INTELLIGENT ROBOTISED PHYSIOTHERAPY TESTED ON AN 8-DOF MECHATRONIC ARM

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Abstract: The successful rehabilitation of people with upper limb neuro-motor impairment depends largely on the appropriate selection and validation of a set of exercises. In this paper a knowledge-based system (KBS) for selecting a set of exercises to suit a particular patient status is proposed. Also a model of a mechatronic limb that simulates the human arm spastic characteristics will be developed. The selected set of exercises will initially be performed on the dummy arm by two industrial robots. *Copyright © 2002 IFAC*

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1. INTRODUCTION

When people suffering from strokes or accidental injuries admitted to hospitals, medical personnel tend to concentrate on assessing only the life-threatening conditions. This is mainly due to shortage in equipment and qualified medical staff in addition to the lack of commercially-available and most importantly self-operable physiotherapy systems (Taub et al., 1997; Sunderland et al., 1992). Unfortunately, this causes a considerable number of cases to miss out the chance of full recovery when the treatment become available.

Research groups worldwide are attempting to develop robotic systems that would assist the physiotherapists with their routine rehabilitation load (Reinkensmeyer et al., 1996; Reinkensmeyer et al., 1997) and hence allow them to devote more of their time to examining and assessing the patients' recovery progress. Despite promising preliminary clinical trials (Lum et al., 1999; Krebs et al., 1999; Aisen et al., 1997), the cost and size of these proposed systems hinder their wider use by the disabled community (Lum et al., 1999; Rosen, 1999).

Acknowledging the need for developing engineering solutions for patients with neuro-motor impairments, in 1999, the European Commission funded a multi-national project, REHAROB (REHAbilitation ROBots), to produce a robotic system to administer physiotherapy to people with upper limb impairments. The project brings together researchers from 4 countries with medical and engineering backgrounds to develop a system utilising the latest technological solutions in robotics and medical diagnostics. The main objective of the REHAROB system is to minimise the time spent by physiotherapists in performing repetitive exercises on patients recovering from upper limb neuro-motor impairments (REHAROB, 2000). Consequently, the introduction of the proposed system will allow more patients to be seen, assessed and rehabilitated.

The proposed system will include two industrial robots adapted for medical applications plus specialised teach-in and control modules (Kovacs et al., 2001). Information from force/torque (F/T) sensors attached to a patient's arm together with data about the robot's angular position and velocity will be used to control and co-ordinate the movements of

the robots. All this will allow the system to perform personalised sequences of exercises. The safety of the patient during the physiotherapy treatment will be closely monitored through a 'watchdog' module which incorporates the necessary actions based on the patient's condition. In addition, a physiotherapy monitoring and documentation system (PMDS) will be used to analyse the status of the patient both before and after the treatment (REHAROB, 2000).

There are two phases in performing the robotised physiotherapy with the proposed system. The first phase is the teach-in phase. During this phase the physiotherapist performs a prescribed exercise on the patient's arm and at the same time the two robots holding the arm freely follow its movements. Simultaneously, the motion trajectories for the next phase are generated by the robot controllers using data captured on the robot joint angles and velocities. The second phase is the play-back phase during which the two robots perform the taught exercises without the help of the physiotherapist (Pham et al., 2001a).

For safety reasons, the system will initially be tested and validated on an artificial arm instead of humans. A mechatronic anthropomorphic arm consisting of rigid bodies (links) connected in a specific way is developed to simulate the characteristics of a human upper limb (Pham et al., 2001b).

In this work, the kinematic/dynamical modelling of the limb is performed using Pro/Engineer and Pro/Mechanica software. Pro/Mechanica is also employed to simulate the limb's performance when certain exercises are conducted with an emphasis on the representation of muscular resistance.

Also the design and functionality of a knowledge-base system (KBS) that assists physiotherapists in choosing the most appropriate sequence of exercises is discussed.

The remainder of this paper is organised as follows. Section 2 describes the setup of the REHAROB system. The design, modelling and resistance control of the anthropomorphic arm are presented in sections 3 and 4 respectively. In sections 5 and 6, the KBS design and knowledge acquisition & representation are discussed. Finally, conclusions and further work are given in section 7.

2. THE REHAROB SYSTEM

The REHAROB system comprises two industrial robots controlled by a personal computer (PC) (Toth et al., 2001). In addition to co-ordinating the movements of the two robots, the PC is also used to advise the physiotherapist in selecting a suitable set of exercises for a particular patient and collect data for further processing by the PMDS. Furthermore, the PC is also employed for on-line visualisation of the physiotherapy.

The architecture of the REHAROB cell is depicted in Figure 1.

3. THE MECHATRONIC LIMB

The basic requirements of the artificial limb system are (Pham et al., 2001b):

• to be adaptive to variation in segment lengths;
• to be able to perform under variable stiffness (spasms);
• to produce accurate Force/Torque (F/T) feedback;
• to have sufficient degrees of freedom to simulate a human arm;
• to allow all possible physiotherapy exercises to be performed;
• to be of an anthropomorphic design;
• to be as compact as possible with all sensors and drives confined within the envelope of the arm itself;
• to have a reversible or symmetrically neutral mechanism, allowing both left and right arms to be created from the same parts;
• to have means of recording the motion trajectory and the F/T measurements.

Kinematically, the limb models the movements of a clavicle attached to the sternum joint (retraction – protraction and elevation – depression), a shoulder joint (abduction – adduction, flexion – extension and internal – external rotation) and an elbow joint (flexion – extension and pronation – supination) (Vitliemov et al., 2001, Marchese et al., 1997).
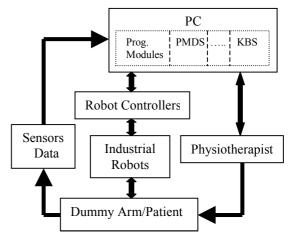

Fig. 1. REHAROB Architecture

To allow generation of the F/T measurements during the various joint movements and in order to realise controlled resistance, the kinematic structure of the arm is developed as an open kinematic chain built from rotational (R) pairs of the 5th class (Figure 2).

However, the shoulder joint structure is different. It is treated as a spherical joint represented by four R pairs of the 5th class, and a fixed centre of rotation corresponding to the physical centre of the joint. The redundancy in the kinematics scheme of the shoulder joint is needed to overcome possible singularities arising in joints represented by three R pairs of the 5th class. In addition, a potentiometric sensor is built into
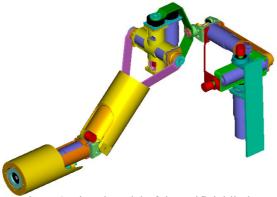
Figure 2 Virtual model of the artificial limb

each kinematic pair and used to measure the rotation of the corresponding joint. The muscle resistance is simulated by DC motor-gearboxes and servo brakes. Changes in the forces and torques of the fore and upper arm joints are measured by 6-component F/T sensors.

Similarly, the dynamical model of the limb, is generated using Pro/Mechanica software. The model elements are introduced as an aggregate of features. Each component is an independent 3D object having different parameters and topological properties. Its dimensions and mass density characterise each segment of the model. The software calculates the segment's volume, mass, surface area, position of the centre of gravity, main moments of inertia and inertial tensor when the limb is manipulated through points 1 and 2 (Figure 3) (Pham et al., 2001b).
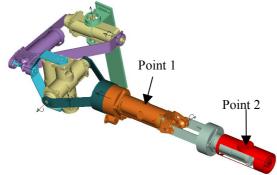

Fig. 3. 3D CAD model of the limb

4. CONTROL OF RESISTANCE OF THE DUMMY LIMB

Two physiotherapist robots are to hold the dummy limb and move it according to prescribed sequences, just as they would manipulate a real arm (Figure 4). To simulate the behaviour of the latter, there has to be means to control the resistance of the dummy limb to motion.

Two types of resistance control systems are described in this section, one based on motors and gears and the other on servo brakes. Both types are to be fitted to the joints of the limb to regulate the joint torques. They rely on the joints being equipped with sensors to detect the direction of joint rotation and the amount of joint torque.

4.1 Resistance control using motors and gears

This "active" method of resistance control is further sub-divided into two categories. The first category uses gearing that is not backdrivable. The second employs fully backdrivable gearing.
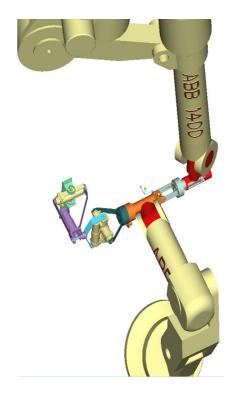

Fig. 4. Manipulation of the dummy limb by two robots

Non–backdrivable gearing. Here, the resistance to motion is provided by friction and inertia in the gearing. The motor turns in the same direction as that necessary for the desired rotation of the corresponding joint. The function of the motor is to generate a torque T_m to reduce the resistance to motion by gearing friction and inertia T_g. When the net resistance $T = T_g - T_m$ reaches the specified level T_s, power to the motor is switched off.

This method of resistance is limited by the mechanical characteristics of the gearing system and damage could occur if the motor turns in a direction opposite to that necessary for the desired rotation of the joint.

Backdrivable gearing. With this method, motion resistance is provided by both the gearing and the motor. If the resistance is to be reduced, the motor turns in the same direction as that required for the desired joint rotation, as in the case of the non–backdrivable gearing system. The net joint resistance torque T is again the difference between the gearing resistance T_g and the motor torque T_m, i.e. $T = T_g - T_m$. If the resistance is to be increased, the motor turns in the opposite direction to that needed for the desired joint rotation. In this case, the net joint resistance T is the sum of T_g and T_m, i.e. $T = T_g + T_m$.

Note that with both the backdrivable and non-backdrivable gearing methods, it is possible to achieve a specified zero net joint resistance. The backdrivable gearing method, though mechanically more demanding, has the advantage of providing more accurate control of the resistance torque.

4.2 Resistance control using servo brakes

This "passive" method is simple but can only increase the resistance to motion. The brakes are applied when the net resistance torque at a joint is below the specified level T_s for that joint and released when T_s is reached. With the brakes applied, the net resistance torque is $T = T_j + T_b$, where T_b is the torque due to the brakes and T_j is the inertia and internal friction torque felt at the joint. If T_b is not zero, T_j and T_b have the same sign. Clearly, with this method, it is not possible to achieve the condition of zero net joint resistance.

5. DESIGN OF THE KBS

The development of the proposed KBS involves the following four stages (Pham et al, 2001a):

1. Encoding of exercises and patient's data.
2. Generation of the rule base for mapping the patient's condition to particular exercises.
3. Integration of components of the KBS.
4. Testing and adaptation.

A video library of 45 exercises has been created by the medical experts involved in REHAROB to include most of the exercises that are commonly performed by physiotherapists on patients with upper limb neuro-motor problems (REHAROB, 2000). The objective is to study the physiotherapist's decision making process and develop a mechanism that proposes a particular sequence of exercises depending on the status of the patient. This intelligent mapping can be achieved by first encoding the exercises and the patient's data into formats suitable for further processing by the KBS. Figure 5 illustrates one of the simple exercises. Here, with the patient lying on a couch, the arm is stretched until it points vertically upwards and then lowered back to the initial position where the upper arm rests against the couch and the lower arm is held vertical.

Fig. 5. Exercise No. 9 – slow and continuous
movement exercise

Formally this exercise can be represented (encoded) as shown in table 1. It can be noted that the table contains information about the ranges of movements in each joint, duration of the exercise cycle, degree of complexity and patient posture.

Patient's Posture	No. of DoFs	Range of Movement		Duration (seconds)	Compl-exity
		DoF1	DoF5		
Lying	2	90^0	90^0	4.0	low

DOF – Degree of Freedom
DoF1 – Shoulder joint   DoF5 – Elbow joint

Table 1. Exercise 9 in a tabulated form.

Medical information about a patient suffering from neuro-motor impairment in the upper arm includes his/her sex, age, cause of injury, level of injury and mobility. A typical set of medical data for a patient is represented as in table 2.

Name:		Address:		Date:	
sex	Age	Level of injury	Cause of injury	Time since injury	Mob-ility
Male	40	Severe	Car accident	35 hrs	restric-ted

Table 2. An example of a typical patient's data.

Table 2 is to be extended to include a detailed record of the ranges of movements of the different degrees of freedom of the patient's elbow and shoulder joints for future progress monitoring of the rehabilitation process.

Furthermore, the dummy arm has been to generate data about joint angles, velocities, accelerations, torques and resistances for each exercise. Figure 6 shows the trajectories of the elbow and shoulder joints obtained with the model for exercise 9.

This information represents the data for a non-injured arm and is compared against actual measurements taken from the patient's arm to assess his/her condition.
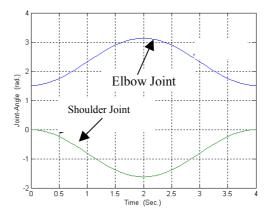

Fig. 6. Elbow and Shoulder Joint Angle
Trajectories for Exercise 9.

Using the patient's data of table 3 and the forward-chaining method of inferencing (Barr and Feigenbaum, 1986), the KBS decides on the set of exercises to be administered. During physiotherapy, the patient's condition is continually assessed and the sequence of exercises determined to produce the best possible effort. The architecture of the proposed KBS is illustrated in Figure 7.

6. KNOWLEDGE ACQUISITION AND REPRESENTATION

Knowledge acquisition and representation are considered major constraints in the development of expert systems in the medical field. This is because doctors either tend to communicate shallow knowledge rather than the required deep knowledge structures, or are unable to detail procedures and routines. In addition, knowledge acquisition from a standard clinical examination is also difficult because patients are often very subjective when describing symptoms (Hopgood, 2001).

The same difficulties exist in acquiring knowledge from physiotherapists for the proposed KBS. To address these problems in the REHAROB project, inductive learning methods will be applied to extract knowledge from the information available in the PMDS. This requires the data stored in this system to be pre-processed in order to prepare it for the rule induction process (Pham and Dimov, 1997).
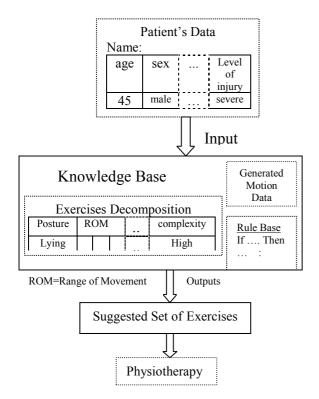

Fig. 7. The architecture of the KBS

The data base module within the PMDS is used for storing 3D-motion data, patient medical data and physiotherapist data all protected by built-in security functions. The patient data includes personal information and condition data acquired during the execution of exercises using the diagnostic module. The status data consists of test results, i.e. F/T and EMG data that takes into account the individual movements of the wrist, elbow and shoulder girdle, multi-joint movements, visiomotor aiming movements and maximum speed movements. The physiotherapist data characterises the physiotherapist's arm movements while exercising a patient. All this is pre-processed and stored in a tabular format for further analysis. The extraction of knowledge from this data is a key to the successful implementation of the KBS. Automatic rule formation based upon stored data will be performed by an inductive learning algorithm. In particular, the RULES-4 algorithm will be used (Pham and Dimov, 1997).

RULES-4 is an incremental learning system that allows the acquired knowledge to be updated and refined rapidly when new data becomes available. A selected set of parameters from the patient data together with the physiotherapy parameters and the encoded data from the library of exercises will be used as the input to RULES-4. The algorithm will extract rules incrementally by processing one record (one row in the table) at a time. The output from the inductive learning process will be rules mapping the state of the patient into appropriate exercises for his/her particular injury or impairment conditions. An example rule is:

If the patient is female **And** age is over 40 **And** mobility is restricted **And** level of injury is severe **Then** suggest exercises 1, 5 and 9.

7. CONCLUSION AND FURTHER WORK

In this paper a mechatronic model of the human arm has been developed. The mechatronic limb is to be used as a dummy to test a robotised physiotherapy system under construction. The limb is designed to provide a similar muscular resistance behaviour to that of a human arm. This will allow the robotised system to be tested thoroughly under realistic conditions before being applied to human subjects.

The paper also describes a KBS that will assist physiotherapists in selecting a set of exercises to be performed on patients with neuro-motor impairments. An inductive learning algorithm is to be used to extract rules from patient and physiotherapy data. The rule set together with the declarative knowledge about the state of the patient represent the knowledge base of the system. A data-driven reasoning mechanism is adopted to propose a particular sequence of exercises depending on the patient's injury or impairment conditions.

The proposed KBS is under development. Further research is being carried out to link the PMDS with the KBS and identify the most appropriate way for pre-processing the patient medical data and physiotherapists expert knowledge.

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