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Knee rehabilitation using an intelligent robotic system

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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, a rule based intelligent control methodology is proposed to imitate the faculties of an experienced physiotherapist. These involve interpretation of patient reactions, storing the information received, acting according to the available data, and learning from the previous experiences. Robot manipulator is driven by a servo motor and controlled by a computer using force/torque and position sensor information. Impedance control technique is selected for the force control.

Keywords Rehabilitation robots · Intelligent control · Impedance control

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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 (CPMs)" shown in Fig. 1, is widely used in many medical centers for therapy and rehabilitation purposes. The CPM concept was first introduced in the 1970s (Salter and Simmonds 1980).

A CPM device cannot be suitable for physical therapy, in some cases. During the rehabilitation process, patients sometimes move their extremities suddenly due to reflexes. Conventional machines like CPM, do not respond in this kind of situations. If a reflex causes a patient's leg to move while the machine is operating, an improper load results and can damage the patient's muscle or tendon tissue (Sakaki et al. 1999). Because of this, there is need for an intelligent device which can accomplish the rehabilitation of extremities based

Fig. 1 CPM's for lower limbs (CPM 2007)

on the patient's complaints and the online feedback during rehabilitation processes.

There have been attempts for developing devices for rehabilitation of limps like leg and arm extremities. Khalili and Zomlefer (1988) introduced a system with two robots, each having two degrees of freedom (DOF), for rehabilitation of lower extremities. This system is also used for prediction of the parameters of human body segments. Lee et al. (1990) developed a robotic system for rehabilitation of upper limbs of paralysed patients using an expert system. Lum et al. (1995, 1997) introduced an assisted rehabilitation system for arms. Another system developed for rehabilitation of upper extremities is a robot manipulator with 5 DOF called MULOS (MULOS Project 1997). Krebs et al. (1998, 2003) have developed and have been clinically evaluating a robot-aided neuro rehabilitation system called MIT-MANUS. This device provides multiple-degree of freedom exercises of upper extremities for stroke patients. Rao et al. (1999) introduced another system using a Puma 240 robot for active and passive rehabilitation of upper extremities. Richardson et al. (1999, 2003, 2005) developed a 3 DOF pneumatic device for rehabilitation of upper extremities using PD control and impedance control methodologies. A similar robotic system for rehabilitation of upper extremities is introduced by Sakaki et al. (1999, 2001). Another work for rehabilitation of upper extremities is the REHAROB project using two industrial robots. A knowledge base is formed by the necessary force and position produced by the sensors placed on the patients during rehabilitation process. Industrial robots then repeat the same procedure using this knowledge base (REHAROB 2000). Reinkensmeyer et al. (2000) and others developed a 3 DOF system called ARM Guide (Assisted Rehabilitation and Measurement Guide) for rehabilitation of upper extremities. Another system with 3 DOF, called GENTLE/s, is developed in England for the rehabilitation of upper extremities, controlled by admittance control method (Loueiro et al. 2003). Okada et al. (2000) employed impedance control methodology in a 2 DOF robotic system for rehabilitation of lower extremities, where position and force information are received and recorded for the robotic system to imitate the corresponding motion. Homma et al. (2002) developed a 2 DOF system around the patient's bed for the rehabilitation of lower extremities. As seen from this overview, amount of work for rehabilitation of upper extremities is much more than that of lower extremities.

It is observed that the devices developed for rehabilitation purpose employ two control methods, namely hybrid control and impedance control. Successful applications of hybrid control were achieved by Ju et al. (2005) and Bernhardt et al. (2005) in LOKOMAT robotic system. It is however commonly accepted that impedance control is more convenient method for the development of rehabilitation systems (Krebs et al. 1998). It is therefore extensively used in developing rehabilitation devices (Aisen et al. 1997; Culmer et al. 2005; Richardson et al. 1999, 2003, 2005; Okada et al. 2000; Krebs et al. 1998, 2003; Tanaka et al. 2000).

Intelligent techniques, on the other hand, are much less common compared to the former two methods (REHAROB 2000; Sakaki et al. 1999; Khalili and Zomlefer 1988; Lee et al. 1990). In this work, a device is introduced employing a rule based control strategy, in combined with impedance control, for rehabilitation of lower extremities, which can interpret the reactions of patient. It stores the information received, acts according to the available data, and learns from the previous experiences. Despite the availability of wide variety of intelligent techniques, like neural networks, fuzzy, genetic algorithms, etc., expert systems technique and knowledge base approach are mostly preferred in developing rehabilitation devices.

The movements and limits for knee rehabilitation

The flexion–extension is one of the important movements in knee rehabilitation process. Flexion is the act of bending of the limb whereas extension is the act of extending the limb. For a human, flexion–extension movements and their limits for knee are shown in Fig. 2.

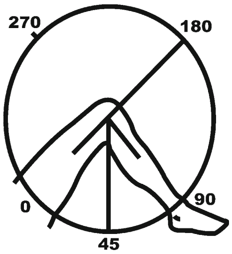

Fig. 2 Extension and flexion movements for knee

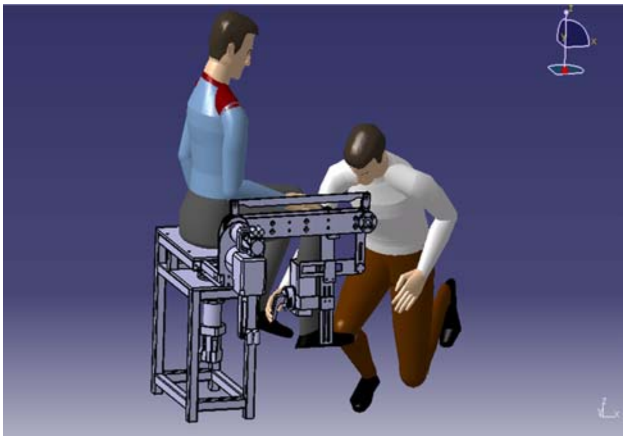

Fig. 3 Architecture of robot manipulator

Features of the knee rehabilitation robot system

The device is designed in such a way that it can rehabilitate both left and right knees. 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 Fig. 3. The system hardware for controlling the robot manipulator is shown in Fig. 4. System hardware has a servo motor and its driver as actuator, force/torque sensor and its 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 work, we use Kollmorgen servo motor, Servostar S300 driver, six axes ATI force/torque sensor and National Instruments 6024E DAQ card.

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 (Yoshikawa 1990). The impedance control which was first proposed by Hogan (1985) is one of the most effective control methods for the robot manipulators in contact with their environments (Jung and Hsia 1998; Nagata et al. 1998; Dutta and Obinata 2002; Tsuji et al. 2004). It is accepted to be the most appropriate control technique for the physiotherapy and is used in many rehabilitation robot applications (Krebs 1998, 2003; Tanaka et al. 2000; Okada et al. 2000; Culmer et al. 2005). In this section, based on the methodology and equations in Yoshikawa (1990) the necessary joint torques for the manipulator to realize the desired impedance parameters during knee rehabilitation are determined.

The desired mechanical impedance for a manipulator end effector is described by

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

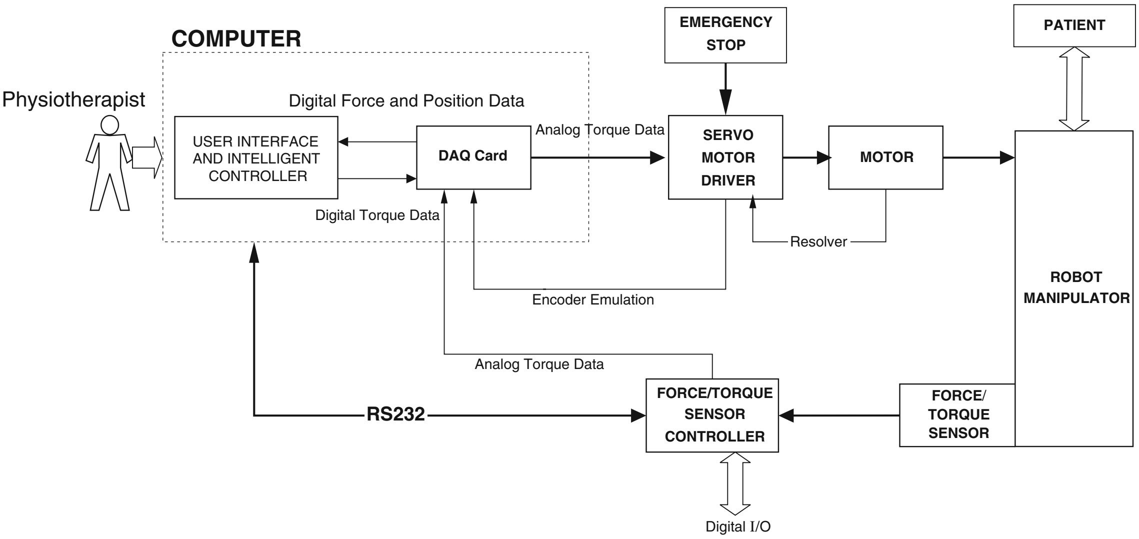

Fig. 4 System hardware

where $\boldsymbol{y}$ is manipulator's end effector position vector, $\boldsymbol{y}_d$ is manipulator's desired end effector position vector, $\boldsymbol{y}_e$ is difference between $\mathbf{y}$ and $\mathbf{y}_d$, $\boldsymbol{F}$ is external force exerted on the end effector by its environment, $\boldsymbol{M}_d \in R^{3\times 3}$ is desired inertia matrix, $\boldsymbol{D}_d \in R^{3\times 3}$ is desired damping coefficient matrix, and $\boldsymbol{K}_d \in R^{3\times 3}$ is desired stiffness coefficient matrix.

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

$$\boldsymbol{M}_y(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}_N(\boldsymbol{q}, \dot{\boldsymbol{q}}) = \boldsymbol{\tau} + \boldsymbol{J}_y^T(\boldsymbol{q})\,\boldsymbol{F} \tag{2}$$

where $\boldsymbol{M}(\boldsymbol{q}) \in R^{3\times 3}$ is inertia matrix, $\boldsymbol{h}_N(\boldsymbol{q}, \dot{\boldsymbol{q}}) \in R^{3\times 1}$ is coriolis, centrifugal force and other effects, $\boldsymbol{q} \in R^{3\times 1}$ is joint angle matrix, $\boldsymbol{q}^T = \begin{bmatrix}\theta_0 & \theta_1 & \theta_2\end{bmatrix}$, $\boldsymbol{J}(\boldsymbol{q}) \in R^{3\times 3}$ is Jacobian matrix, and $\boldsymbol{\tau} \in R^{3\times 1}$ is joint torque vector.

Since the relation between robot manipulator and its environment is essential, Eq. 2 that is described in joint space must be described in task space.

$$\boldsymbol{M}_y(\boldsymbol{q})\ddot{\boldsymbol{y}} + \boldsymbol{h}_y(\boldsymbol{q}, \dot{\boldsymbol{q}}) = \boldsymbol{J}_y^{-T}(\boldsymbol{q})\,\boldsymbol{\tau} + \boldsymbol{F} \tag{3}$$

where $\boldsymbol{M}_y(\boldsymbol{q}) \in R^{3\times 3}$ is inertia matrix described in task space, $\boldsymbol{h}_y(\boldsymbol{q}, \dot{\boldsymbol{q}}) \in R^{3\times 1}$ is coriolis, centrifugal force and other effects described in task space, and $\boldsymbol{J}_y(\mathbf{q}) \in R^{3\times 3}$ is Jacobian matrix in task space

$$\boldsymbol{y} = \boldsymbol{f}_y(\boldsymbol{q}) \tag{4}$$

$$\dot{\boldsymbol{y}} = \boldsymbol{J}_y(\boldsymbol{q})\dot{\boldsymbol{q}} \tag{5}$$

$$\ddot{\boldsymbol{y}} = \dot{\boldsymbol{J}}_y\dot{\boldsymbol{q}} + \boldsymbol{J}_y\ddot{\boldsymbol{q}} \tag{6}$$

The terms $\boldsymbol{M}_y(\boldsymbol{q})$ and $\boldsymbol{h}_y(\boldsymbol{q}, \dot{\boldsymbol{q}})$ are described in terms of joint space variables as

$$\boldsymbol{M}_y(\boldsymbol{q}) = \boldsymbol{J}_y^{-T}\boldsymbol{M}(\boldsymbol{q})\,\boldsymbol{J}_y^{-1}(\boldsymbol{q}) \tag{7}$$

$$\boldsymbol{h}_y(\boldsymbol{q}, \dot{\boldsymbol{q}}) = \boldsymbol{J}_y^{-T}\boldsymbol{h}_N(\boldsymbol{q}, \dot{\boldsymbol{q}}) - \boldsymbol{M}_y(\boldsymbol{q})\,\dot{\boldsymbol{J}}_y(\boldsymbol{q})\,\dot{\boldsymbol{q}} \tag{8}$$

Using Eqs. 3, 7 and 8, the necessary joint torques to obtain desired impedance parameters $\boldsymbol{M}_d$, $\boldsymbol{D}_d$ and $\boldsymbol{K}_d$ are computed as

$$\begin{aligned}\boldsymbol{\tau} &= \boldsymbol{h}_N(\boldsymbol{q}, \dot{\boldsymbol{q}}) - \boldsymbol{M}(\boldsymbol{q})\,\boldsymbol{J}_y^{-1}(\boldsymbol{q})\,\dot{\boldsymbol{J}}_y(\boldsymbol{q})\,\dot{\boldsymbol{q}}\\ &\quad - \boldsymbol{M}(\boldsymbol{q})\,\boldsymbol{J}_y^{-1}(\boldsymbol{q})\,\boldsymbol{M}_d^{-1}\left(\boldsymbol{D}_d\dot{\boldsymbol{y}}_e + \boldsymbol{K}_d\boldsymbol{y}_e\right)\\ &\quad + \left[\boldsymbol{M}(\boldsymbol{q})\,\boldsymbol{J}_y^{-1}(\boldsymbol{q})\,\boldsymbol{M}_d^{-1} - \boldsymbol{J}_y^T(\boldsymbol{q})\right]\boldsymbol{F}\end{aligned} \tag{9}$$

The impedance control block diagram is shown in Fig. 5.

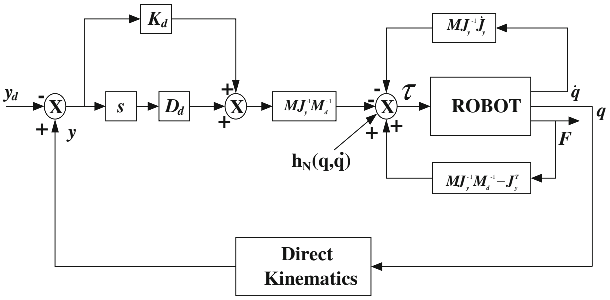

Fig. 5 Impedance control block diagram

For knee rehabilitation system (see Fig. 6a) after the following substitutions,

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

Eq. 9 reduces to

$$\begin{aligned}\tau &= \tau_{\text{gravity}} - \left[\frac{I}{L_g M_d}\left(D_d\dot{\theta}_e + K_d\theta_e\right)\right]\\ &\quad + \left[\frac{I}{L_g M_d} - L_g\right]F\end{aligned} \tag{10}$$

$$\tau_{\text{gravity}} = mg\sin\theta L_g \tag{11}$$

where I is the inertia of the knee link and L_g is distance between the knee joint and the mass center of knee link (Fig. 6b).

Intelligent controller

Intelligent controller is the central unit between physiotherapist and robot manipulator. It consists of impedance controller, rule base, data base, user interface and central interface units (Fig. 7). This architecture allows the system to monitor position, reaction force of the patient, and the force applied by the robot manipulator. The system interpret them together with data base using rules in the rule base to calculate impedance parameters to be sent to impedance controller, and produces desired position and torque of the robot manipulator. When the therapy is started the system requires basic features of the patient, like age, sex, height, weight, length of leg, etc. These values are stored in the data base and used to calculate system parameters. Main aim of this architecture is to learn the action of physiotherapist for each patient recorded, and to imitate this behavior in the absence of physiotherapist. Therefore, the system has two modes: teaching mode, and therapy mode.

Teaching mode

In this mode, as therapist assists the patient manually to perform the required motion, force values, position values and time history are recorded to data base in real time. This data are used to calculate the corresponding impedance parame-

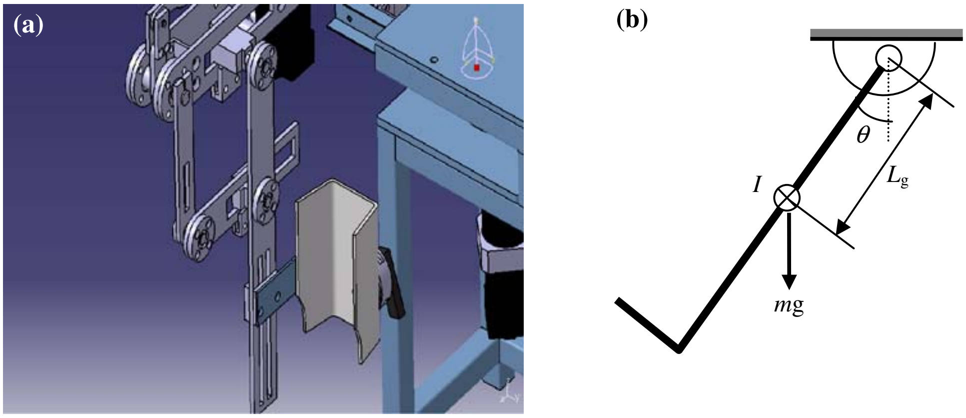

Fig. 6 Knee link **a** pictorial view and **b** schematic model

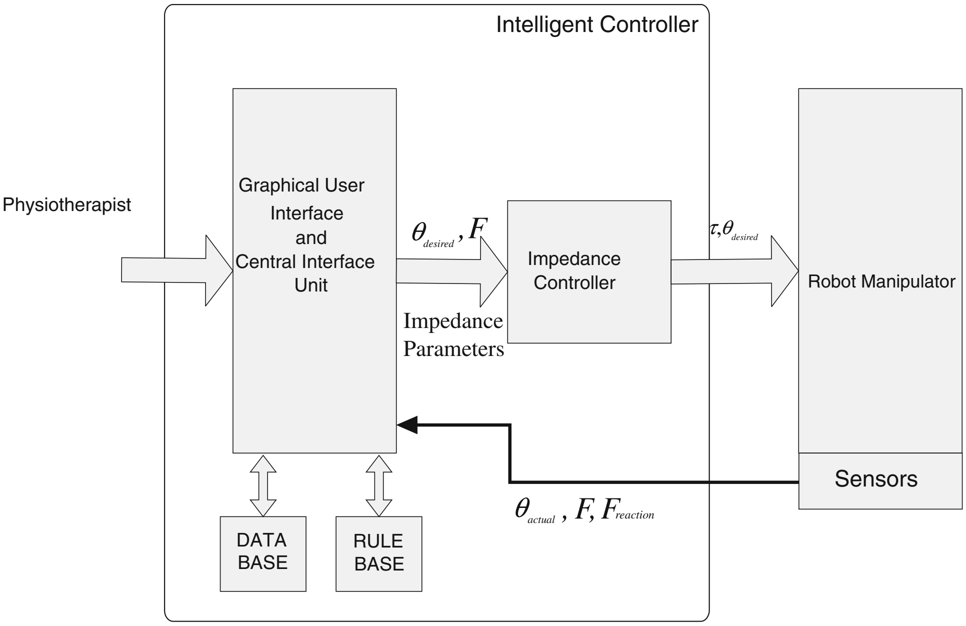

Fig. 7 Intelligent control block diagram (θ_{desired}: desired position, θ_{actual}: actual position, F: force applied by robot manipulator, F_{reaction}: reaction force of patient, τ: torque)

ters by the intelligent controller to produce the same behavior. This approach is called "direct teaching."

Therapy mode

In this mode, the robotic system realizes the therapy in the absence of physiotherapist using the information recorded during teaching mode. This information involves many values including the reaction force of the patient which may exist or not depending on the kind of disability. If the patient can not resist then the robotic system forces the knee of the patient to move within the limits learned from physiotherapist during teaching mode. This action is called "direct therapy". In direct therapy mode, the robotic system simply repeats the motion of physiotherapist.

On the other hand, if the patient is able to perform a limited motion then the robotic system assists the patient to complete the motion by forcing the knee within limits. This action is called "therapy with reaction".

The data base contains force–position values for 10° of interval within motion limits, taken from healthy people with various weights. This data serve as desired position and force values for the patient to achieve during therapy with reaction. If the patient resists against the motion the intelligent controller forces the knee to move up to the limit based on the corresponding desired force and position values stored in the data base. Data base is handled by the rules set in the rule base according to weight of the patient and maximum position angle. A sample of such a rule is given below;

> <**Rule:** *if* ***BW*** *bigger than 70 kg and less than 73 kg and* ***MXP*** *less than 10 degree, then* ***FN*** *is 1*>

where ***BW***, ***MXP*** and ***FN*** are weight of patient, maximum position saved during teaching, and the corresponding file number, respectively. The maximum positions and force values of the corresponding data file are used as limit values for "therapy with reaction".

In "direct therapy" and "therapy with reaction", when the limit of force values are reached, the robotic system stops and the position is initialized. In addition to the limit values set during teaching mode, there are additional software limitations and hardware limit switches for the sake of safety.

Implementation details

The system is developed using MATLAB Simulink Real Time Windows Target Toolbox. Sampling time is selected to be 1 ms. Rule base of the system contains a total of 70 rules. Figure 8 illustrates a sample teaching mode, and the corresponding "direct therapy". This shows that the robotic system can almost perfectly repeat the motion of physiotherapist as learned during teaching mode. Figure 9 shows the torque response of the same motion in both teaching mode and "direct therapy" mode. As can be seen from this figure, during the change of motion from extension to flexion, or the vice versa, the error (the difference between these curves) increases, but the robotic system can still perform the motion learned during teaching mode.

Figure 10 illustrates a sample therapy with reaction for a patient with 80 kg up to a limit position of 75°. As seen from this figure, when the position is above 10°, the reaction force becomes negative indicating that the patient is resisting against motion. It may be because of reflexes or disabilities. The patient applies just above 20 N reaction force for the position of 75°, and then the rest of the motion is completed by means of the robot manipulator by forcing the patient's knee within limits.

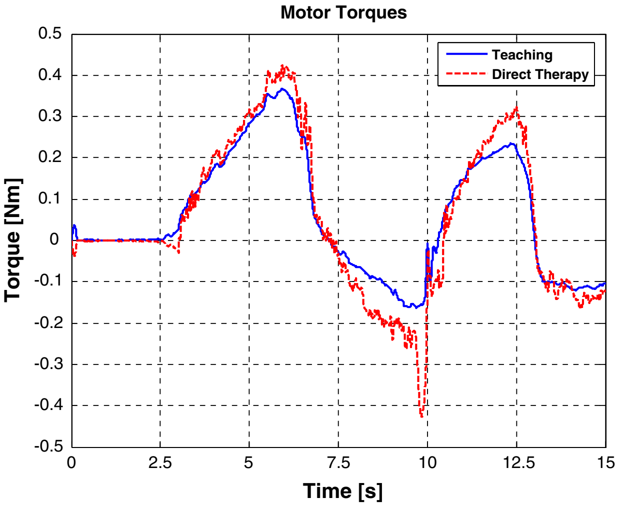

Fig. 9 Motor torques

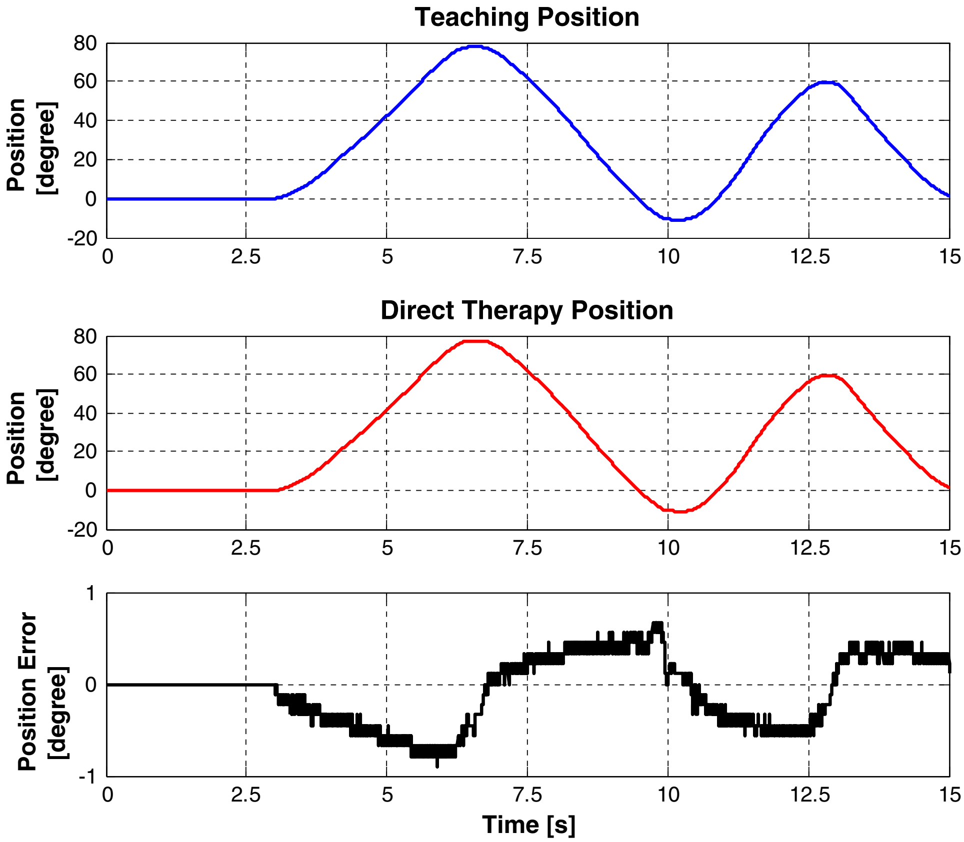

Fig. 8 Teaching position (p_t), direct therapy position (p_{td}) and error ($p_t - p_{dt}$)

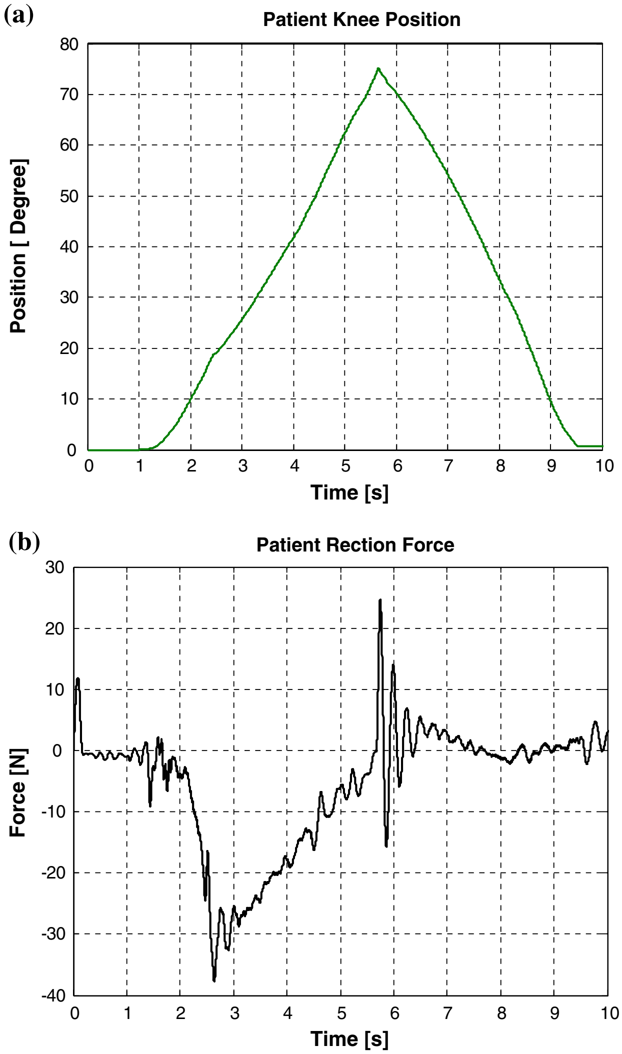

Fig. 10 **a** Experimental results of knee position and **b** patient's reaction force

Conclusion

An intelligent controller structure for a knee rehabilitation robot manipulator is proposed. The robot manipulator works based on impedance control which is known to an appropriate control method for physiotherapy. The robot manipulator system operates in two stages: teaching and therapy. As the patient reacts during the rehabilitation process, the intelligent controller evaluates the situation by monitoring the data from the force and position sensor. Experimental results show that, in direct teaching, the intelligent robotic system introduced can follow the path and the force configurations of the physiotherapist learned during teaching mode. In case of "therapy with reaction", the system assists the patient to complete the motion by forcing the knee within a limited range as learned during teaching mode. When the limit is reached, then system stops and goes back to the initial position. The system security is controlled by both hardware, like limit switches, as well as software.

If the mobility of robot manipulator is increased for more complex therapy movements, then building knowledgebase may be increasingly sophisticated, so it may have to be supported by some other intelligent techniques may have to be employed.

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

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