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INTELLIGENT CONTROL OF A ROBOT MANIPULATOR FOR KNEE REHABILITATION

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Abstract

There is an increasing trend in using robots for medical purposes. One specific area is the rehabilitation. There are some commercial exercise machines used for rehabilitation purposes. However, these machines have limited use because of their insufficient motion freedom. In addition, these types of machines are not actively controlled and therefore can not accommodate complicated exercises required during rehabilitation. In this study, an intelligent control structure for one degree of freedom exoskeletal robot manipulator is proposed for knee rehabilitation. It can make flexion-extension movement for knee. This manipulator is driven by servo motor and controlled by a computer using force/torque and position sensor information.

The robot operates in two modes; learning and therapy. Impedance control technique is selected for the force control. The impedance control which was first proposed by Hogan (Hogan 1985) is appropriate control technique for the physiotherapy. The aim of impedance control is to specify the relationship between position and force. Proposed intelligent controller structure is used to impedance controller parameters tuning and can modify itself for reactions that come from patient.

Keywords: Rehabilitation; intelligent control; impedance control; robot manipulator.

1. Introduction

Complaints from legs and arms are the main source of human movement problems and are very common among people. Muscle weaknesses due to old ages, traffic and labour accidents or injuries during wars are the main reasons for human movement disabilities. To regain the ability of motion, one needs to strengthen the weak muscles. The process of strengthening muscles to their normal values is a costly labour which requires time and patience. In general, a person with movement disabilities due to arm or leg problems needs to undergo periods of physiotherapy sessions (spread in a long time) which comprises a series of repeated and routine physical movements with the assistance (and under the observation) of a physiotherapist. Transporting the patient to the place of physiotherapy or calling a physiotherapist to the place of the patient are the factors that further increase the cost of this process. An intelligent instrument which replaces the duty of the physiotherapist and can accomplish such routine physical movements without the guidance and assistance of a physiotherapist will simplify the process and lower the costs drastically.

Device called "Continuous Passive Motions (CPM)" shown in Figure 1, is widely used in many medical centers for therapy and rehabilitation purposes. The CPM concept was first introduced in the 1970' s (Salter & Simmonds 1980). A continuous passive motion (CPM) device is not suitable for physical therapy. During the rehabilitation process, patients sometimes move their extremities suddenly due to reflexes. On conventional machines like CPM, don't respond in this kind of situations. If a reflex causes a patient's leg move while the machine is operating, an improper load results and can damage the patient's muscle or tendon tissue (Sakaki, 1990). Because of this, there is need for an intelligent device which can accomplish the rehabilitation of extremities based on the patient's complaints and the on line feedback during rehabilitation processes.

Figure 1 . CPM's for Lower Limbs (Ref. 1)

Many researchers have developed different rehabilitation devices. For example, Krebs et al. have developed and have been clinically evaluating a robot-aided neuro rehabilitation system called MIT-MANUS. This device provides multiple-degree of freedom (DOF) exercises of upper extremities for stroke patients (Krebs et. Al 1998). They are not actively controlled and do not incorporate any feedback from the patient during the motion. Also, the patient's reactions during the exercises need to be taken into consideration to change and control the exercises actively as a real physiotherapist will do. This can only be done with intelligent devices which can decide the type and pace of exercises based on the patient's complaints and reactions during the physiotherapy.

There are an increasing number of researches about the robot manipulators that will be used for physical therapy or rehabilitation purposes. Advances in intelligent control techniques have accelerated the research in this field. Most of the research is concentrated on devices which are used for rehabilitation of upper limb. Research projects run at University of California (Lum et. al 1993), MIT (Krebs et. al 1999), VA Palo Alto HCS (Lum et. al 1997), University of Deleware (Lum et. al 1999), Loughborough University (Taylor 1997), Harvard University and Boston Biomotion Inc. (Matsuoka&Miller 1993) are examples to this. But for lower limb rehabilitation researches haven't been as much as upper limb researches. For lower limbs rehabilitation, a device named as TEM (Therapeutic Exercise Machine) has been proposed and developed by Sakaki et. al (1999). Also, Homma et. al (2002), have proposed a rehabilitation system that employed a wire – driven mechanism.

With this study we proposed a new intelligent controller structure for a robot manipulator which can accomplish the knee rehabilitation based on impedance control.

2. The Movements and Limits for Knee Rehabilitation

In knee rehabilitation exercises, the process has an important movement. This is flexion – extension. Flexion is the act of bending of the limb where as extension is the act of extending the limb. For a human, flexion-extension movements and their limits for knee are shown in Figure 2.

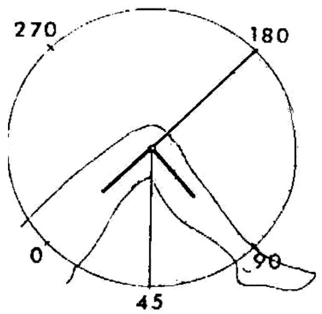

Figure 2. Extension and Flexion movements for knee

3. Features of The Knee Rehabilitation Robot System

It is designed such that it can rehabilitate both left and right knee. In addition, it can be adjusted for different limb dimensions.

The manipulator can perform the flexion – extension motions for the knee rehabilitation. The architecture of the rehabilitation manipulator is shown in Figure 3.

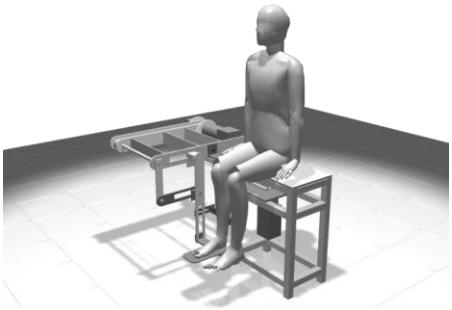

Figure 3. Architecture of Robot Manipulator

The system hardware for controlling the robot manipulator is shown in Figure 4.

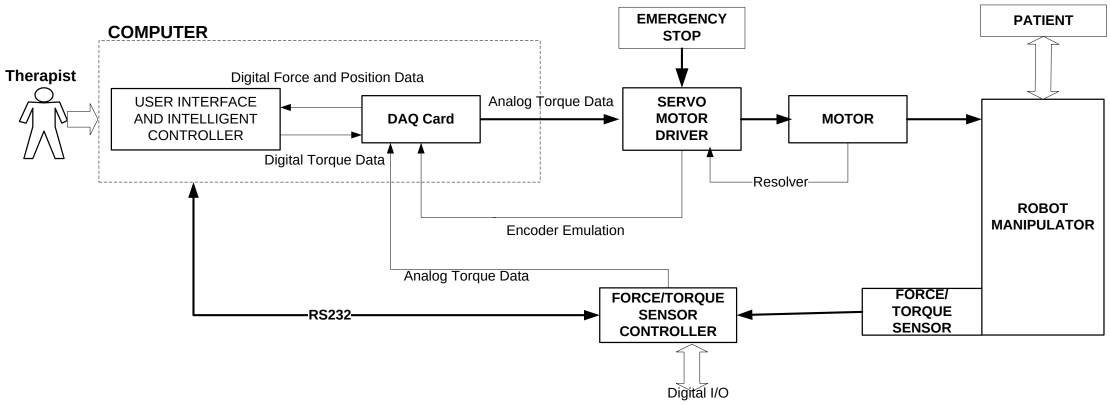

Figure 4. System Hardware

System hardware has a servo motor and its driver as actuator, force torque sensor and controller for measurement of force data that come from therapist and patient and a data acquisition card for analog to digital – digital to analog conversion. Position data are taken by encoder emulation. In this project, we use Kollmorgen servo motor Servostar S300 driver, ATI force/torque sensor that can measure 3 axis force and 3 axis torque, National Instruments 6024E DAQ card.

4. Impedance Control

Impedance control aims at controlling position and force by adjusting the mechanical impedance of the end-effector to external forces generated by contact with the manipulator's environment. Mechanical impedance is roughly an extended concept of the stiffness of a mechanism against a force applied to it. Impedance control can further be divided into passive and active impedance control. In the passive impedance method, the desired mechanical impedance of the end-effector is achieved by using only mechanical elements, such as springs and dampers. The active impedance methods, on the other hand, realizes the desired mechanical impedance by driving joint actuators using feedback control based on measurements of end-effector position, velocity, contact force and so on. It is shown in figure 5. (Yoshikawa, 1990). The impedance control which was first proposed by Hogan (Hogan 1985) is the most appropriate control technique for the physiotherapy.

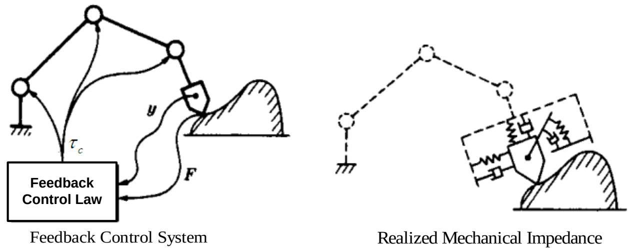

Figure 5 . Active Impedance Method

In this method desired mechanical impedance for its end effector is described by

$$M_d \ddot{y} + D_d \dot{y}_e + K_d y_e = F \qquad (1)$$

where,

y: robot manipulator position vector
y_d: desired position vector
y_e: difference between y and y_d
F: external force exerted on the end effector by its environment
$M_d \in \mathrm{R}^{3\times3}$: desired inertia matrix
$D_d \in \mathrm{R}^{3\times3}$: desired damping coefficient matrix
$K_d \in \mathrm{R}^{3\times3}$: desired stiffness coefficient matrix

The dynamic equation of robot manipulator that contacts with its environment in joint space is given by

$$M(q)\ddot{q} + h_N(q,\dot{q}) = \tau + J^T(q)F \qquad (2)$$

where,

$M(q) \in \mathrm{R}^{3\times3}$: inertia matrix
$h_N(q,\dot{q}) \in \mathrm{R}^{3\times1}$: Coriolis+centrifugal force and other effects.
$q \in \mathrm{R}^{3\times1}$: joint angle matrix, $\boldsymbol{q}^T = [\theta_0 \quad \theta_1 \quad \theta_2]$
$J(q) \in \mathrm{R}^{3\times3}$: Jacobian vector
$\tau \in \mathrm{R}^{3\times1}$: joint torque matrix

Because that the essential thing is the relation of robot manipulator and its environment, equation 2 that is described in joint space must be described in workspace.

$$M_y(q)\ddot{y} + h_y(q,\dot{q}) = J_y^{-T}(q)\tau + F \qquad (3)$$

$M_y(q) \in \mathrm{R}^{3\times3}$: inertia matrix
$h_y(q,\dot{q}) \in \mathrm{R}^{3\times1}$: Coriolis+centrifugal force and other effects
$J_y(q) \in \mathrm{R}^{3\times3}$: Jacobian vector

$$y = f_y(q) \qquad (4)$$

$$\dot{y} = J_y(q)\dot{q} \qquad (5)$$

$$\ddot{y} = \dot{J}_y \dot{q} + J_y \ddot{q} \qquad (6)$$

The inertia matrix $M_y(q)$ that is described in workspace and $h_y(q,\dot{q})$ vector which is consisted of non linear terms is described with $M(q)$ and $h(q,\dot{q})$ that is in joint space.

$$M_y(q) = J_y^{-T} M(q) J_y^{-1}(q) \qquad (7)$$

$$h_y(q,\dot{q}) = J_y^{-T} h_N(q,\dot{q}) - M_y(q)\dot{J}_y(q)\dot{q} \qquad (8)$$

Necessary joint torques to obtain desired impedance parameters M_d, D_d and K_d from equation 3, 7 and 8 as

$$\begin{aligned} \tau = {} & h_N(q,\dot{q}) - M(q)\, J_y^{-1}(q)\dot{J}_y(q)\dot{q} \\ & - M(q) J_y^{-1}(q) M_d^{-1}(D_d \dot{y}_e + K_d y_e) \\ & + \left[M(q) J_y^{-1}(q) M_d^{-1} - J_y^T(q) \right] F \end{aligned} \qquad (9)$$

Impedance control block diagram is depicted in Figure 6.

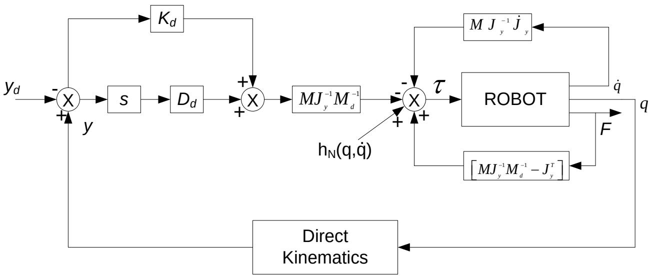

Figure 6 . Impedance Control Block Diagram

For knee rehabilitation system, impedance control law is

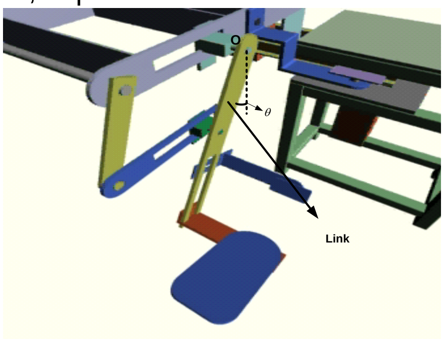

Figure 7 . Knee link of robot manipulator

$$M = I \qquad J_y = J_y^T = L_g \qquad J_y^{-1} = 1/L_g$$

$$M(q)\ddot{q} + h_N(q,\dot{q}) = \tau + J_y^T F_{ext}$$

$$I\ddot{\theta} + \tau_{ext} = \tau + J^T{}_y F_{ext}$$

where L_g is distance between O point and mass center of link.

$$\tau = \tau_{gravity} - \left[\frac{I}{L_g M_d} \left(D_d \dot{\theta}_e + K_d \theta_e \right) \right] + \left[\frac{I}{L_g M_d} - L_g \right] F_{ext}$$

5. Intelligent Controller

The robot manipulator will be controlled by an intelligent controller which will incorporate the preloaded data about the patient and provide an interface for information flow between the manipulator and patient. Intelligent controller has an inference engine, a knowledge base, a data base, a user interface, parameter estimation unit and an impedance controller as shown in figure 8. The robot manipulator system has to main stages: learning and therapy.

Through user interface, physiotherapist selects exercise mode covering information regarding exercises and patient extremities. Some exercise modes may not need learning process. In these modes, physiotherapist enters exercise information to start the system for therapy. According to the selected mode, necessary parameters are taken from the knowledge base.

In the exercise modes that needs learning process, the rehabilitation process is performed by physiotherapist with robot manipulator system. During the rehabilitation process, the realized forces that arise and position data are taken by parameter estimation unit to estimate impedance control parameters. Estimated impedance parameters (inertia, stiffness, damping), desired force and position data are conveyed to the knowledge.

In therapy stage, the robot manipulator performs therapy motion instead of physiotherapist or the other therapeutic exercise devices. Using force and position sensors, the reactions that come from the knee will be feedback to the manipulator and these data are received by rule base and the system tunes the forces or stop the rehabilitation process, if requires.

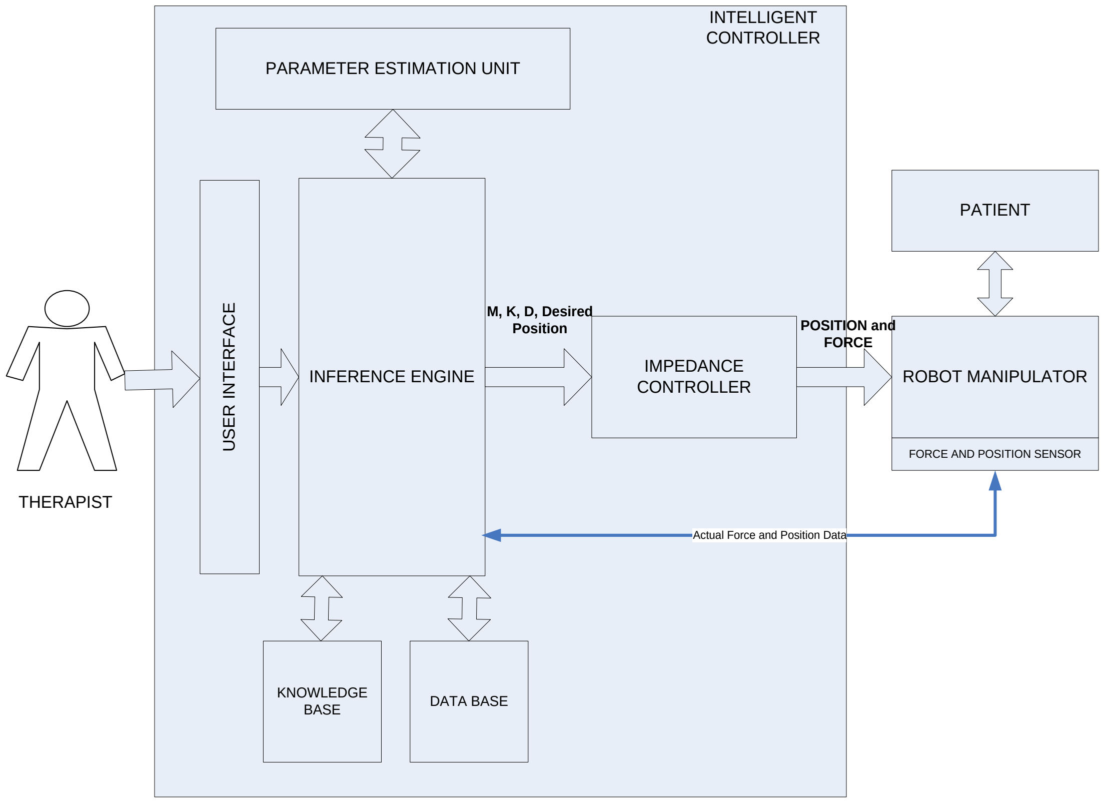

Figure 8 . Intelligent Controller Structure

6. Results and Discussion

An intelligent controller structure for a knee rehabilitation robot manipulator is proposed. The robot manipulator works based on impedance control. Impedance control is known to be an appropriate method for physiotherapy. The robot manipulator system works in two stages: learning and therapy. As of patient reacts during the rehabilitation process, the intelligent controller evaluates the situation. These conditions are monitored by force and position sensor.

Robot manipulator can make flexion-extension movement for the knee. The system security is controlled by both hardware, like limit switches as well as software security.

If the mobility of robot manipulator' is increased for more complex therapy movements, then building knowledgebase may be extremely sophisticated, so some other technique may have to be employed.

As a continuation of this research, besides force and position data with feedback data, bio-feedbacks such as EMG can be used. Also, the variations in joint muscles can be tracked by a graphical unit.

ACKNOWLEDGMENT

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