Position controlled Knee Rehabilitation Orthotic Device for Patients after Total Knee Replacement Arthroplasty

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Abstract. Knee rehabilitation after total knee replacement arthroplasty is essential for patients during their post-surgery recovery period. This study is about designing one degree of freedom knee rehabilitation equipment to assist patients for their post-surgery exercise. The equipment is designed to be used in sitting position with flexion/extension of knee in sagittal plane. The range of knee joint motion is starting from 0 to90 degrees angle for knee rehabilitation motion. The feature includes adjustable link for different human proportions and the torque feedback control at knee joint during rehabilitation and the control of flexion/extension speed. The motion of the rehabilitation equipment was set to move at low speed (18 degrees/sec) for knee rehabilitation. The rehabilitation link without additional load took one second to move from vertical hanging up to 90^o while the corresponding torque increased from 0 Nm to 2 Nm at 90^o. When extra load is added, the link took 1.5 seconds to move to 90^o. The torque is then increased from 0 Nm to 4 Nm. After a period of time, the speed of the motion can be varied. User can adjust the motion to 40 degrees/sec during recovery activity of the knee and users can increase the level of exercise or motion up to 60 degrees/sec to strengthen the muscles during throughout their rehabilitation program depends on each patient. Torque control is included to prevent injury. Patients can use the equipment for home exercise to help reduce the number of hospital visit while the patients can receive an appropriate therapy for their knee recovery program.

1. Introduction

Knee osteoarthritis is the most common disease in orthopedic. The osteoarthritis of knee is a chronic condition that affects the lives of the elderly. After total knee arthroplasty, patients can return to their daily activities with an improvement as compared to the preoperative condition. Rehabilitation after total knee replacement arthroplasty aims to decrease pain, recovery the range of motion, and help patients improve knee function for their daily activities. After the surgery, patients are usually evaluated with Risk Assessment and Prediction Tool (RAPT)[1] by doctors and specialist to lead to rehabilitation program for each specific patient. The numbers of patients who need to go through rehabilitation process are increased. The increased number of patient who requires knee rehabilitation results in the increasing demand of physical therapy and time to assist all patients. Therefore hospitals world-wide create their rehabilitation equipment and initiated rehabilitation programs to help assist patients' knee performance.

In the past, researchers designed and developed control techniques for rehabilitation equipment for patients. Many designed rehabilitation equipment are developed for one degree of freedom, considering the knee's range of motion and the amount of torque handle by the knee during its movement[2]. Biomechanical analysis of lower limb simulation helped researchers gathered information and understood the relationship of the limb motion and the forces which occur during each rehabilitation activity. These information was design requirement of the device for rehabilitation

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in each program[3]. The Continuous passive motion(CPM) was developed with accurate alignment of the same actual human knee joint using linear actuator to drive the link structure mechanism[4]. An example of the knee and hip rehabilitation for patients after a spinal cord injury[5] was a three degrees of freedom system with Human-Machine Interface which provided connection between user and the designed device during rehabilitation exercise. Nikitczuk et al. applied eletrorheological fluid (ERF) to provide resistive torque during the motion and designed a control law to control the amount of torque exerted atthe knee joint. Control techniques were applied on the orthosis through adjustable actuate torque for the flexion/extension at the knee joint[6]. To obtain a robust system for knee rehabilitation, Mefoued, et al. applied Sliding Mode Control(SMC) to improve the response of the actuator in knee joint by tracking trajectory of the motion and compared it with the one after applied a PID control system [7]. In gait rehabilitation, a compact robot was designed with controllable actuator to assist patients in gait exercises with the knee-ankle-foot robot[8].

In this study, we propose our design of knee rehabilitation equipment for patients after total knee replacement arthroplasty in sitting position. The equipment main focus is on knee flexion and extension of knee joint in rehabilitation. The study includes the design of a control system to control knee joint position to assist user along with torque monitoring to provide user safety and prevent injury during rehabilitation.

2. Hardware design

2.1. Design requirements

The designed knee rehabilitation equipment has one degree of freedom at the knee joint and the device is used in sitting position for flexion and extension. The length of thigh link is adjustable within the range of 38 – 50cm. The calf link is 28-40cm long and can be altered depends on the size of the patient's limb. The rehabilitation equipment can be used for exercise within the range of 0^o-80^o. The speed of the motion is set at 40 degrees/sec, which is normal speed for knee recovery program. However, the speed can be increased up to 60 degrees/sec to strengthen the muscles after a period of rehabilitation program.

2.2. The device kinematics

The forward kinematics of the device is based on two links which are the thigh link and the calf link in sagital plane, as shown in figure 1. The DH (Denevit-Hertenberg) parameter of the device is shown in table 1.

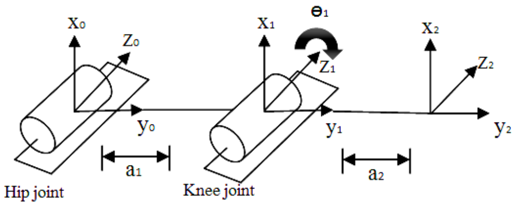

Figure 1. Kinematics diagram of the device.

Table 1. Table of DH (Denevit-heartenberg) parameter.

Link i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0.4	0	0	0
2	0.52	0	0	0

Substitute the parameter in the table 1 in equation (1) to the transformation matrix in equation (1) and workspace of the end effector of the device in figure 2.

$$T_2^0 = A_1A_2 = \begin{bmatrix} c\theta_1 & -s\theta_1 & 0 & a_1c\theta_1 + a_2c\theta_1 \\ s\theta_1 & c\theta_1 & 0 & a_1s\theta_1 + a_2s\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

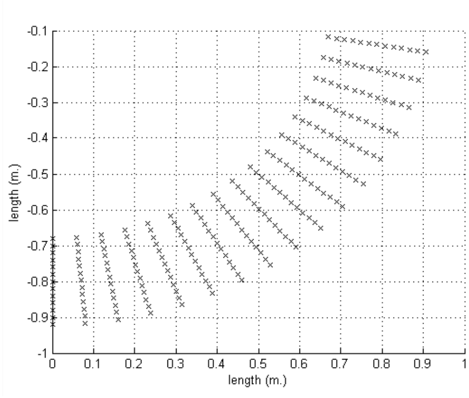

Figure 2. Workspace of the designed knee rehabilitation equipment.

2.3 *Design mechanism*

The knee rehabilitation device consists of a 36 Watt DC motor which was connected to the gear box, the encoder (Roundss RCC38S6) and the torque sensor (Sensor Technology RWT321-DG). The system was connected to the analog output NI9215. The DC motor was connected to the NI9505 full H-bridge brushed dc servo drive module. The NI9215 module and NI9505 module were plugged into the National Instruments (NI) CompactRIO 9104, 8 slot field programmable gate array (FPGA) which is the real-time controller and controlled through LabVIEW. A bevel gear was used to transmit and change the direction of the dc motor drive to the thigh link during the motion. The system together with the lower limb was attached to the set as shown in figure 3. User gets to exercise one leg at a time, while the link is attached to the leg and the support.

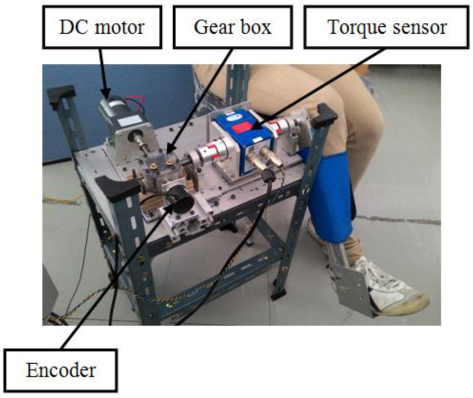

Figure 3. The designed prototype.

3. Control system design

During a physical therapy, the system is designed to prevent injury and at the same time assist user with the provided torque. We simulated the movement of a device model with a human model using Matlab. First, the equipment was modeled through Lagrange-Euler equation as shown in equation (2).

$$I\ddot{\theta} - mg\frac{L}{2}\sin\theta = T \quad (2)$$

Where L is the length of the link, I is the inertia, T is the input torque from the motor, and θ is the angle of the link as measured from the vertical direction. The transfer function (3), which was derived from (2) where input is torque and output is θ, is used in control simulation in Matlab.

$$\frac{\theta(s)}{T(s)} = \frac{1}{Is^2 - mg\frac{L}{2}} \tag{3}$$

3.1. Human model

Human model is represented by the relation between the torque requires (input) to move the lower link to 80° at the knee joint (output) for rehabilitation. Where the inertia of the leg (I_{leg}) is 0.43 kgm^2mass of the patient (m_{human}) is 4.8kg, and length of the leg (L_{human}) is 0.52m.

3.2. Device model

Device model is relation between the torque requires (input) to move the lower link to 80° at the knee joint (output) for rehabilitation. Where the inertia of the device (I_{device}) is 0.07 kgm^2, mass of the device (m_{device}) is 0.8kg, and length of the device (L_{device}) is 0.52m.

The human model and the device model are similar except for the value of the parameters. These two models are used to determine the controller through simulation in Matlab. The position control of the rehabilitation equipment is necessary; the position of the setup should not exceed the range of motion of the legs to prevent injury. The interaction between human legs with the device is controlled through position feedback of the human leg which moves along the desired position input of the system. The system is controlled using PID controller. The system is controlled through Labview program with graphical user interface (GUI) on a computer which is connected to the real-time controller (cRIO-9012) via communication with I/O devices. In this experimental set up, we use NI9505 module by National instrument to control the speed of the DC motor which drives the moving mechanism of the system and used NI9215 to acquire an analog output signal from the torque sensor (Sensor Technology RWT321-DG).

4. Result and Discussion

The designed equipment was tested at 18 degrees/sec, which is considered low speed for the flexion and extension of the knee rehabilitation[5] to ensure that the designed position control is suitable for the system. The motor speed was monitored through NI9505 and NI9215module was used to collect the torque signal from the equipment. We observed that when the link (with no extra load) was set to move at 18 degrees/sec, the calf angle started moving from 0^o at vertical position and up to 90^o. The link took approximately 1 second to move up to 90^o as shown in figure 4a). The torque increased up from 0 Nm to 2 Nm at 90^o and then the calf moved down from $90^o$with the torque 2 Nm and moved down to 0^o returned to the vertical position with the torque 0 Nm as shown in figure 4b). When extra load is added, the corresponding position and torque profile are shown in figure 5a). However, the link took approximately 1.5 seconds to move to 90^o. The torque increased up from 0 Nm to 4 Nm and then the link returned to the vertical position with the torque 0 Nm as shown in figure 5b). The test was performed continuously and the result appeared to be the same through each run. The position of the equipment are shown in figure 4a) and 5a). The actual position (dashed line) is following up the desire position the controller will have to be adjusted with careful consideration of the effect of acceleration on the position of the equipment.

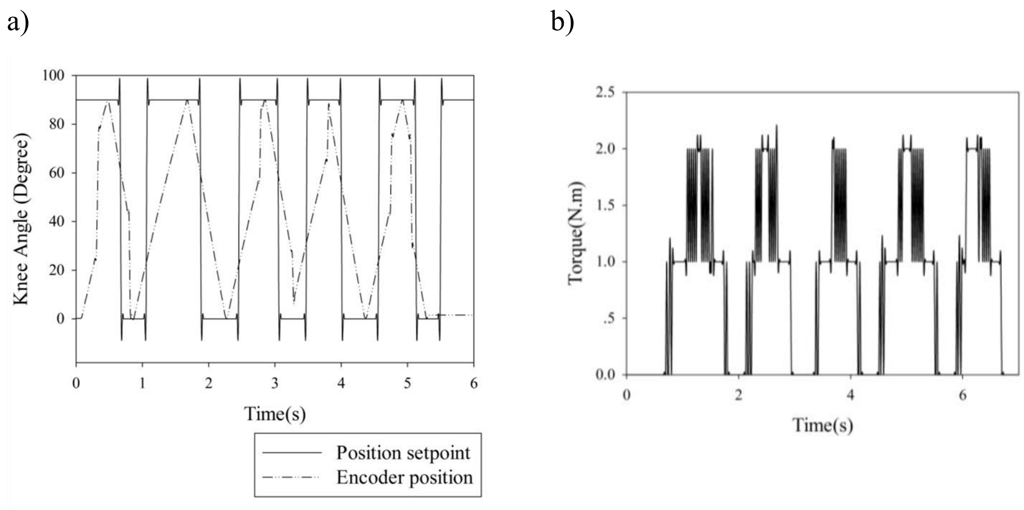

Figure 4. a) Desired position and actual position of the calf link at the velocity 18 degrees/sec. b**)** Torque at the knee joint in the experiment at the velocity 18 degrees/seconds.

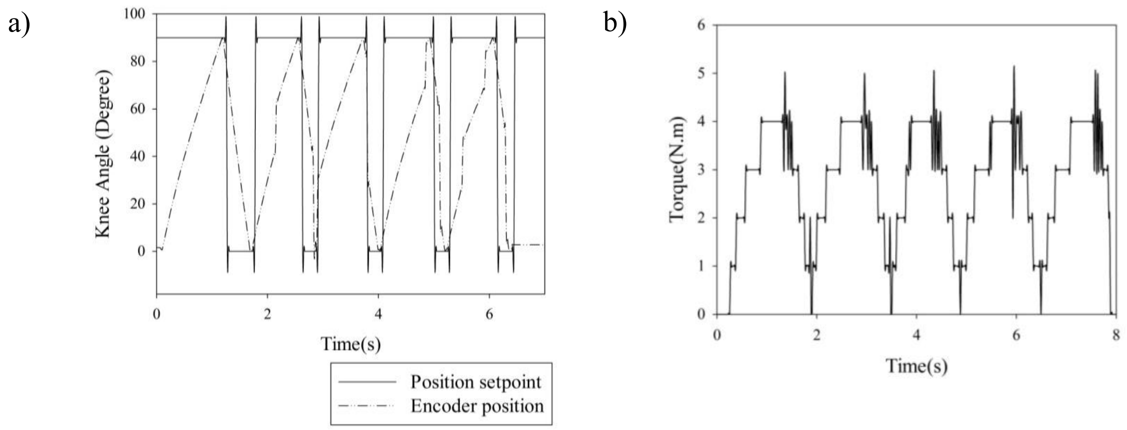

Figure 5. a) Desire position and actual position of the calf link with a 1 kg mass at the velocity 18 degrees/sec. b) Torque at the knee joint in the experiment at the velocity 18 degrees/seconds.

5. Conclusion

In this paper, we presented knee rehabilitation equipment for patients after total knee replacement arthroplasty in sitting position. The position applied by the motor on the patient's knee was controlled in order to assist patients for their knee exercise as well as prevent themselves from injuries. The result show that the link can move to the desire position. The motor torque was monitored in order to confirm device safety while using this equipment. In the future, the measured torque will be used to model a torque feedback system to help assist the patients when they have difficulty moving the knee at the beginning session of the therapy. The level of exercise can be challenged up to 40 degrees/sec for knee recovery and up to 60 degrees/sec to strengthen the muscles. In future work, the impedance control will be imposed the position of the system and control the motor torque when function together with the torque exerted by user during rehabilitation. With this knee rehabilitation equipment, the system helps recovery the range of motion for knee joint while the patients can use the device for exercise at home to decreases the number of hospital visit and receive an appropriate therapy.

Acknowledgments

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