that path. All points outside a set tolerance (e) are noted and at the end of the evaluation the noted point with the largest deviation from the path is marked and added to the filtered data. If a new point is added to the filtered set it means that the previous simplification was inadequate. Therefore, a new path is formed using the updated filtered data set which subdivides the previous path into two new paths. This algorithm continues recursively until all of the points in the data set are within the tolerance of the path established by the filtered data set, indicating an adequate simplification.

3.5 Exercises

There are three different exercise modes available in the system that can be used depending on the severity of the subject’s disability. In passive mode the patient has no effect on the robot’s motion, and the robot will travel through the programmed trajectory until the number of repetitions is complete. The active mode relies on the patient to direct the manipulator’s motion through the exercise using force control. The robot will move in the direction of the force vector applied by the subject allowing the subject to control the motion of the robotic. The final mode is a combination of passive and active modes that works similar to the active mode, but becomes passive if the patient stops progressing though the exercise. The purpose of the final mode is to allow the subject to use as much of their range of motion as possible, but in the event that the patient is not capable of proceeding further the robot will slowly pull the subject through the exercise until the subject is capable of continuing the exercise on his/her own. When subjecting a new patient to the exercise scheme, the intentional method of progression is to start with the passive exercise and then move through the active/passive exercise until the patient is capable of completing repetitions in the completely active mode.

With the "Teach and Repeat" method of acquiring exercise trajectories allowing exercises in both 2D and 3D, the exercises can also perform such that they are limited to 2D planes when completing 2D exercises. This technique can further simplify exercise regimes for weaker patients.

4 Experimental Results

The first set of trials was performed on healthy patients with the intention of testing the capabilities of the bio-mechanical model and the visual feedback systems. Three simple exercises were developed to isolate different joints of the arm, an elbow exercise consisting of flexion and extension of the elbow, a shoulder exercise that keeps the arm straight at all times and consists of flexion/extension and abduction/adduction of the upper arm, and a exercise the combined the motions of the first two exercises.

The results from the experiments showed that the biomechanical model isolated the forces and torques about the specific joints that were manipulated in the specific exercises. During the elbow exercises The 4th DOF representing elbow flexion/extension showed drastically larger forces than the stationary joints during the exercise. Similarly during the shoulder exercises the 2 DOF of the elbow joint did not register as producing much if any of the forces resulting at the end effector. A thorough analysis of the model is and experiments can be seen in [12, 15].

5 Conclusion

This paper has described the general requirements of a robotic rehabilitation system and presented the main characteristics and functional aspects of the RRS developed in the School of Engineering at the University of Guelph. It explained how the different software and hardware modules are interconnected and contribute in the process of rehabilitation. The paper also describes briefly the novel arm model, which we estimate to contribute, in addition to other modules, to an effective quantitative evaluation of the recovery level. This aspect is still under active research by many other research groups in the field and we believe that the use of the biomechanical model will be useful in developing a standard for quantitative evaluation. The paper shows some experimental results from our on-going tests on healthy subjects, which are very encouraging since they confirm the expectations of the system behaviour. The developed RRS is proving to be flexible and user friendly, but work is still being performed to improve it further.

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