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Study on the transient response of lower limb rehabilitation actuator using the pneumatic cylinder

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Abstract

A lower limb rehabilitation device was designed using the compressed air cylinder in order to answer the particular request in Viet Nam. This paper is presenting the results of a study of the device response. Dynamic equation of the actuator and equations of the proportional valve have been established. The relationship between the input signal and the output signal of the actuator was derived. Inventor® software was used to design the mechanical structure of the device. Matlab® software was used to calculate the parameters values of the PID controller by simulating the response of the actuator. The results show that the response time of both knee drive and hip drive mechanisms are 8 seconds while the overshoot of both knee drive and hip drive mechanisms are 1%. Moreover, the starting torque of the knee drive mechanism is 17 Nm, and the starting torque of the hip drive mechanism is 35 Nm. The simulation results show that the PID controller gives a fast response time and a low overshoot.

Keywords: lower limb rehabilitation; hip and knee joint; pneumatic cylinder; PID controller.

I. Introduction

At present, the mechanical engineering industry contributes greatly to the development of society. The products of the mechanical industry are diversified and rich in various fields. In the biomedical field, there are also many products that help the patients and physicians in treating the disease [1]. In the treatment of herniated disc patients with spinal stretch bed, many authors are interested in research, design, manufacture and have achieved certain success [2][3][4].

Some studies have applied robots to support rehabilitation for patients with underlying limb disease, helping patients to shorten treatment and helping doctors to monitor the course of treatment for patients [5]. However, in the treatment of patients with hemiplegia due to a cerebrovascular accident in *Viet Nam*, at present, there is no automatic device that supports the treatment of equipment for purely mechanical treatment. Overseas studies have also been available for the treatment of patients and have also been successful [6][7].

Today, compressed air is widely used in industry as well as in social life. The main advantages of compressed air include large capacity, low cost, and ability to be used in harsh environments. These advantages can make the actuator extremely useful in the applications of rehabilitation techniques for stroke or knee pain patients [8][9][10]. The use of compressed air to drive the lower limb rehabilitation device has also been investigated. Previous research had used compressed air to control the actuators and produce very promising results [11][12][13].

The request for equipment to support the treatment of patients with hemiplegia caused by accident has been approved by the researchers. This paper has studied the response of an exercise support structure, which evaluates the feasibility of the structure before practical modeling is expected to contribute to patient treatment

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support. This paper's aim is studying the use of pneumatic cylinders to drive rehabilitation equipment for the hip and knee joint. The advantage of this solution is to build passive exercises for patients with levels 1 to 3 and active impedance exercises for patients with muscle levels of 3 to 5. Combining two active and passive exercises will help the patient shorten the joints rehabilitation time.

II. Materials and methods

A. The lower limb research model

Analysis of the lower limb joints including hip joints, knee joints, and ankle joints shows the total degrees of freedom of the lower limb are 9, as shown in Figure 1 [14]. However, this paper introduces the degrees of hip and knee arthritis that are commonly used in rehabilitation exercises in hospitals and centers nationwide, as illustrated in Figure 2 and Figure 3. Hip and knee joints are reduced to a two-degree system, and the model is shown in Figure 4.

B. Model of lower limb rehabilitation actuator

The functional lower limb rehabilitation actuator model is illustrated in Figure 5. Its structure consists of two stages with two degrees of freedom around the z axis. Stitches are driven by pneumatic cylinders, controlling the cylinders through pneumatic servo valves.

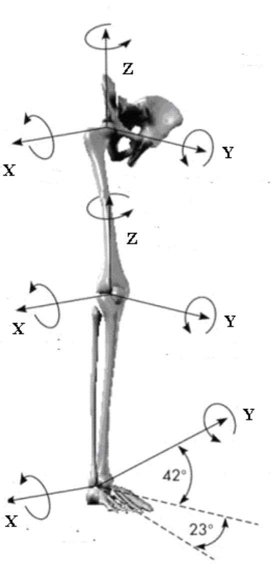

Figure 1. The degrees of freedom of the lower limb

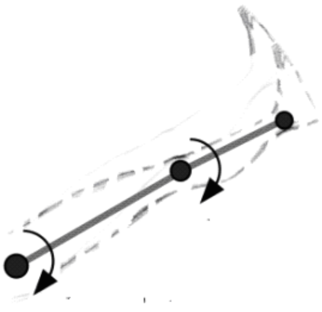

Figure 2. Hip and knee joints in extension state

C. The dynamic equations of the actuator

The dynamic equation of the actuator is expressed by equation (1) and (2).

$$D(q)\ddot{q}+H(q,\dot{q})+G(q)=\tau \quad (1)$$

$$\tau = \tau_n + \tau_{cc} + \tau_{ms} \quad (2)$$

where τ_n is the torque caused by the hip, and thigh muscles τ_{cc} and τ_{ms} are the friction torque components at the robotic stage.

Because torque components have negligible effects, both components can be ignored and only observing the torque generated by the mechanism. Inertial matrix, centrifugal force and Coriolis matrix, and gravity force matrix are given as follow.

1) Inertial matrix $D(q)$:

$$D_{11} = \frac{1}{3}m_1 l_1^2 + m_2\left(l_1^2 + \frac{1}{3}l_2^2\right) + m_2 l_1 l_2 C\theta_2$$

$$D_{12} = D_{21} = \frac{1}{3}m_2 l_2^2 + m_2 l_1^2 + m_2 l_1 l_2 C\theta_2$$

$$D_{22} = \frac{1}{3}m_2 l_2^2$$

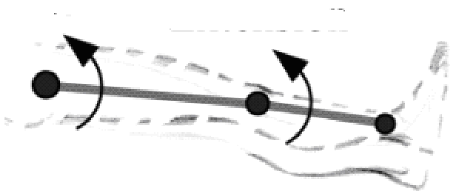

Figure 3. Hip and knee joints in the contraction state

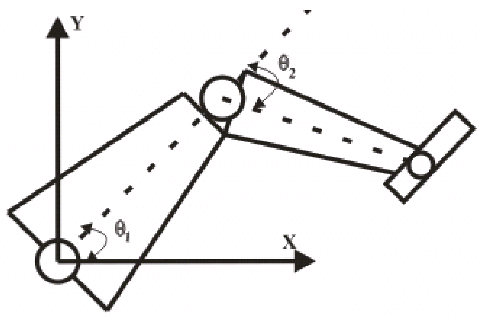

Figure 4. Lower limb model

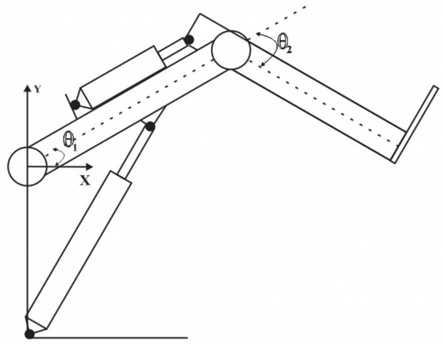

Figure 5. Model of rehabilitation lower limb actuator

2) Centrifugal force and Coriolis matrix:

$$H = \begin{bmatrix} -\frac{1}{2}m_2l_1l_2\dot{\theta}_2^2S\theta_2 - m_2l_1l_2\dot{\theta}_1\dot{\theta}_2S\theta_2 \\ \frac{1}{2}m_2l_1l_2\dot{\theta}_1^2S\theta_2 \end{bmatrix}$$

3) Gravity force matrix:

$$G_1 = \frac{1}{2}m_1gl_1C\theta_1 + \frac{1}{2}m_2gl_1C(\theta_1+\theta_2) + m_2gl_1C\theta_1$$

$$G_2 = \frac{1}{2}m_2gl_2C(\theta_1+\theta_2)$$

From the above matrix D, H, G, the dynamical equation (1) becomes:

$$\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix} = \begin{bmatrix} \frac{1}{3}m_1l_1^2 + m_2\left(l_1^2 + \frac{1}{3}l_2^2 + l_1l_2C\theta_2\right) & m_2\left(l_1^2 + \frac{1}{3}l_2^2 + l_1l_2C\theta_2\right) \\ m_2\left(l_1^2 + \frac{1}{3}l_2^2\right) + m_2l_1l_2C\theta_2 & \frac{1}{3}l_2^2m_2 \end{bmatrix}\begin{bmatrix}\ddot{\theta}_1\\ \ddot{\theta}_2\end{bmatrix} + \begin{bmatrix} -\frac{1}{2}m_2l_1l_2\theta_2^2S\theta_2 - m_2l_1l_2\dot{\theta}_1\dot{\theta}_2S\theta_2 \\ \frac{1}{2}m_2l_1l_2\theta_1^2S\theta_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{2}m_1gl_1C\theta_1 + \frac{1}{2}m_2gl_1C(\theta_1+\theta_2) + m_2gl_1C\theta_1 \\ \frac{1}{2}m_2gl_2C(\theta_1+\theta_2) \end{bmatrix} \quad (3)$$

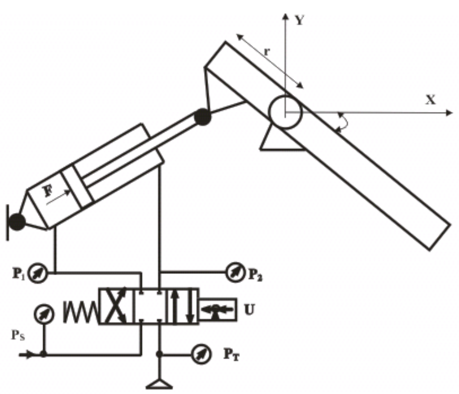

Figure 6. Model of control at each joint

D. Design of controller for the actuator

Figure 6 shows a model of control mechanism at each joint. At each torque joint, the piston's impact force in the cylinder creates the following torque equation:

$$\tau = \begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix} = F.r.\sin\theta \quad (4)$$

where F is the force generated by the pressure in the cylinders affecting the piston area, r is the rotational radius of the link.

Force equation in the cylinder is given by (5).

$$F = \Delta p.A \quad (5)$$

where A is the area of the piston. The valve pressure dependent gas pressure is given by (6).

$$p = K_v.u \quad (6)$$

From equations (3), (4), (5), and estimating point θ, the equation between torque and voltage can be found as follow [15].

$$\tau = \begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix} = K_v.r.A.\theta.u \quad (7)$$

PID controller was used to examine and evaluate the response of the structure as shown in Figure 7. Furthermore, equation (1) has been transformed into the equation (8).

$$\ddot{q} = \frac{1}{D(q)}\left[-H(q,\dot{q}) - G(q)\right] + \frac{1}{D(q)}\tau \quad (8)$$

The PID controller is described as follow:

$$u = K_pe + K_I\int_0^t edt + K_D\dot{e} \quad (9)$$

In controlling the actuator, it is necessary to provide the valve opening and closing pressure, from which the pneumatic pressure acts on the piston to produce the torque that controls rotates the rotation at each joint.

The rotation angle of the stages are as follows:

$$\begin{cases} e_1 = \theta_{1d} - \theta_1 \\ e_2 = \theta_{2d} - \theta_2 \end{cases}$$

where θ_{1d}, θ_{2d} are the angles set values of joints 1 and 2. Additionally, denoted control voltage can be found as:

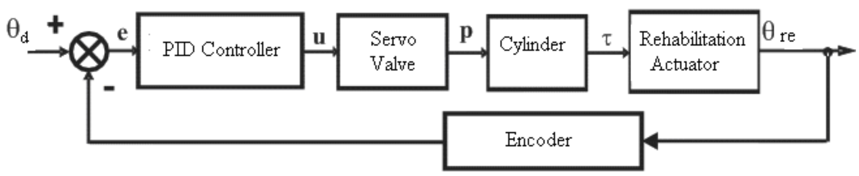

Figure 7. Control chart for the actuator

$$u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (10)$$

Equation (11) can be found by substituting equation (9) into equation (10):

$$\begin{cases} u_1 = K_{P_1}\left(\theta_{1d} - \theta_1\right) + K_{I_1}\int_0^t e_1 dt - K_{D_1}\dot{\theta}_1 \\ u_2 = K_{P_2}\left(\theta_{2d} - \theta_2\right) + K_{I_2}\int_0^t e_2 dt - K_{D_2}\dot{\theta}_2 \end{cases} \quad (11)$$

The define state variable as follows :

$$\begin{cases} x_1 = \int_0^t e_1 dt \Rightarrow \dot{x}_1 = \theta_{1d} - \theta_1 \\ x_2 = \int_0^t e_2 dt \Rightarrow \dot{x}_2 = \theta_{2d} - \theta_2 \end{cases} \quad (12)$$

Equation (13) can be made by substituting equation (12) into equation (10):

$$\begin{cases} u_1 = K_{P_1}\dot{x}_1 + K_{I_1}x_1 - K_{D_1}\dot{\theta}_1 \\ u_2 = K_{P_2}\dot{x}_2 + K_{I_2}x_2 - K_{D_2}\dot{\theta}_2 \end{cases} \quad (13)$$

Moreover, substituting equation (12) into equation (6) can emerge equation (14):

$$\tau = \begin{bmatrix} K_v.r_1.A_1.\theta_1.\left(K_{P_1}\dot{x}_1 + K_{I_1}x_1 - K_{D_1}\dot{\theta}_1\right) \\ K_v.r_2.A_2.\theta_2.\left(K_{P_2}\dot{x}_2 + K_{I_2}x_2 - K_{D_2}\dot{\theta}_2\right) \end{bmatrix} \quad (14)$$

Combining equations (8) and (14) will generate this following equation

$$\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} = \frac{1}{D(q)}\left[-H(q,\dot{q}) - G(g)\right] + \frac{1}{D(q)}\begin{bmatrix} K_v.r_1.A_1.\theta_1.\left(K_{P_1}\dot{x}_1 + K_{I_1}x_1 - K_{D_1}\dot{\theta}_1\right) \\ K_v.r_2.A_2.\theta_2.\left(K_{P_2}\dot{x}_2 + K_{I_2}x_2 - K_{D_2}\dot{\theta}_2\right) \end{bmatrix}$$

III. Results and discussions

A. Device 3D model

After analyzing the dynamics of the lower limb rehabilitation actuator, Inventor® software was used to design mechanical structure for the device. A 3D drawing of the device is shown in Figure 8. The device supports the patient to practice both feet. The patient is able to sit and lie down for training. At the extension and Flexion exercise, the limit angle of the knee is from 0° to 135°. For the hip joint, when the patient is in the sitting position, the limit angle is 0° to 60° in the extension exercise. When the patient is lying down, the limit angle is 0° to 110° at the extension and Flexion exercise.

B. Simulation results

This study was using Simulink® tool in Matlab® to simulate the dynamics of the actuator. The parameter values are selected as follows.

$A_1 = 0.00524\ (m^2)$;

$A_2 = 0.002826\ (m^2)$;

$l_1 = 0.5\ (m)$;

$l_2 = 0.45\ (m)$;

$p = 4.105\ (N/m^2)$;

$m_1 = 13\ (kg)$; $m_2 = 10\ (kg)$;

$K_v = 0,0283\ (N/m^2.V)$;

$$q_0 = \begin{bmatrix} \theta_{01} \\ \theta_{02} \end{bmatrix} = \begin{bmatrix} 0 \\ -\frac{\pi}{2} \end{bmatrix}; \quad q_d = \begin{bmatrix} \theta_{1d} \\ \theta_{2d} \end{bmatrix} = \begin{bmatrix} \frac{\pi}{4} \\ -\frac{\pi}{4} \end{bmatrix}$$

$K_P = 50$;

$K_I = 15$;

$K_D = 5$;

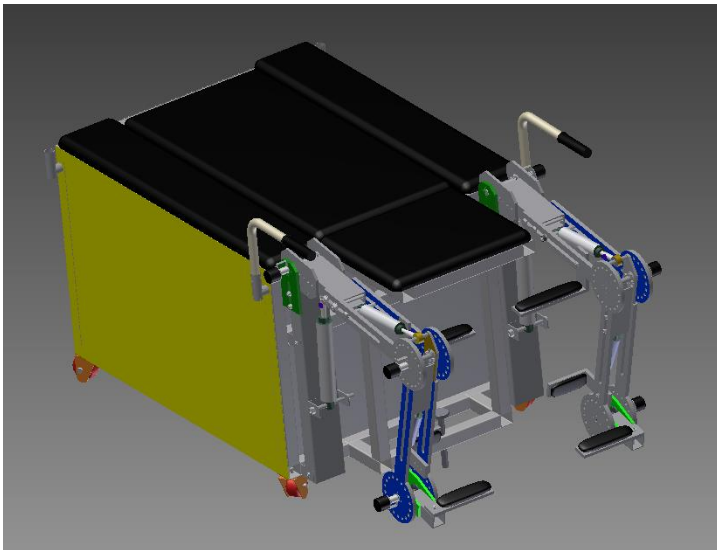

Figure 8. 3D model of the device

Figures 9 to Figure 14 show simulated responses of the actuator. Analysis and discussion of the simulation results are described as follows. In Flexion exercises, the initial values and set point were set using this configuration: the knee joint initial angle was 90°, and the angle set point was 45°, while the hip initial angle was 0° and angle set point was 45°. The following results are obtained:

1) The response time of the knee drive mechanism is 8 seconds, and the response time of the hip drive mechanism is 8 seconds.
2) Overshoot of the knee drive mechanism is 1%, and overshoot of the hip drive mechanism is 1%.
3) The starting torque of the knee drive mechanism is 17 Nm, and the starting torque of the hip drive mechanism is 35 Nm.

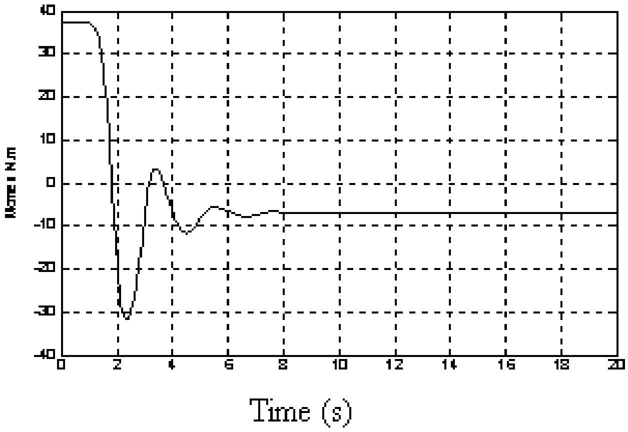

Figure 9. Torque response of joint 1

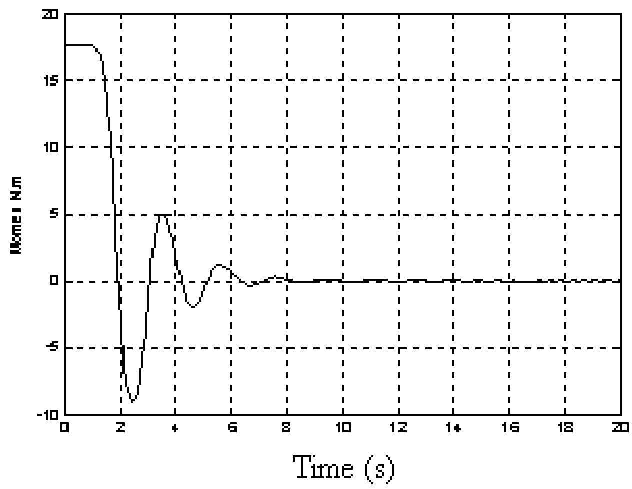

Figure 10. Torque response of joint 2

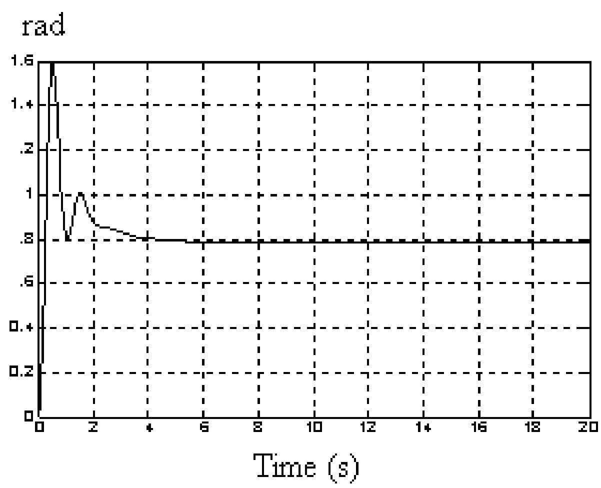

Figure 11. Angle response of joint 1

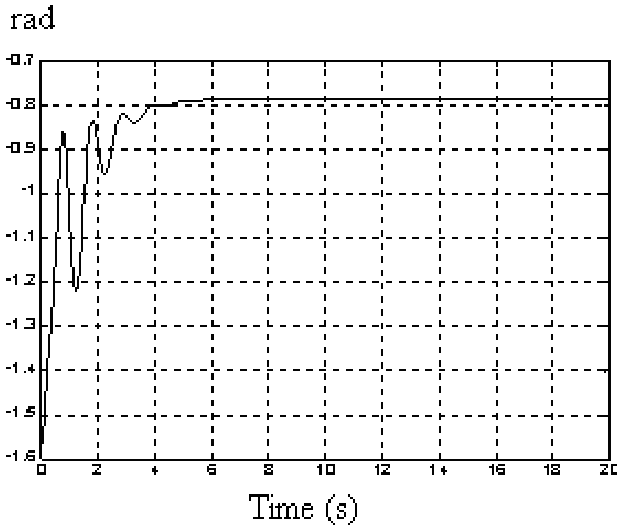

Figure 12. Angle response of joint 2

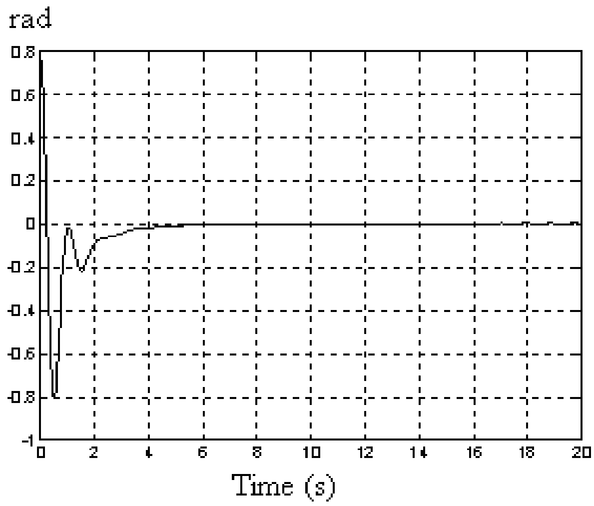

Figure 13. Error angle response of joint 1

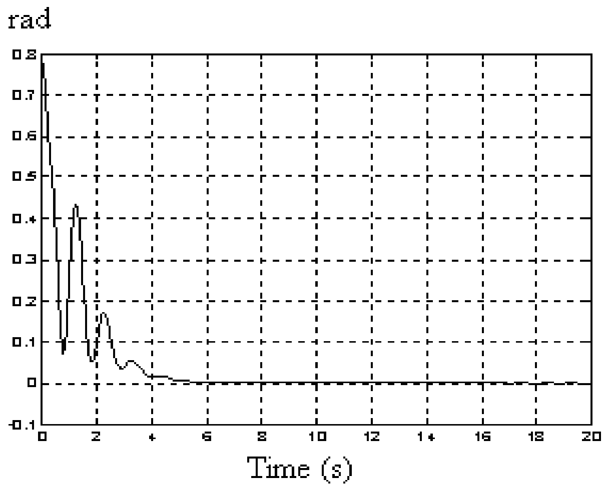

Figure 14. Error angle response of joint 2

From the simulation results of the actuator at Flexion exercise for knee and hip, the error is zero and the overshoot is low. However, the response time is long (approximately 6 to 8 seconds), and the starting torque is quite large. These results are due to the actuator and the human load are quite large. Therefore, the high level of torque is very much required to drive the actuator. From this result, the application of pneumatic cylinder can be used for practical experiments.

IV. Conclusion

In this paper, a dynamic equation for the actuators of a lower limb rehabilitation device was derived, and their responses were simulated using Matlab®. In a Flexion exercise simulation, initial values, and set points were set as: the knee joint initial angle was 90° and its angle setpoint was 45°, while the hip initial angle was 0° and its angle set point was 45°. The results show that the response time for both knee drive and hip drive mechanisms are 8 seconds while the overshoot of both knee drive and hip drive mechanisms are 1%. Moreover, the starting torque of the knee drive mechanism is 17 Nm, and the starting torque of the hip drive mechanism is 35 Nm. The simulation results show that the response is consistent throughout the training of the patient. In the next step, it would be best to examine the empirical model in order to evaluate the results obtained in theoretical simulation.

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