Design of a Special Lower Limb Rehabilitation Robot for Leg Patients

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Abstract: We describe the design of a special lower limb rehabilitation robot for leg patients and its operation. The lower limb rehabilitation robot is composed of linear motion mechanisms, links, a foot plate, a joint and two-axis force sensors. The links and the foot plate are rotated according to the linear motion mechanisms. The bending motions of the hip, knee, and ankle are performed. The designed rehabilitation robot was subjected to tests involving hip joint bending, knee joint bending, and ankle joint bending exercises, and the robot operated smoothly. Therefore, it can be concluded that the designed rehabilitation robot can be used on leg patients, for the three exercises stated above.

1 INTRODUCTION

They are usually rehabilitated by a professional therapist while in bed, because leg patients face difficulties in walking. Lower limb rehabilitation exercises include bending and stretching the knee joint, ankle joint, and hip joint. It is very difficult for a rehabilitation therapist to rehabilitate such patients, because their legs are heavy. Recently, various rehabilitation robots have been developed owing to a dearth of rehabilitation therapists.

Yu, H. designed and controlled a robot capable of rehabilitating the knee and ankle joints while a patient walks. The robot is divided into two actuators, one for the ankle joint and another for the knee joint. These actuators convert the rotational motion of the motor into a linear motion and turn it into a rotational motion using an eccentric disc. This robot can rotate each joint only when the motor rotates and the knee joint and the ankle joint can be rehabilitated. Akdogan, E. designed and controlled a 3-degree-of-freedom therapeutic exercise robot for lower limb rehabilitation in patients with spine, stroke, and muscle diseases. The patient is placed in a chair that allows sitting and lying down. The rehabilitation treatment of the knee joint is performed by pushing up and down the calf, and the rehabilitation of the hip joint is performed by pushing up and down the thigh. The robot lifts and lowers the legs by kinematic interpretation, and the force sensor is attached to a device for pushing up the calf and thigh, measuring the pushing force, including the weight of the lower limb. This robot can only rehabilitate the knee joint and the hip joint, not being possible to perform rehabilitation treatment on the ankle joint. Zhang, J. F. conducted modeling to control a robot along a walking path when a stroke patient wears a 4-degree-of-freedom walking assistant robot and performs a walking exercise. The theoretical position of the knee joint and of the hip joint was compared with the test position, and the torque of the hip and knee joints was measured.

Pennycott, A. performed posture control during a walking assist robot motion. The robot performs a walking athletic treatment on a patient who can walk. Malcolm, P. designed a robot for an exoskeleton exercise, which uses a linear motion mechanism mounted on a calf to push and pull the heel, in order to rotate the ankle joint. This can only rehabilitate the patient's ankle. Wu, M. designed a robot that hangs the patient's body vertically, binds the rope to the lower limb, and performs walking training, by using the robot's motor and pulley. This is appropriate for gait training for mild patients and is not suitable for the rehabilitation of patients with severe stroke who are lying down. Martins, M. M. designed a mobile robot, consisting of a body with three wheels spaced 90 degrees apart and capable of supporting the patient's arm. This robot can be walked on while a patient with an uncomfortable leg

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is supported by the force of his/her arm and shoulder, and can be used for a patient's gait rehabilitation. Karavas, N, designed and controlled a robot for an assisted knee exoskeleton. The robot was made by connecting two links, such as a link of a calf part and a link of a thigh part with a joint, and attaching a motor to the joint part. This robot can handle the patient's knee joints. Rajasekaran, V. safely controlled a wearing robot that can apply rotational force to the ankle joint, knee joint, and hip joint of a person. The robot can be used to assist walking by a minor patient, or for ankle rehabilitation. However, it is not suitable for use in patients with severe stroke. Mohammeda, S. performed nonlinear control of a knee joint robot consisting of a thigh link and a calf link. The robot can fix the thigh and the calf using an adhesive cloth and then rehabilitate the knee joint while patient sits on a chair. Asbeck, A. T. designed a robot for hip rehabilitation. The robot consists of a device that can rotate a pulley with a line wound around it and a device that winds a band around the thigh. The robot can rotate accurately in the direction of pulling of the string and can also rotate the hip joint backward while sensing the force with the force measuring sensor. However, it cannot rotate in the opposite direction. The robot already developed is able to treat only the ankle joint, only the knee joint, and both the knee joint and the hip joint, while walking on a patient who can walk. However, severe stroke patients lie on the bed and the hip, knee joint and ankle joint cannot be treated at the same time by the robots that were developed.

In this study, all the links of the designed rehabilitation robot are constrained to each other, and the constrained robot is accompanied by errors such as link length and installation angle due to machining errors and assembly errors. Therefore, it is difficult to control the angle of rotation of the motor by the inverse kinematic analysis. Consequently, it is difficult to precisely control the robot presented in this paper, because of position control. Due to this, we intend to perform force control for the basic operation. In order to perform force control, a force sensor must be attached to the link of the robot. Nagai, K. al. developed the multi-axial force sensors until now, which measure the force in various directions, mainly include a four-axis force sensor and a six-axis force sensor. These are bulky, difficult to attach, and do not fit the rated capacity, making them unsuitable for rehabilitation robots. Therefore, the force sensors of the rehabilitation robot are designed and manufactured on the links of the robot.

In this paper, we designed a special lower limb rehabilitation robot that can treat the hip joint, knee joint, and ankle joint while patient is lying on the bed. For this purpose, the body of the lower limb rehabilitation robot was designed and fabricated, and tests involving hip joint and knee joint bending exercises were performed to confirm the operation of the lower limb rehabilitation robot.

2 DESIGN AND MANUFACTURE OF THE LOWER LIMB REHABILITATION ROBOT

2.1 Principle of Lower Limb Rehabilitation Robot

Figure 1 shows the principle of the lower limb rehabilitation robot, which consists of a body, a thigh link mechanism, a calf link mechanism, a foot mechanism. The body consisted of a bed, LM Guide 1, LM Guide 2, and a Hip Motor. The thigh link mechanism consisted of a linear motion mechanism 1, a joint 1, and a link 1 with a two-axis force sensor. The calf link mechanism consisted of a linear motion mechanism 2, a joint 2, and a link 2 with a two-axis force sensor. The foot mechanism consisted of a foot plate, an uniaxial force sensor, and link 4. When rehabilitating the hip, knee, and ankle joints of leg patients, the patient is first placed on the bed in, and the patient's thigh, calf, and foot are fixed to each part of the robot using Velcro, as shown in Figure 1. Second, when the hip joint bending exercise is performed, and the linear motion mechanism 1 is driven, the thigh link mechanism

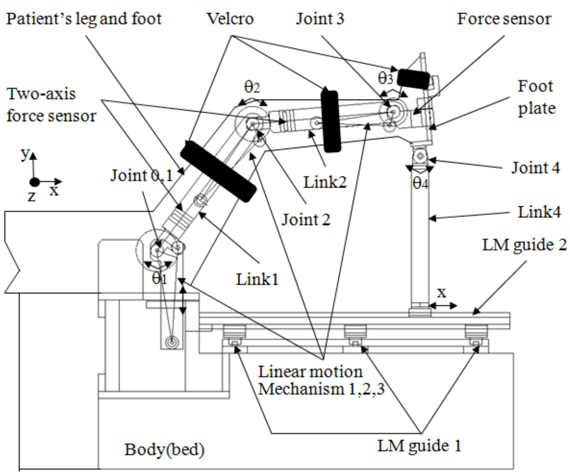


Figure 1: Principle of lower limb rehabilitation robot.

makes joint 1 rotate forward and backward at a rotational angle θ_1, and, as a result, each joint angle θ_2, θ_4 is rotated, and link 4 slides in the forward and backward directions along the LM guide 2.

Third, when the bending knee joint exercise is performed and the linear motion mechanism 2 is driven, the calf link mechanism rotates forward and backward with the rotation angle θ_2 of joint 2. As a result, each joint angle θ_1, θ_4 is rotated, and link 4 slides in the forward and backward directions along the LM guide 2. Fourth, in the bending motion of the ankle joint, and the linear motion mechanism 3 is driven, the joint 3 rotates forward and backward at an angle of rotation θ_3. As a result, each joint angle is rotated, and link 4 slides in the forward and backward directions along the LM guide 2. As described above, the lower limb rehabilitation robot rotates and slides with all links restrained. Such a robot often fails to operate smoothly due to a fitting phenomenon originated from a precision machining error of each mechanism, as well as from a control error of an assembly error linear motion mechanism. To solve this problem, force sensors Fy and Fz, which can measure the force in the y and z directions, respectively, were designed and fabricated on link 1 and link 2, and an uniaxial force sensor was designed and fabricated on link 3 (foot plate). In each rehabilitation exercise, the linear motion mechanisms 1, 2 and 3 are controlled based on the Fy force values of link 1, link 2, and link 3, respectively, so that the links and mechanisms of the robot are smoothly operated.

2.2 Kinematics Analysis of Rehabilitation Robot

The rehabilitation exercise using the lower limb rehabilitation robot should be performed on the hip joint and on the knee joint simultaneously, and should be performed separately on the ankle joint. Figure 2 shows a schematic diagram of the kinematic analysis for the rehabilitation exercise using the lower limb rehabilitation robot. Figure 2 (a) shows a schematic diagram for the hip and knee joints rehabilitation exercise. For this exercise, the ankle joint shown in Figure 1 (joint 3, θ_3) should be fixed, so that it is not allowed to move. Link 4 is reciprocated in the x-axis, and the actual rotational movement is only in joint 1 and joint 2. Therefore, the rotating joints of the lower limb rehabilitation robot for hip and knee joints rehabilitation movements are the hip joints (θ_1) and the knee joints (θ_2), and the joints of the lower limb rehabilitation robot for the ankle joint rehabilitation movements are the hip joints (θ_1) and the ankle joints (θ_3).

As the motion of each joint of the lower limb rehabilitation robot is similar in the two rehabilitation exercises, the forward kinematic and the inverse kinematic formulas for the hip joint and knee joint rehabilitation exercise can also be used on the ankle joint rehabilitation exercise. In other words, the equations for the knee joint rehabilitation exercise can be changed by replacing θ_2 with θ_3 in the equation for the hip and knee joint rehabilitation exercise.

The forward kinematic equation for hip and knee joints rehabilitation can be expressed as a matrix of orientation and position, and the equation can be written as:

$$T_3^0 = \begin{bmatrix} \cos(\theta_1-\theta_2) & -\sin(\theta_1-\theta_2) & 0 & l_2\cos(\theta_1-\theta_2)+l_1\cos(\theta_1) \\ \sin(\theta_1-\theta_2) & \cos(\theta_1-\theta_2) & 0 & l_2\sin(\theta_1-\theta_2)+l_1\sin(\theta_1) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

The forward kinematic equations for x and y of joint 4 are as follows:

$$\begin{aligned} x &= l_2\cos(\theta_1-\theta_2)+l_1\cos(\theta_1) \\ y &= l_2\sin(\theta_1-\theta_2)+l_1\sin(\theta_1) \end{aligned} \tag{2}$$

To obtain the inverse kinematic equations θ_1 and θ_2, we can use $\cos\theta_2$ and $\sin\theta_2$ using x and y in Eq. (1). The inverse kinematic equations of $\cos\theta_2$ and $\sin\theta_2$ are as follows:

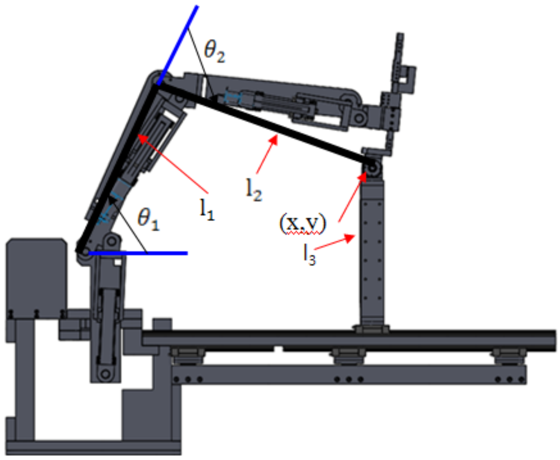
$$\begin{aligned} \cos\theta_2 &= \frac{x^2+y^2-l_1^2+l_2^2}{2l_1l_2} \\ \sin\theta_2 &= -\sqrt{1-\cos^2\theta_2} \end{aligned} \tag{3}$$

In addition, $\cos\theta_1$ and $\sin\theta_1$ can be derived by using x and y in eq. (1). They are as follows:

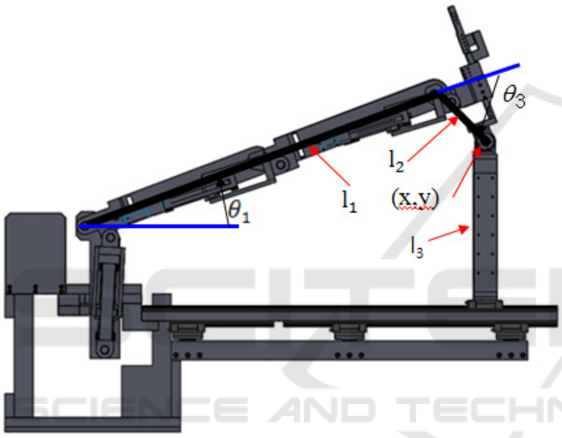
$$\begin{aligned} \cos\theta_1 &= \frac{(l_1+l_2\cos\theta_2)x+l_2\sin\theta_2 y}{(l_1+l_2\cos\theta_2)^2+(l_2\sin\theta_2)^2} \\ \sin\theta_1 &= \frac{(l_1+l_2\cos\theta_2)y-l_2\sin\theta_2 x}{(l_1+l_2\cos\theta_2)^2+(l_2\sin\theta_2)^2} \end{aligned} \tag{4}$$

The inverse kinematic equations θ_1 and θ_2 are as follows:

$$\begin{aligned} \theta_2 &= \tan^{-1}\frac{\sin\theta_2}{\cos\theta_2} \\ \theta_1 &= \tan^{-1}\frac{\sin\theta_1}{\cos\theta_1} \end{aligned} \tag{5}$$

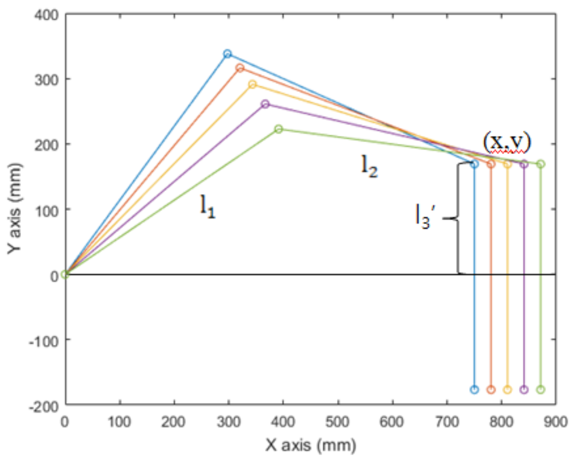


(a) Hip and knee joint rehabilitation exercise.

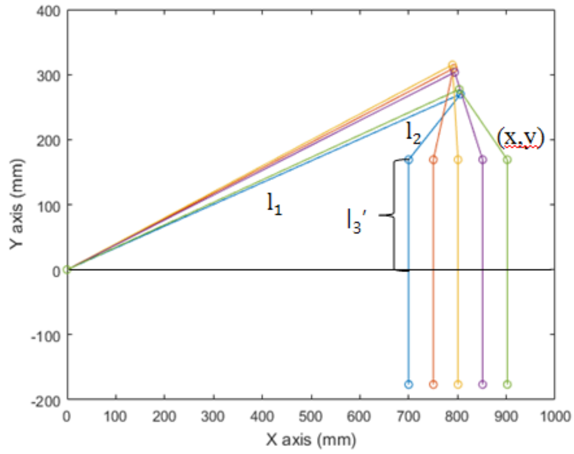


(b) Ankle joint rehabilitation exercise.

Figure 2: Schematic of forward kinematics and inverse kinematics.



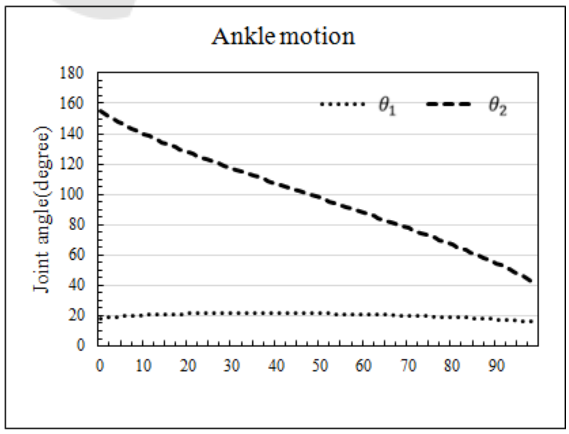
(a) Hip and knee joint rehabilitation exercise.



(b) Ankle joint rehabilitation exercise.

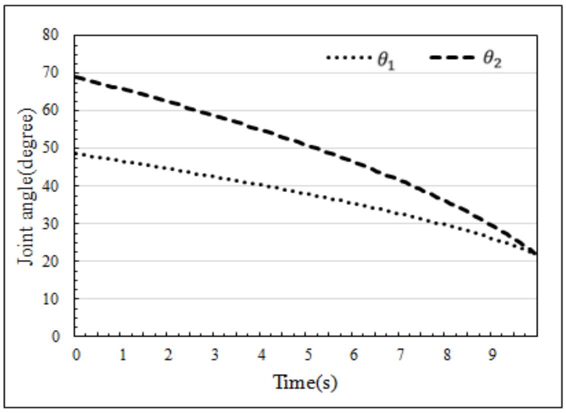
Figure 3: Graph of kinematic analysis.

Figure 3 (a) shows the results of the simulation using the forward kinematic equation (2) for the hip and knee joint rehabilitation exercise. The length of each link, $l_1 = 450mm$, $l_2 = 483mm$, and $l_3 = 169mm$ was obtained by substituting y=169 mm, rotation angle θ_1 (48.64268°~29.64264°), and knee joint rotation angle θ_2 (69.0903°~36.01507°) into the forward kinematic equation (2). Figure 3 (b) shows the results of the simulation using the forward kinematic equation (2) for the ankle joint rehabilitation exercise. The length of each link, $l_1 = 850mm$, $l_2 = 146mm$, and $l_3 = 169mm$ was obtained by substituting y=169 mm, rotation angle θ_1 (18.4956°~21.7367°), and knee joint rotation angle θ_2 (155.0053°~66.7051°) into the forward



(a) Hip and knee joint rehabilitation exercise.

Figure 4: Graph of inverse kinematic analysis.



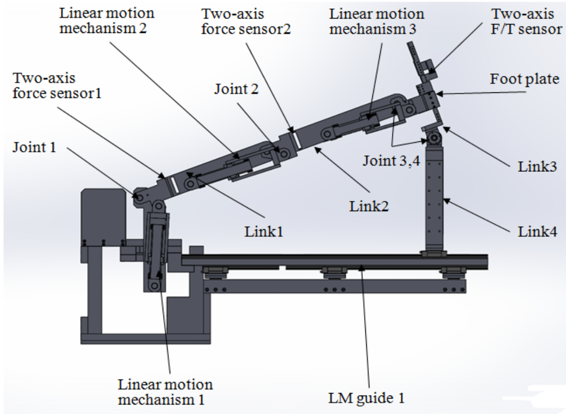
(b) Ankle joint rehabilitation exercise.

Figure 4: Graph of inverse kinematic analysis (cont.).

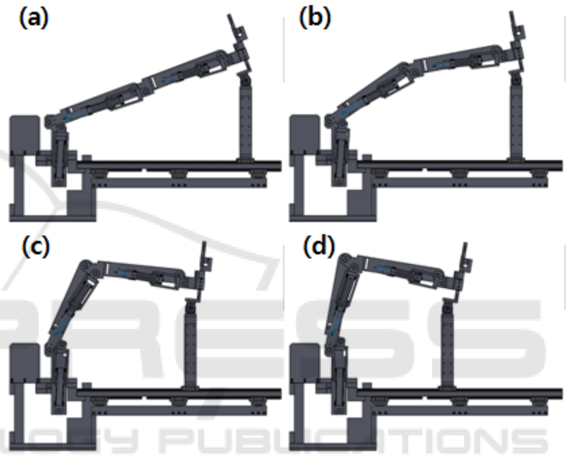
kinematic equation (2). Figure 4 (a) is a graph plotted using the inverse kinematic equation (5) for the hip and knee joint rehabilitation, and Figure 4 (b) is a graph plotted using the inverse kinematic equation (5) for ankle joint rehabilitation. In the rehabilitation robot, three links are constrained, and as the size of y is vertically constant, θ_1 and θ_2 are obtained according to the change of x. Therefore, x, θ_1, and θ_2 of Figure 3 and Figure 4 are related with each other.

2.3 Design and Simulation of Lower Limb Rehabilitation Robot

Figure 7 shows the simulation of the lower limb rehabilitation robot: Figure 7 (a) shows the state of the lower limb rehabilitation robot, and Figure 7 (b) shows the simulation of the mechanism for hip joint exercise and knee joint exercise. Link 1 can be bent over 80° in relation to the horizontal plane, and link 2 can be bent over 90° in relation to the central line of link 1. Rotating the hip joint clockwise and the knee joint counter-clockwise first pushes the linear motion mechanism 1 and then rotates link 1 clockwise about joint 1. At the same time, the linear motion mechanism 2 is pulled to rotate link 2 counter-clockwise about the joint 2. Thereafter, joint 4 rotates freely and link 4 moves forward along LM guide 1. When the hip joint is rotated counter-clockwise and the knee joint is rotated clockwise, the operation is reversed. Link 4 is designed to adjust the height from 340 mm to 500 mm in relation to the surface of the bed. This is because the patient feels comfortable at about 340 mm from the bed surface during the ankle joint bending exercise and during the knee joint bending exercise.



(a) Lower limb rehabilitation robot.



(b) Motion of hip joint exercise and knee joint bending exercise.

Figure 5: Simulation of lower limb rehabilitation robot.

2.4 Manufacture of Lower Limb Rehabilitation Robot

Figure 7 shows the manufactured lower limb rehabilitation robot, which consists of two controllers, a left-leg robot mechanism, and a right-leg robot mechanism. The controller unit consists of two controllers, one for the left leg robot mechanism and the other for the right leg robot mechanism. The purpose of using two controllers is to receive data from two force sensors on each robotic mechanism leg, and to operate quickly when controlling four motors. The lower limb rehabilitation robot consists of a body, a thigh linkage, a calf linkage, and a footplate.

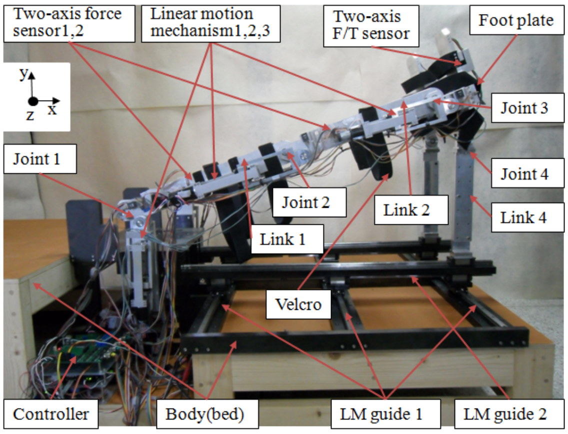


Figure 6: Fabricated lower limb rehabilitation robot for leg patient.

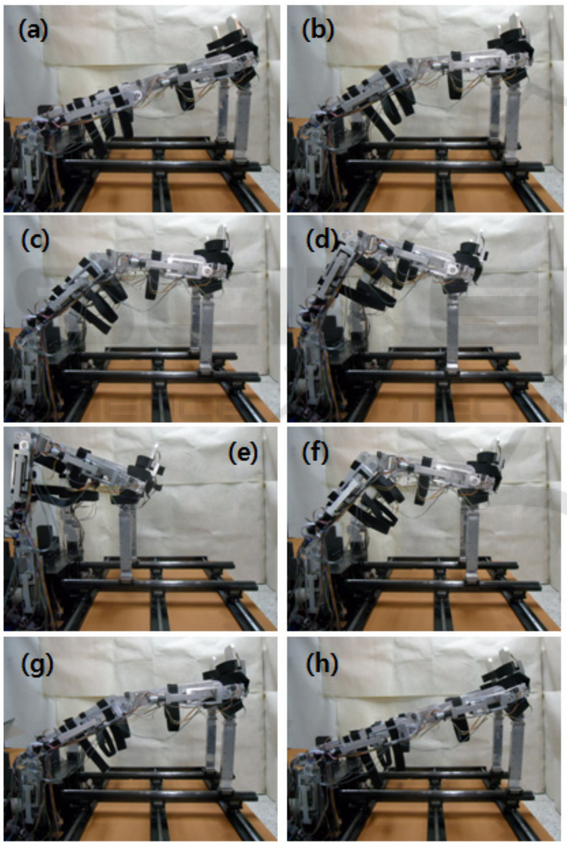


Figure 7: Hip and knee bending exercises of the lower limb rehabilitation robot.

The body is a bed that patient can be laid, LMM 1 is used to rotate the thigh link up and down, LM guide 1 is used when the entire leg moves left and right during the hip joint exercise, and LM guide 2 is used to move forward and backward during the knee joint bending exercise. The thigh link mechanism includes a LMM 2, that is used to rotate the calf link up and down, a joint 1 for rotating the thigh link, a Fy force sensor , a Fz force sensor (two-axis force sensor) 1. The calf link mechanism includes a LMM 3, that is used to rotate the ankle mechanism, a joint 2 for rotating the calf link, and a link 2, which is produced by directly processing the Fy force sensor and the Fz force sensor (two-axis force sensor 2).

The foot mechanism consisted of a foot plate for fixing the foot, and link 3 and link 4 for rotating the ankle during the ankle bending exercise. The operation of the lower limb rehabilitation robot is such that when LMM 1 is pulled, link 1 rotates in the clockwise direction based on the joint 1 and when LMM 1 is pushed in the opposite direction, link 1 rotates in the counter-clockwise direction. When LMM 2 is pulled by rotating the motor, link 2 rotates based on the joint 2, and, at the same time, link 1 rotates in the counter-clockwise direction. When LMM 3 is pulled by rotating the motor, link 2 rotates in the clockwise direction, based on the joint 3, and, at the same time, link 1 rotates in the counter-clockwise direction. When pushed in the opposite direction, each link rotates in the opposite direction. At this time, joint 3 freely rotates clockwise and counter-clockwise, according to the situation, so that link 4 moves back and forth along LM guide 1.

Figure 7 shows photographs of the hip and knee joint bending exercise of the lower limb rehabilitation robot performed without a person. It starts from the initial state (Figure 7 (a)), completes the bending (Figure 7 (b)~(e)), and returns to the initial state (Figure 7 (f)~(g)).

3 CONCLUSIONS

In this study, we designed a lower limb rehabilitation robot that can treat the hip joint, knee joint, and ankle joint while the patient is lying on the bed. We controlled the robot by force control. We designed and manufactured the lower limb rehabilitation robot for stroke patients. The robot uses the linear motion mechanisms, the links. The hip and knee bending exercises were performed normally. To verify the stability of the system, with the goal of applying the developed rehabilitation robot, the exercise was performed stably. Therefore, it can be concluded that the lower limb rehabilitation robot designed in this study can perform the hip and knee bending exercise, with leg patients. In future studies, the designed lower limb rehabilitation robot will be used to perform the hip and knee bending exercise with leg patients.

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