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ORIGINAL ARTICLE

Research control for ankle joint rehabilitation device

D.M. Duc[1], P.D. Phuoc[2], T.X. Tuy[2]

[1] Faculty of Technology and Engineering, Universiti Pham Van Dong , 509 Phan Dinh Phung , Quang Ngai, Vietnam
Phone: +084905423314
[2] Faculty of Mechanical Engineering, University of Da Nang, Da Nang, 084, Vietnam

ABSTRACT – The ankle is one of the joints that is often injured when playing sports or in daily activities. Improper handling due to lack of knowledge about the ankles causes these injuries to last long, cause disability and affect our daily activities. Rehabilitation treatment is important for the purpose of maintaining and improving the mobility of joints. This paper, presenting the experimental results of the training device to rehabilitate ankle joints for human in dorsiflexion/plantarflexion exercises. The PD controller has been applied and controlled device. During the training, the angle of the ankle joint is monitored by the Arduino IDE software. The error of the set angle and the experimental angle is 1^0. The device manufactured in the workshop of Pham Van Dong university base on aluminum material. Experiments were conducted on both without load mode and with human mode. For human safety, besides the program containing the Arduino Mega controller, the device has mechanical brakes and an emergency button. The device's tracking performance was determined by comparing the input and output angular position of the device.

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INTRODUCTION

The ankle joint is the part that bears the entire body weight. Therefore, daily activities such as playing football and volleyball, exercising vigorously in the legs are capable of damaging joints, causing symptoms such as swelling, pain, red inflammation. The pain often appears suddenly and makes the person surprised and uncomfortable. In particular, for patients with arthritis, the ankle will have many injuries. Ankylosing spondylitis is mainly seen in middle-aged people over 40 years old, especially after 60 years of age if there is no timely treatment, it will cause bursitis, to the quality of life of the patients [1].

In addition, patients with stroke also affected ankles due to sequelae hemiplegia. Hemiplegia is a condition in which one side of the body is weak, right or left side numbness depends on the area of the brain that has been damaged by a stroke or other causes. Injury to the left brain will cause paralysis of the right side and vice versa. The paralyzed party will have weaker movements than the other party or may not even move [2]. After accidents and illnesses, rehabilitation therapy plays a very important role. Firstly, maintaining and improving the range of motion (activity) of the joints, strengthening the muscles around arthritis help them support and protect the joints better. Secondly, strengthening the stamina and joints of the sick person. Thirdly, improve the functional activities of the patient and reduce fatigue, improve fitness, lose weight, help people sleep better and feel better. Finally, especially early restoration of motor functions for patients to walk and normal activities [3, 4]. The exercises and the ranges of motion (ROM) for the human ankle are shown in Figure 1 and in Table 1. Figure 1 shows the three movements in the ankle that can be made: Abduction-Adduction, Plantarflexion-Dorsiflexion, Inversion-Eversion. There is a limit for each motion according to characteristics of human ankle construction which are measured in degrees (°). The ranges of each motion described are listed in Table 1 below according to Liu et al [5].

The researching automatic device supporting ankle rehabilitation for patients is interested in many authors around the world. These devices will help patients to perform exercises for the ankles according to the instructions of a doctor or technician. The research works are divided into two groups:

Group 1: Devices to help patients focus on exercising on the plantarflexion/dorsiflexion exercise for the ankle joint. The advantage of this group is that the device is a simple structure and easy to operate. The disadvantage is only training for 1- degree freedom of the ankle joint. The representative for group 1 is the research works of the following authors. Roy *et al*. designed the Ankle Bot ankle training device to rehabilitate the ankle joint function for patients with complications [6]. The mechanism is driven by two unidirectional brushless motors, the angle values are measured by two encoders, the driving torque is used by the motor current sensor. The torque created during folding is 23Nm/rad, the torque created during stretching is 15Nm/rad. The authors used PD controllers to control the device. The device was tested on 4 patients and resulted in a relationship between the torque and the angle of exercise for the normal 9-34 N.m/rad. Lin *et al.* have designed smart pastern training equipment to rehabilitate the ankle joint function for patients with complications [7]. The device is driven by an AC servo motor, the mechanism for folding and flexing ankle joints (1 degree of freedom), using a sensor that measures the torque between the motor and the rotary joint. Using a PCI card to control the device, the sensor measures the dynamic angle of an encoder. The authors use the Fuzzy + PD controller to

*CORRESPONDING AUTHOR | D.M. Duc | dmduc@pdu.edu.vn

control. Ding *et al.* have designed ankle training equipment to rehabilitate the ankle joint function for patients in sitting and standing states [8]. The device uses a DC motor to drive, force measurement and accelerometer sensors that are used to measure the required parameters. The author and his colleagues developed virtual reality software to create the orbital movement of the structure during the patient's training. The results of the group tested the position accuracy and the measured force value of the device through 6 volunteers with the result that right-footed practitioners gave better results. The results of the study will set the stage for the creation of a device for training the ankle joint for patients with complications, using a virtual environment to practice.

Group 2: Devices to help patients focus on exercise exercises for 3-degrees of freedom of the ankles. These devices often use parallel mechanisms to create a movement for the ankles. The advantage of this group is that they can do many exercises for the ankle joint. The disadvantage is that the structure is complex and the control is difficult to precise. The representative for group 2 is the research works of the following authors. Park et al have designed ankle training equipment to rehabilitate the ankle joint function for patients using pneumatic muscle actuator [9]. The authors designed a muscle-like device to drive people through 4 pneumatic mechanical mechanisms, controlled via an on-off valve, ankle movement following movements. Use strain gauge sensors and accelerometer sensors to determine the parameters that control the angle of the structure. The authors have experimented with different frequencies and different angular values, resulting in small errors when using 0.1Hz frequency. Zhou et al have designed ankle training equipment to practice ankle joint rehabilitation for patients with passive test results in 3 months of exercise [10]. The authors used an engine to drive the actuator, the torque measuring sensor was mounted on the motor shaft, in addition to the mechanical force value during the training, the group used EMG measuring sensor. Using the PID controller to control the actuator, using Labview software to monitor the patient's training parameters. The results have determined the value of the patient's torque during the exercise, building the torque adjustment levels of the device corresponding to the practice angle.

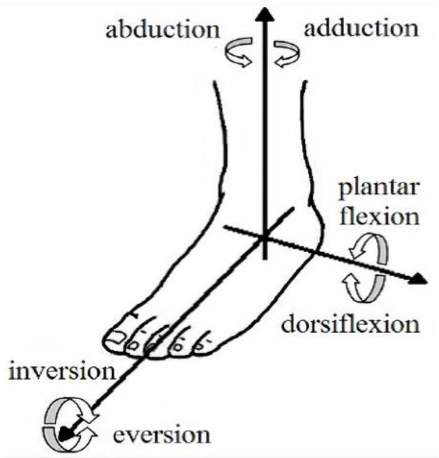

Figure 1. Foot –ankle movements

Table 1. Angle range of motion

Type of the motion	Range of the motion
Dorsiflexion	20.3^0 to 29.8^0
Plantarflexion	37.6^0 to 45.8^0
Inversion	14.5^0 to 22.0^0
Eversion	10.0^0 to 17.0^0
Abduction	15.4^0 to 25.9^0
Adduction	22.0^0 to 36.0^0

This paper presented the manufacturing and experimental results of the ankle joint rehabilitation exercise device using a linear actuator. it helps the patient to exercise the ankles in the dorsiflexion/plantarflexion exercise. Besides, it protects the patient when an emergency is triggered by the emergency push button and the motor's current sensor. The paper is organized as follows: Section 2 presents the setting of the transfer function and the simulation result of the device by Matlab Simulink software. Section 3 presents the results of device manufacturing and experimental. Section 4 presents the conclusions.

DYNAMICAL MODEL AND SIMULATION

Research Model

In this study, we used a linear actuator to drives the foot platform around the axis to make the patient's ankle joint in the dorsiflexion/plantarflexion exercise. Figure 2 show the research model of device which includes the linear actuator and the foot platform mechanism. In addition, the linear actuator transmits rotation to the working shaf through a rotational joint. The shaf will to drive the anke of human though foot platform. Angle of the working shaf is used as an angle sensor to measure the angle with amplitude is 0-80^0. The control voltage signal of linear actuator is proportional to the displacement of the linear actuator to drive the foot platform in the dorsiflexion/plantarflexion exercise.

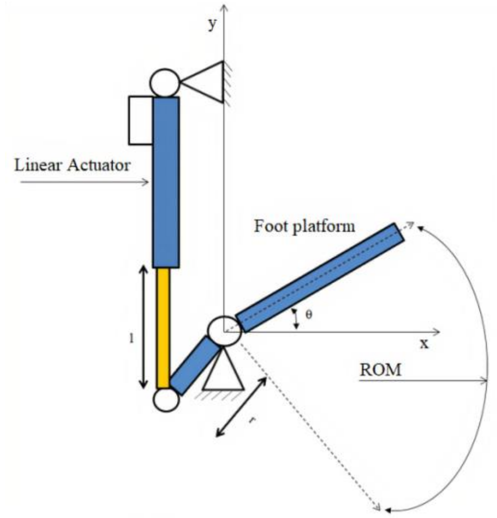

Figure 2. The ankle rehabilitation device

Mathematical Model

From the research model, the linear actuator is role important for create the movement of the foot platform. In order to find the relationship between the input signal (control voltage of the linear actuator) with the output signal (rolational angle of foot platform), we collapsed the rotary drive assembly to load mass on the linear actuator. The basic components of the linear actuator are illustrated in Figure 3 [11], [12]. It consists of an electric motor, a gearbox and a nut/screw mechanism. The operation can be briefly described as follows: Firstly, an electrical motor transmits a rotational movement to a ball-screw in which the nut has been locked in rotation, but left free to displace alongits axis (by means of an anti-rotation mechanism). The induced displacement of the nut is then transmitted to a rotational joint, which finally drive a linear of the mass load. The analysis model of device is shown Figure 3, and the system parameters are shown in Table 2. With the established mathematical model and the hypotheses of the device dynamics, we describe the mathematical formulation of the device as follows:

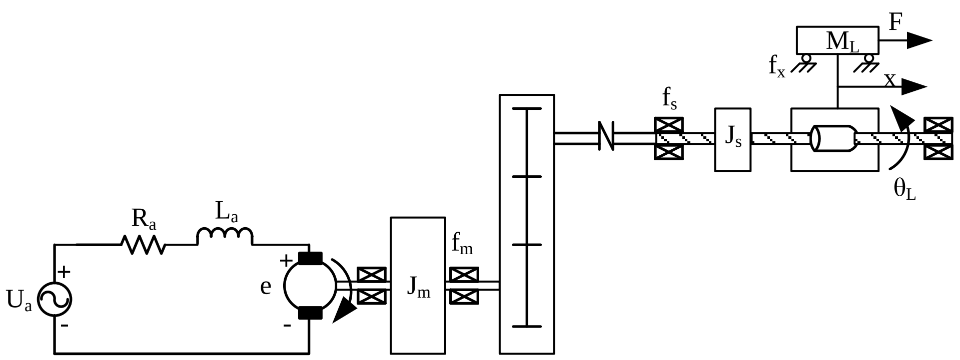

Figure 3. Modeling of an ankle rehabilitation device

Conllapse M_L and f_x to lead screw:

$$J_L = J_L + M_L.\left(\frac{t_x}{2.\pi}\right)^2 \tag{1}$$

$$f_L = f_s + f_x.\left(\frac{t_x}{2.\pi}\right)^2 \tag{2}$$

Conllapse f_L and J_L to motor shaft:

$$J = J_m + J_L.n^2 \tag{3}$$

$$f = f_m + f_L.n^2 \tag{4}$$

The mathematical formulation in the DC electric motor:
(i) Voltage equation:

$$U_a(t) = R_a.i_a(t) + L_a.\frac{di_a(t)}{dt} + K_i.\frac{d\theta_m(t)}{dt} \tag{5}$$

(ii) Moment equation:

$$M(t) = K_a.i_a(t) = J.\frac{d^2\theta_m(t)}{dt^2} + f.\frac{d\theta_m(t)}{dt} + M_m^F(t) \tag{6}$$

Calculator $M_m^F(t)$ (Moment of load):

$$\begin{gathered} F.v = M_L.\Omega_L \text{ with } \quad v = \frac{t_x}{2.\pi}.\Omega_L \\ F.\frac{t_x}{2.\pi}.\Omega_L = M_L.\Omega_L \\ M_L = \frac{t_x}{2.\pi}.F \\ M_m^F(t).\Omega_m = M_L.\Omega_L \\ M_m^F(t) = M_L\frac{\Omega_L}{\Omega_m} = M_L.n \end{gathered} \tag{7}$$

Or:

$$M_m^F(t) = \frac{t_x}{2.\pi}.F.n$$

Convert the equations (5), (6) and (7) to Laplace:

$$U_a(s) = R_a.i_a(s) + L_a.\frac{di_a(s)}{dt} + K_i.\frac{d\theta_m(s)}{dt} \tag{8}$$

$$K_a.i_a(s) = J.\frac{d^2\theta_m(s)}{dt^2} + f.\frac{d\theta_m(s)}{dt} + M_m^F(s) \tag{9}$$

$$M_m^F(s) = \frac{t_x}{2.\pi}.n.F(s) \tag{10}$$

Function transfer on motor shaft:

$$\frac{\theta_m(s)}{U_a(s)} = W_m(s) \tag{11}$$

Block diagram on motor shaft:

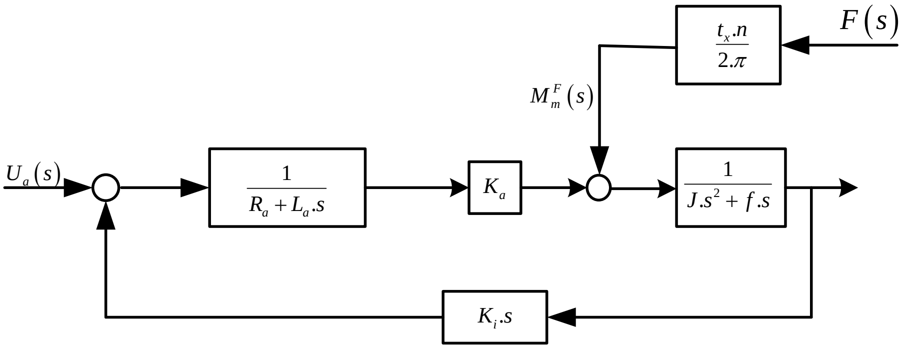

Figure 4. Block diagram on motor shaft

Suppose force F=0, conllapse block diagram on motor shaft:

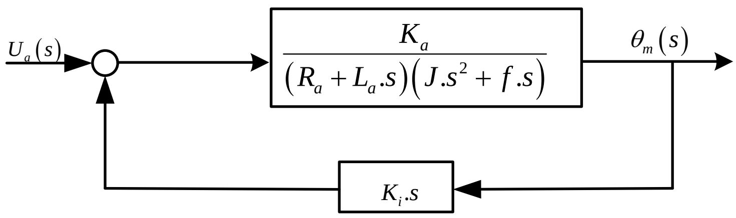

Figure 5. Conllapse block diagram on motor shaft

Finally function transfer:

$$W_m = \frac{\theta_m(s)}{U_a(s)} = \frac{K_a}{L_a.J.s^3 + L_a.f.s^2 + (R_a.f + K_a.K_i)s} \tag{12}$$

From the Figure 2, the relationship between dispalcement of linear actuator (x) with the rolational angle of foot platform (θ) indicated by equation 13.

$$x = R.\theta \rightarrow x(s) = R.\theta(s) \tag{13}$$

Block diagram of the relationship between control voltage of linear actuator (U_a) with the rolational angle of foot platform (θ):

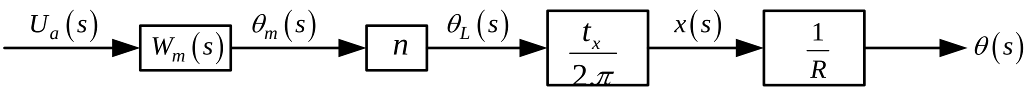

Figure 6. Block diagram of the relationship between control voltage and angle

Function transfer express the relationship between control voltage of linear actuator (U_a) with the rolational angle of foot platform (θ) :

$$W(s) = \frac{\theta(s)}{U_a(s)} = W_m(s).n.\frac{t_x}{2.\pi}.\frac{1}{R} \tag{14}$$

Or:

$$\frac{\theta(s)}{U_a(s)} = \frac{K_a}{L_a.J.s^3 + L_a.f.s^2 + (R_a.f + K_a.K_i)s}.n.\frac{t_x}{2.\pi}.\frac{1}{R} \tag{15}$$

Notation and parameters of values in the transfer function are shown in Table 2.

Table 2. Parameter values used to simulate in Matlab/Simulink software

Parameter	Notation	Value
The equivalent inertia of the motor and the load	J_m	0.00004(kg.m^2)
The equavalent inertia of the load	J_L	0.88234(kg.m^2)
The equavalent viscous damping of the motor	f_m	0.00152(N.m.s/rad)
The equavalent viscous damping of the load	f_L	0.0485(N.m.s/rad)
The proportionality constant of Moment	K_a	0.030891(N.m/A)
The fem constant	K_b	0.036868(V/rad.s^{-1})
Length of the link	R	0.003(m)
Transmission ratio of the gearbox	N	40:1
The step of the lead	t_X	2e-3(m/rev)
Resistance of the motor	R_a	0.4(Ω)
Inductance of the motor	L_a	0.8(mH)
Mass of load	M_L	3(kg)

Simulation

In this research, we used Matlab/Simulink software to simulate the response of the device. Using the PD controller to control the device, the parameters of the PD controller can be found by the genetic algorithm. The values of the parameters in the transfer function (14) are taken from Table 2. The simulation diagram in the MatLab/Simulink software is shown in Figure 4-5. Where e is the error between input signal θ_d and output signal θ. The simulation result of the response of the device is shown in Figure 6 with an overshoot is 0 and a setting time is 1.5s.

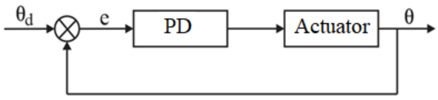

Figure 7. Block diagram of a PD controller with angular position feedback

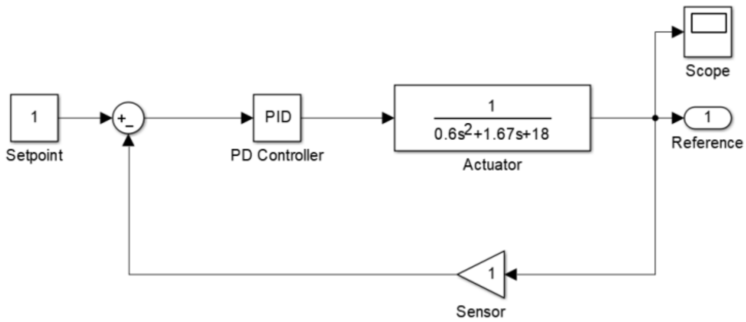

Figure 8. Diagram of closed-loop control of the PD controller in Matlab/Simulink

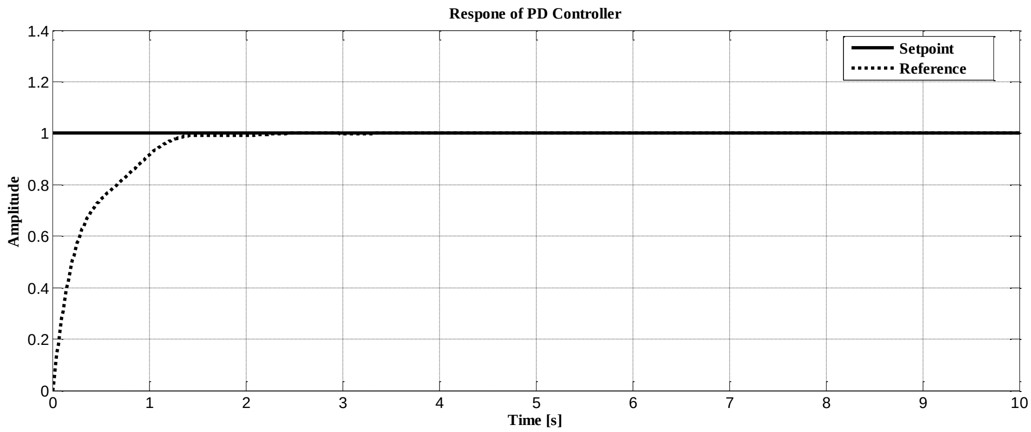

Figure 9. Result of the simulation of the PD controller response in Matlab/Simulink software

ANKLE REHABILITATION DEVICE

The current prototype of the device developed by the Pham Van Dong Univsersity. This device is powered by the linear actuator to realize one DOF for ankle rotational movement, that is dorsi-flexion/plantarflexion. The frame of the device and the foot platform are made of aluminum, the drive shaft is made of stainless steel. Parts are precision machined by CNC milling machines and lathes machine. After that, the drive shaft is assembled with the frame by M5 bolts and assembled with the foot platform by the shaped aluminum rod. The results of the complete manufacturing and assembly process are shown in Figure 10-11. In this study, we will concern the actuated DOF in ankle dorsi-flexion/plantarflexion movement and the device will be kept passively free during operation. The maximum ranges of motion for ankle is 0-80^0. The foot platform supporting the weight of the human shank and ankle is adjustable to suilt differentpatients. General specification of the device: Range of motion 30^0(Dorsi-flexion) -50^0 Plantarflexion. Height 420-450(mm), weight 2 kg and maximum payload 35(N.m).

Figure 10. The frame of Ankle rehabilitation device

Figure 11. The rehabilitation ankle device

Figure 12 shows the diagram control of ankle rehabilitation. Firstly, the human sets the angle for the device by the computer. Secondly, the computer will transmit the control signal to the control board which controls the linear actuator by the control voltage. Finally, the linear actuator drives the foot platform with the ankle of humans following the angle setpoint. Nowadays, Arduino control circuits are widely used in the field of automatic control, with the advantage of being easy to program and low cost [13]. In this experiment, we used the Arduino 2560 board to control the ankle joint rehabilitation device. The control circuit is Arduino Mega 2560 which is responsible for receiving the set angle and set cycle then output the control signal to the linear actuator. It read the angle sensor signal and displays parameters on the screen from the monitor of Arduino IDE software. In order to read the angle of foot platform, we used encoder with the resolution 12 bit of Hall. Moreover, a current sensor is used to mesure the current of linear actuator during the contac of the device with human which is module ACS712. The parameters of an ankle rehabilitation device are shown in Table 3.

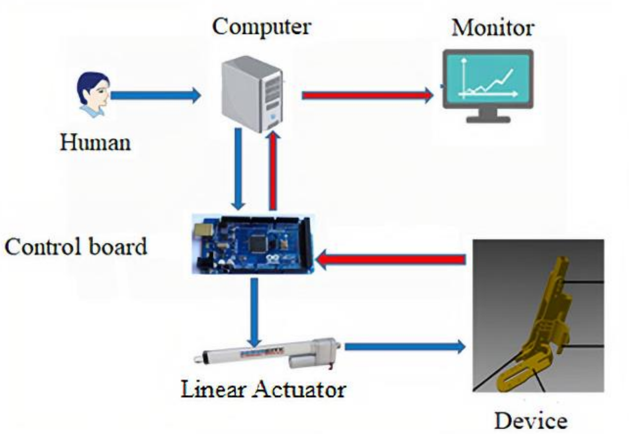

Figure 12. Diagram control of the ankle rehabilitation device

Table 3. Parameters of the ankle rehabilitation device

Description	Sourse of information
Anggle sensor	Encoder 12 bit Hall
Current sensor	Module ACS712
Controller board	Arduino Mega 2560
Linear actuator	HDLS-6-30-12V Servocity

Firstly, the experiment for device operating in without load mode and Plantarflexion exercise. The setpoint rotational angle is a sinusoidal function with an amplitude of 45 degrees and frequency is 50hz, the drive result of the device is shown in Figure 13. Figure 14 shows the experimental tracking trajectory for the device. The routine that was programmed in the device shown by the full line, while the trajectory generated by the device measured by the encoder in real-time is shown in the dotted line. As can be observed, they are very similar. Figure 15 shows the tracking error of the device without load mode, where the error is the range between the maximum and the minimum values (0 to 1 degree). To quantitatively evaluate the trajectory tracking error, the root means square error (RMSE) is used. For the device in the without load mode, the RSME values are 0.86 degrees.

Figure 13. Rehabilitation ankle device without load mode

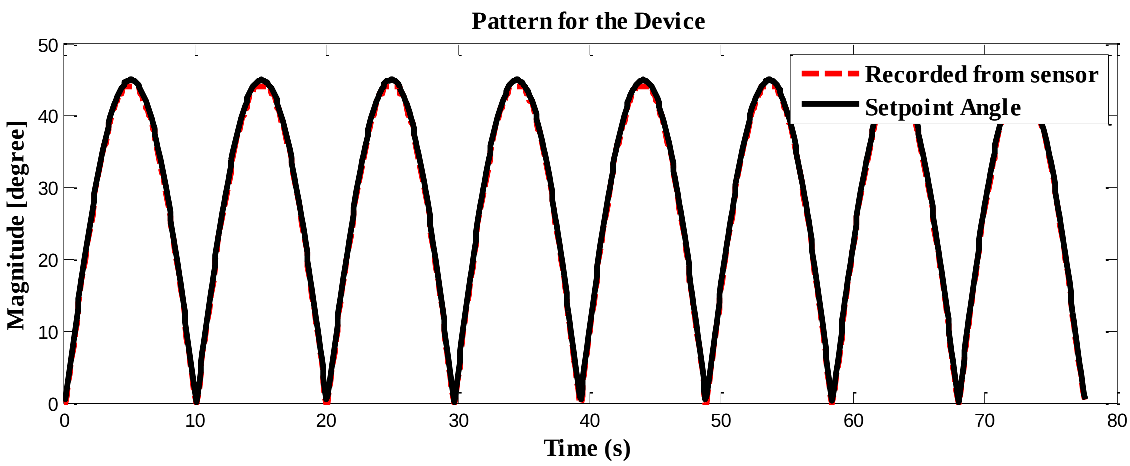

Figure 14. Pattern for the device without load mode

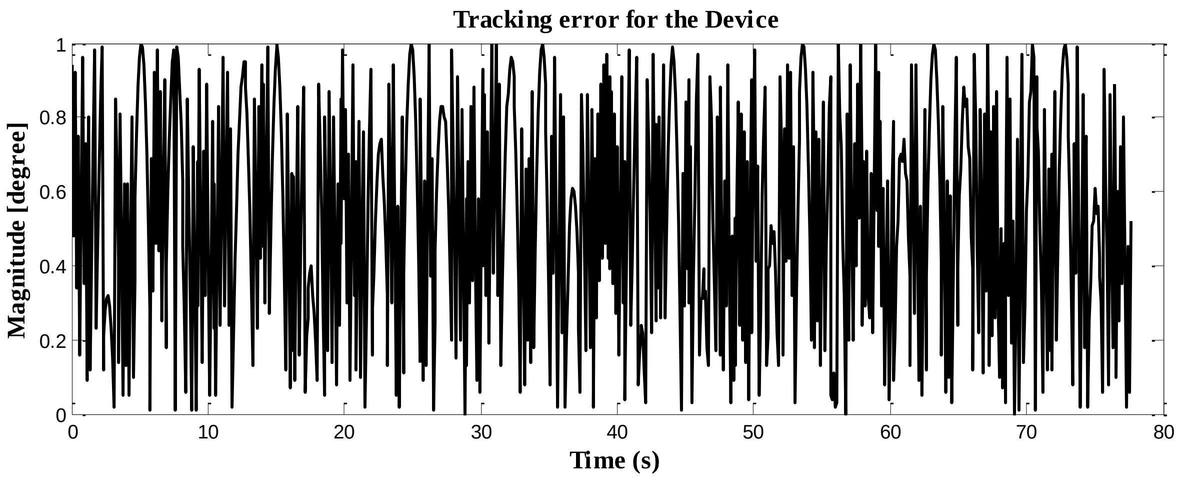

Figure 15. Tracking error for the device without load mode

Secondly, the experiment for device operating in with load mode and Plantarflexion exercise. The setpoint angle is a sinusoidal function with an amplitude of 45 degrees and frequency is 50hz. To applying on human subjects, various measures had been taken to guarantee safety during operation. The device includes an emergency stop button which means the device can be stopped immediately at ant time when the humans press this button. Moreover, the controller boar in the device will read the current signal from the linear actuator when current values increase over the current setting due to the device stop immediately that exceeds the human's comfortable level. The experiment was conducted on human objects with parameters of 1.62m height and weight of 60kg (see Figure 16). The data is captured and displayed on the graph by Matlab software, the training process results are shown in Figure 17. The routine that was programmed in the device shown by the full line, while the trajectory generated by the device measured by the encoder in real-time is shown in the dotted line. As can be observed, they are very similar. Figure 18 shows the tracking error of the device with load mode, where the error is the range between the maximum and the minimum values (0 to 1 degree). For the device in the with load mode, the RSME values are 0.90 degrees.

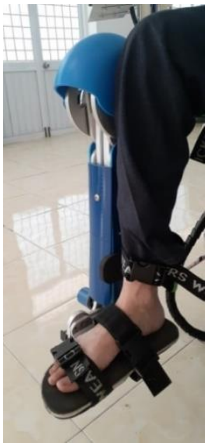

Figure 16. Rehabilitation ankle device load mode

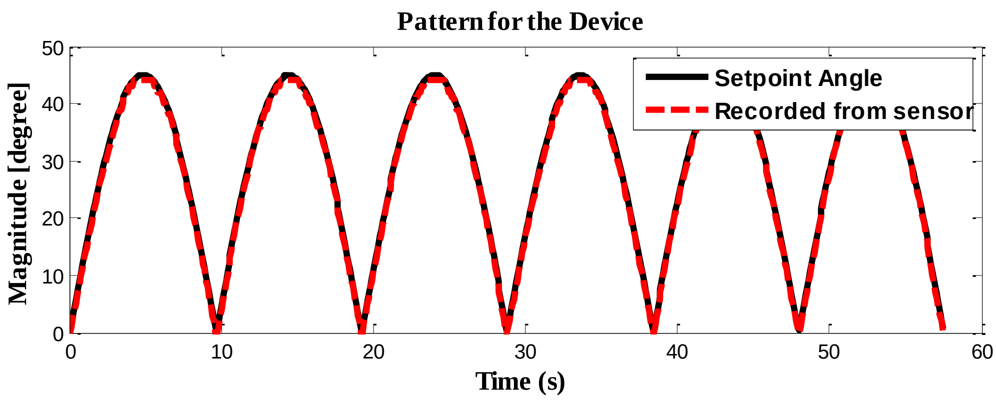

Figure 17. Pattern for the device with load mode

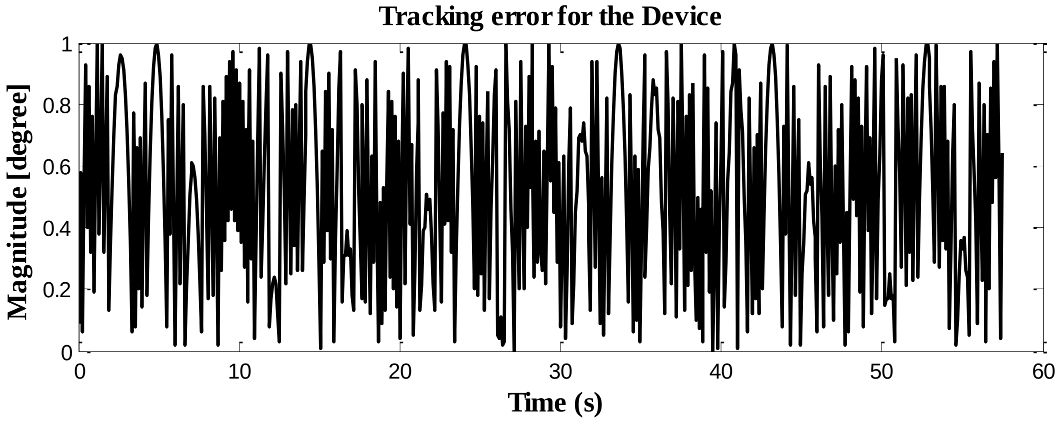

Figure 18. Tracking error for the device with load mode

In this study, we have experimented with two modes of operation: no-load and human for ankle rotational movement that is dorsiflexion/plantarflexion. The RSME values of the device are 0.90 degrees. Compare with previous studies such as the results of Liu et al with the RSME values are 2.1 degrees and Zhang et al with the RSME values are 1.01 degrees [14], [15]. The results of the device when it experimented with humans are similar to those of previous studies. The highlight of the device is its simple structure and low cost (500$). However, this study also has some limitations, there is only 1 degree of freedom for the ankle joint to operate and the experiment is performed on only one person.

CONCLUSION

In this paper, model research for the ankle rehabilitation device ankle was designed and built. Then, the mathematical equation descriptions showing the relationship between the input and output signals in the device can be obtained. Furthermore, the application of PD controllers has been presented on the specific subject of ankle joint training device. Using MatLab/Simulink software to simulate the angular position response of the device, the simulation results have overshoot of 0.1% and the setting time is nearly 2s. The device manufactured in the workshop of Pham Van Dong university base on aluminum material. Experiments were conducted on both without load mode and with human mode. For human safety, besides the program containing the Arduino Mega controller, the device has mechanical brakes and an emergency button. The device's tracking performance was determined by comparing the input and output angular position of the device. The error of the set angle and the experimental angle is 1^0 which this is because the encoder sensor has a relatively small resolution (12 bits).

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