Development of Knee Joint Robot with Flexion, Extension and Rotation Movements - Experiments on Imitation of Knee Joint Movement of Healthy and Disable Persons -

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Abstract We have developed a knee joint robot as an educational simulation tool for students becoming physical therapist or occupational therapist. The knee joint robot (Knee Robo) has two degrees-of-freedom to simulate both flexion/extension movement and rotation movement of a human knee joint. This paper presents knee joint models of healthy and disabled persons for the Knee Robo. The Knee Robo can simulate skew home movement (SHM) in a human knee joint. Moreover, the Knee Robo can simulate the knee joint movements of not only a healthy person but also a patient with knee joint troubles, such as range of motion (ROM) trouble, contracture, rigidity, spasticity and so on. The effectiveness of the knee joint models and the control algorithms has been verified experimentally.

1 Introduction

In Japan the number of schools for students becoming a physical therapist (PT) or an occupational therapist (OT) is increasing. However, several problems concerning educational effect have been pointed out. One of them is the shortage of experience of clinical training in medical institutions. During clinical training, the students learn patient troubles, manual training/testing techniques and so on.

Before clinical training, in the schools the students learn manual training/testing techniques, such as manual muscle training, manual muscle testing, range of motion

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testing and so on. In order to deepen the understanding the students play the role of a therapist and a patient by turns mutually, and repeat the skill training of manual training/testing techniques to a healthy student instead of a patient. However, the students cannot experience patients' troubles before clinical training. Therefore, a patient robot imitating patients' troubles is necessary for the students to experience patient's troubles virtually and to learn the manual training/testing techniques before clinical training. In the previous works of other research group, Masutani et al. have developed the patient leg robot as an educational training tool for students becoming PT or OT. By introducing the robot to the school, it is shown that the students' motivation went up [1]. However, the mechanism of the robot has only one degree-of-freedom in the knee joint. This mechanism is not enough to imitate actual troubles of knee joints. In Ref. [2] a leg-robot for demonstration of spastic movements of brain-injured patients has been developed.

We have developed a knee joint robot as an educational simulation tool of human knee joint movement [3,4]. The mechanism is designed on the basis of the idea that the human knee joint movement consists of three kinds of movement, namely "sliding", "rolling" and "coming off". We have designed the optimal arrangement of four pulleys in the wire drive system by introducing performance indices [4]. In addition we have designed the control algorithms and the knee joint models to imitate three kinds of human knee joint troubles by using only the flexion/extension motion mechanism of the Knee Robo, and verified the effectiveness by fundamental experiments.

In this paper we design knee joint models and control algorithms in which not only the flexion/extension motion mechanism but also the rotation motion mechanism of the Knee Robo are considered. The models can imitate skew home movement, range of motion (ROM) trouble, lead pipe rigidity, cogwheel rigidity, spasticity, contracture and so on. The effectiveness is verified experimentally.

2 Knee Joint Robot [2,3]

We have developed the knee joint robot (Knee Robo) as shown in Fig.1. The Knee Robo is used as the simulator to feel resistance of knee joint passive movement. Then the Knee Robo does not move automatically. Only a subject can move the lower leg of the Knee Robo. When a subject holds the femur of the Knee Robo and extends and retracts the lower leg of the Knee Robo, as shown in Fig.2, the subject feels various resistance of normal and disabled knee joint movements.

A lower limb of human being consists of a femur, a lower leg and a knee joint. Human knee joint movement consists of the flexion/extension movement and the rotation movement. When a human being extends his/her lower leg from the bended position to the full extended position on the seating posture, the tibia rotates outward slightly at the vicinity of the full extended position. This movement is called skew home movement (SHM). Therefore, students should pay attention to this movement in manual testing and training on patients.

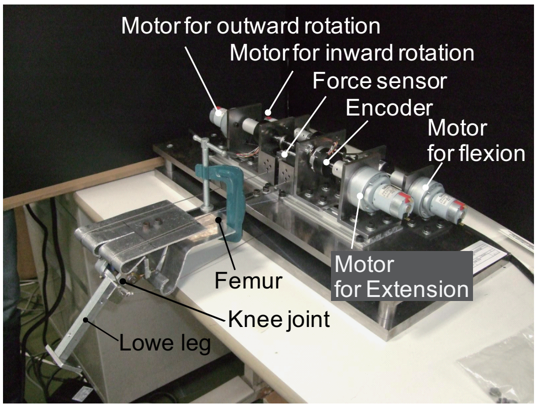

Fig. 1 Knee Robo.

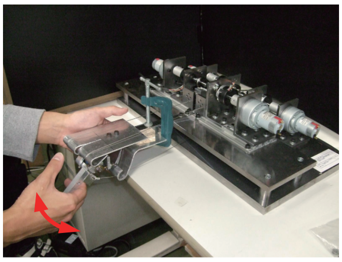

Fig. 2 Training scene of manual testing technique.

The Knee Robo consists of the link corresponding to a femur, the link corresponding to a tibia, and the knee joint. The Knee Robo simulates a left leg. The Knee Robo is three fourths of sizes compared with a standard adult male. The Knee Robo is driven by four motors and four wires corresponding to muscles. The four motors are used for outward rotation, inward rotation, flexion, and extension. The motor angles are measured with the rotary encoders, and the wire tensions with the force sensors. Four guide pulleys are used for each wire. It is noted that not guide pulleys but guide plates are used in Fig.1. Since the Knee Robo has two degrees of freedom, various passive movements of a human knee joint can be imitated, which is our original and advantage.

3 Models of Knee Joint Movement

3.1 Educational effect by Knee Robo

The structure and movement of a knee joint are very complicated. By introducing the Knee Robo to schools the improvement of the educational effects is expected. The educational effects are as follows;

1. Students learn the structure and movement of normal and disabled knee joints.
2. Students learn the prohibited operation in leg passive movement in manual tastings and trainings.
3. Student learn the manual training/testing technique for knee joint troubles.

The Knee Robo can imitate resistance of a knee joint during the passive leg movement. In the Knee Robo, ROM trouble, lead pipe rigidity, cogwheel rigidity, spasticity and contracture can be simulated as reproducible knee joint troubles,

3.2 Healthy knee joint movement

The models of a healthy human knee joint movement during the passive leg movement are derived for the Knee Robo. Let $\theta_{FE}(t)$ and $\theta_R(t)$ denote the flexion/extension angle and the rotation angle. Let $\tau_E(t)$, $\tau_F(t)$, $\tau_{OR}(t)$ and $\tau_{IR}(t)$ denote the extension torque, the flexion torque, the outward rotation torque and the inward rotation torque. Let $\theta_{shm}(t)$ denote the desired rotation angle to imitate SHM. We assume that in the full extended knee position, the flexion/extension angle $\theta_{FE}(t)$ is equal to zero, and the rotation angle $\theta_R(t)$ is equal to θ_{shmb}. When the flexion/extension angle $\theta_{FE}(t)$ is equal to θ_{shm0}, the rotation angle $\theta_R(t)$ is equal to zero. The knee joint model of a healthy person including SHM is represented as follows;

$$\tau_E(t) = \tau_{basic} + \tau_g + M_{FE}\ddot{\theta}_{FE}(t) + D_E\dot{\theta}_{FE}(t) + K_E(\theta_{FEmin} - \theta_{FE}(t)), \quad (1)$$

$$\tau_F(t) = \tau_{basic} + \tau_g + M_{FE}\ddot{\theta}_{FE}(t) + D_F\dot{\theta}_{FE}(t) + K_F(\theta_{FE}(t) - \theta_{FEmax}), \quad (2)$$

$$\tau_{OR}(t) = \begin{cases} \tau_{basic} + M_R\ddot{\theta}_R(t) + D_{OR}\dot{\theta}_R(t) + K_{OR}\theta_R(t) & (\theta_{FE}(t) > \theta_{shm0}), \\ \tau_{basic} + \hat{K}_{Rshm}(\theta_{shm}(t) - \theta_R(t)) & (\theta_{FE}(t) \leq \theta_{shm0}), \end{cases} \quad (3)$$

$$\tau_{IR}(t) = \begin{cases} \tau_{basic} + M_R\ddot{\theta}_R(t) + D_{IR}\dot{\theta}_R(t) + K_{IR}\theta_R(t) & (\theta_{FE}(t) > \theta_{shm0}), \\ \tau_{basic} + \hat{K}_{Rshm}(\theta_{shm}(t) - \theta_R(t)) & (\theta_{FE}(t) \leq \theta_{shm0}), \end{cases} \quad (4)$$

$$\theta_{shm}(t) = \begin{cases} \theta_{shmb}(1 - \frac{1}{\theta_{shm0}}\theta_{FE}(t)) & (\theta_{FE}(t) \leq \theta_{shm0}), \\ 0 & (\theta_{FE}(t) > \theta_{shm0}), \end{cases} \quad (5)$$

$$K_E = \begin{cases} 0 & (\theta_{FE}(t) \geq \theta_{FEmin}), \\ K_{Erom} & (\theta_{FE}(t) < \theta_{FEmin}), \end{cases} \quad K_F = \begin{cases} 0 & (\theta_{FE}(t) \leq \theta_{FEmax}), \\ K_{From} & (\theta_{FE}(t) > \theta_{FEmax}), \end{cases} \quad (6)$$

where τ_{basic} is the constant wire tension for not sagging, τ_g is the gravitational torque of a lower leg, (M_*, D_*, K_*) are the impedance parameters, θ_{FEmin} and θ_{FEmax} are the minimum and maximum values of the ROM, θ_{shm0} is the starting flexion/extension angle of SHM, θ_{shmb} is the maximum value of the rotational angle by SHM, and $\hat{K}_{Rshm}$ is the proportional control gain. When $\theta_{FE}(t) \leq \theta_{shm0}$, proportional angle control is used so that the rotation angle $\theta_R(t)$ becomes the desired rotation angle $\theta_{shm}(t)$ as shown in the upper equations of Eqs.(3) and (4). When $\theta_{FE}(t) > \theta_{shm0}$, impedance control is used to realize the desired outer and inner rotation torques as shown in the lower equations of Eqs.(3) and (4).

3.3 Disabled knee joint movement

In order to imitate troubles in a knee joint in the Knee Robo, we modify the impedance parameters and the parameters of ROM in Eqs.(1)-(6).

3.3.1 Range of motion trouble

In hospitals, therapists perform range of motion (ROM) testing on patients. The patient with the ROM trouble in his/her knee joint can move his/her lower leg only in the limited range. When the therapist moves the patients lower leg, the therapist feels resistance at the end of patient's ROM. The resistance is called end feel, which is very important for a therapist in the ROM testing. When the ROM for flexion is 0 to θ_{rom}, the ROM trouble can be imitated in the Knee Robo by replacing θ_{FEmin} and θ_{FEmax} with 0 and θ_{rom}, respectively.

3.3.2 Lead pipe rigidity and cogwheel rigidity

Rigidity and spasticity are troubles of knee joints caused by disorder of the central nervous system. In both troubles, when the therapist moves the patient's lower leg, the therapist feels resistance of a knee joint during the passive leg movement. There are two types of rigidity, namely lead pipe rigidity and cogwheel rigidity. In this paper we assume that rigidity occurs only during passive flexion.

In the case of lead pipe rigidity the resistance force is constant during the passive leg movement. In order to generate a constant torque τ_{rig} the damping coefficient D_E in Eq.(1) is replaced with the following equation;

$$D_E = \begin{cases} \dfrac{\tau_{rig}}{\dot{\theta}_{FE}(t)} & (\dot{\theta}_{FE}(t) \geq v_{rig}), \\ 0 & (\dot{\theta}_{FE}(t) < v_{rig}), \end{cases} \tag{7}$$

where v_{rig} is the threshold value, which is introduced so as to avoid division by zero.

In the case of cogwheel rigidity, the resistance force is generated intermittently during the passive leg movement. The damping coefficient of cogwheel rigidity is denoted by multiplying the damping coefficient of lead pipe rigidity of Eq.(7) and a square wave function $X(\theta_{FE}(t))$ depending on the flexion/extension angle as follows;

$$D_E = \begin{cases} \dfrac{\tau_{rig}}{\dot{\theta}_{FE}(t)} X(\theta_{FE}(t)) & (\dot{\theta}_{FE}(t) \geq v_{rig}), \\ 0 & (\dot{\theta}_{FE}(t) < v_{rig}), \end{cases} \tag{8}$$

$$X(\theta_{FE}) = \begin{cases} 1 & (n\theta_{gr} \leq \theta_{FE}(t) \leq n\theta_{gr} + \Delta\theta_{gr}) \\ 0 & ((n\theta_{gr} + \Delta\theta_{gr} < \theta_{FE}(t) \leq (n+1)\theta_{gr}) \end{cases} \quad (n = 0, 1, 2, \cdots, N), \tag{9}$$

where θ_{gr} and $\Delta\theta_{gr}$ are the parameters of the square wave function.

3.3.3 Spasticity

In the case of spasticity the resistance force depends on the flexion/extension angular velocity of a knee joint. In order to generate the resistance force for spasticity the damping coefficient D_E in Eq.(1) is adjusted. Moreover clasp-knife spasticity is caused by rigidity of the extensor muscles of a knee joint. At the beginning of the passive flexion of the patient with clasp-knife spasticity, a therapist feels resistance. During the passive flexion a therapist does not feel resistance suddenly. This implies that the knee joint gives resistance to passive flexion, but suddenly does not give resistance and allows easy flexion. It is assumed that clasp-knife spasticity occurs when $\theta_{FE}(t) = \theta_{ck}$. Then in order to imitate clasp-knife spasticity the damping coefficient in Eq.(1) is replaced with the following equation;

$$D_E = \begin{cases} D_{spa} & (\dot{\theta}_{FE}(t) \geq 0, \theta_{FE}(t) < \theta_{ck}), \\ 0 & (\text{else}), \end{cases} \quad (10)$$

where D_{spa} is the damping coefficient for spasticity.

3.3.4 Contracture

Contracture is one kind of troubles in knee joints. A patient suffers from contracture when the patient does not move his/her body after onset of the disease, such as cerebral apoplexy. Then it will become harder to move his/her body. In hospitals therapists perform a stretching program for a patient with contracture. The therapist rotates the lower leg outward and inward repeatedly, and then retracts the lower leg. The Knee Robo can imitate such passive movement.

4 Experiments

The basic experiments are performed to verify the effectiveness of the proposed knee joint models of healthy and disabled persons. In order to imitate resistance of a knee joint during passive leg movement, impedance control is applied to the Knee Robo as shown in Fig. 3. The desired knee joint torques for impedance control are calculated by using the knee joint torques of Eqs.(1) - (4). The parameters of the proposed models are determined from the therapists' opinion in the demonstration of the Knee Robo.

4.1 Knee joint movement of healthy person

In order to imitate knee joint movement of healthy person we use the parameters as follows; θ_{shmb} =4deg, θ_{shm0} =10deg. The experimental results are shown in Fig.4. It is seen that the rotation movement due to SHM is realized in the robot.

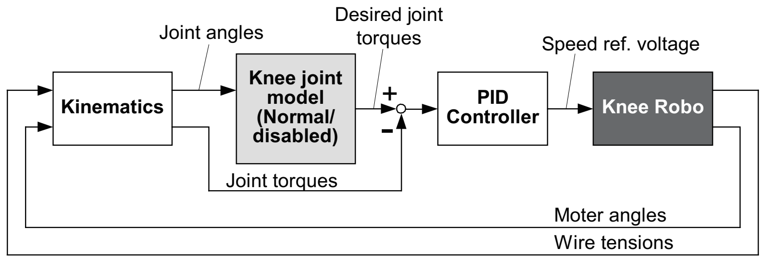

Fig. 3 Block diagram of control system of Knee Robo.

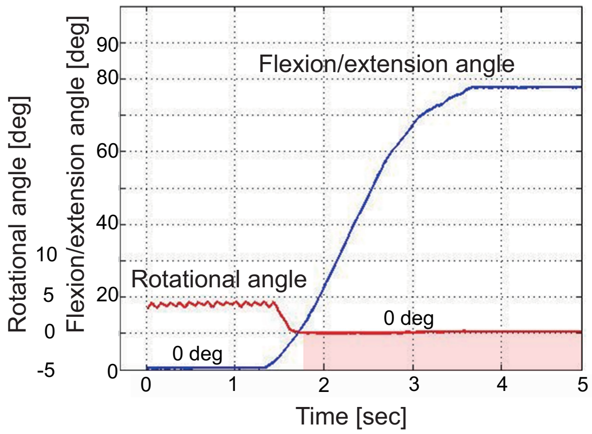

Fig. 4 Experimental results of imitation of knee joint movement of healthy person

4.2 Knee joint movement of range of motion trouble

In order to imitate range of motion trouble we use the parameters as follows; $\theta_{rom} = 45\pi/180$rad (=45deg) and K_{Erom} =0.2Nm/rad. Two kinds of end-feel are imitated at the end of ROM by using K_{From} =0.1Nm/rad and K_{From} =0.01Nm/rad. The simulation results are shown in Fig. 5. It is seen in the case of K_{From} =0.1Nm/rad in Fig. 5 that the knee joint angle is held about 45deg, although the knee joint torque is increasing by external human force.

4.3 Knee joint movement of lead pipe rigidity and cogwheel rigidity

In order to imitate lead pipe rigidity and cogwheel rigidity we use the parameters as follows; τ_{rig}=0.08Nm, $\theta_{gr} = 7$deg and $\Delta\theta_{gr}$ =2deg. The imitation of cogwheel

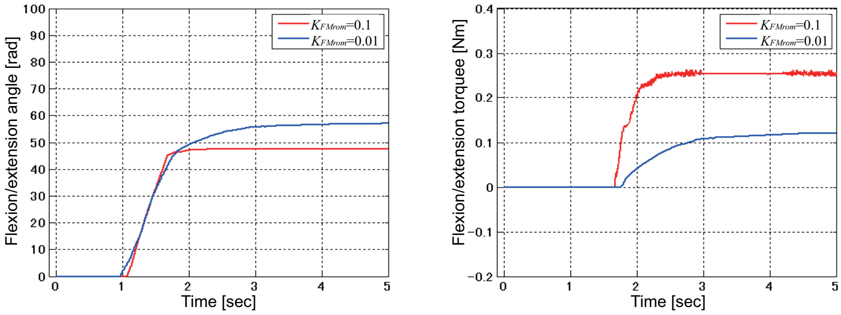

Fig. 5 Experimental results of imitation of ROM trouble

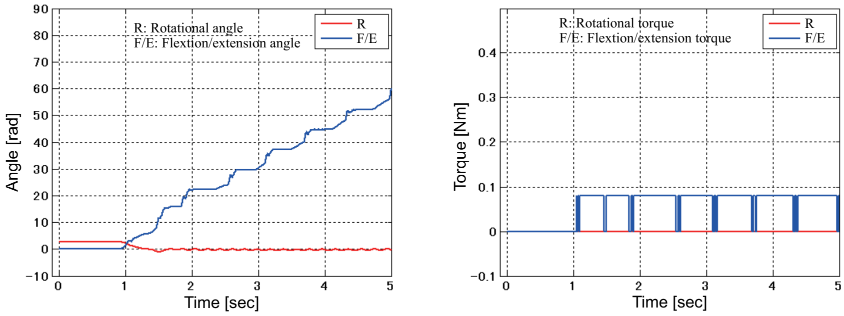

Fig. 6 Experimental results of imitation of cogwheel rigidity

rigidity is shown in Fig.6. The periodical torque is seen during the passive leg movement.

4.4 Knee joint movement of clasp-knife spasticity

In order to imitate clasp-knife spasticity we use the parameters as follows; $\theta_{rom} = 90\pi/180$rad(=90deg) and $\theta_{ck} = 45\pi/180$rad(=45deg). The imitation of clasp-knife spasticity is shown in Fig.7. When the knee joint angle is less than 45deg, the knee joint torque is generated. This implies that the subject feels resistance. After 45deg the knee joint torque is decreasing, although the knee joint angle increases. This implies that the subject does not feel resistance. It is seen from Fig.7 that clasp-knife spasticity is imitated in the Knee Robo.

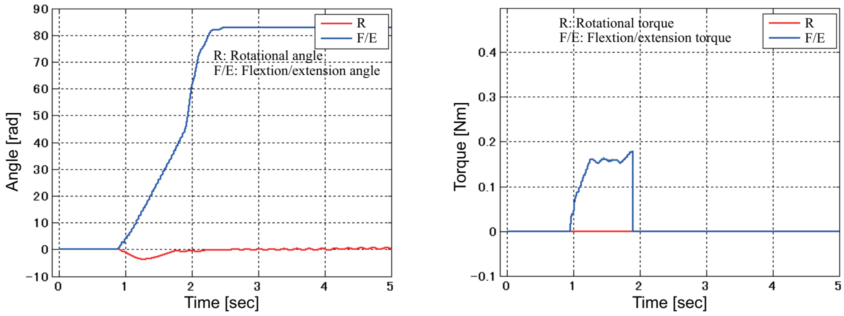

Fig. 7 Experimental results of imitation of clasp-knife spasticity

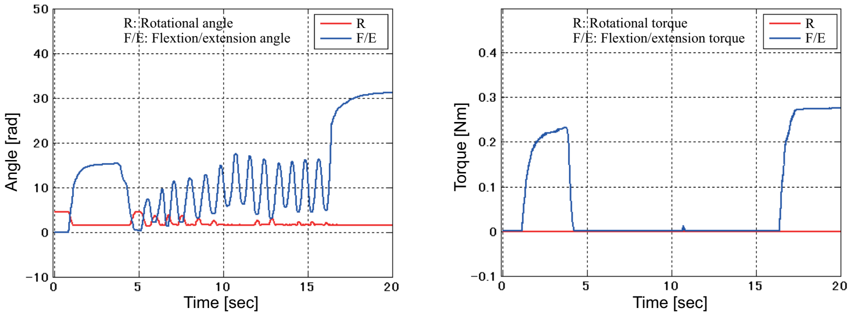

Fig. 8 Experimental results of imitation of training for contracture

4.5 Knee joint movement during training for contracture

A subject can experience training for contracture by using the Knee Robo. In the training for contracture there are traction treatment and repetitive movement treatment. In this paper the repetitive movement treatment is imitated. In general after repetitive movement treatment the ROM becomes larger. For this purpose the ROM which is improved by repetitive movement treatment is modeled by the following equation;

$$\theta_{FEmax}(t) = \theta_{rom\_init} + K_{rom\_train} \int_0^t |\dot{\theta}_{FE}(t)| dt. \tag{11}$$

$\theta_{FEmax}(t)$ increases according to the repetitive passive movement of the lower leg. θ_{rom_init}=15deg and K_{rom_train}=0.5 are used in the Knee Robo. The imitation results of the training for contracture are shown in Fig.8. It is shown that the ROM is 15deg at the beginning of the treatment, and the ROM becomes larger, namely about 30deg, after the treatment by the subject.

5 Conclusions

We have proposed knee joint models of healthy and disabled persons on the basis of flexion/extension movement and rotation movement. These models can imitate the human knee joint movements, namely SHM, range of motion trouble, lead pipe rigidity, cogwheel rigidity, clasp-knife spasticity and contracture. Consequently, it was found from the fundamental experiments that the Knee Robo enable us to learn the knee joint movement of healthy and disabled persons by feeling resistance of a knee joint.

The future works are to introduce the Knee Robo to PT/OT training schools, and to improve the knee joint models and the control algorithms on the basis of the opinions from therapists, educational staffs and students.

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