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Design and Development of Lower Limb Exoskeleton of Robotic Gait Trainer

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Abstract. Abnormalities of gait can be caused by neurological impairment. However, the cost of therapy is one of the greatest obstacles to rehabilitation following neurological impairment. A simple, low-cost two-degree-of-freedom exoskeleton for the lower leg of the gait trainer has been designed and developed. This device can assist those who have walking difficulties in their rehabilitation process. This article discusses designing and developing a lower limb exoskeleton for a gait trainer with a PID controller. A microcontroller controls the dc motors in the hip and knee joints by utilizing a predetermined trajectory pattern, using data derived from healthy subjects. Experiments show that the PID controller produces a stable system, with steady-state errors between 0 and 10 degrees.

INTRODUCTION

Gait and Gait Analysis

Gait is a term that refers to the way one walks [1]. While gait analysis is a methodical examination of human walking [2], using manual observation or a device that records bodily movement, mechanics, and muscle activity. This analysis is used to evaluate, prepare for, and treat individuals who have walking-related disorders. Additionally, it is frequently utilized to ascertain the patient's position or movement issues. Dr. Perry [3] illustrates gait cycle phases, as illustrated in Figure 1 [4]. When walking, roughly 60% of total stride time is spent in support and 40% in the swing. As shown in Figure 2, one foot is always on the ground when walking, followed by a short time on the ground with both feet, resulting in an alternating pattern of single and double support [5]. The graphs in Figure 3 illustrate the angular kinematics throughout the gait cycle[6]. The graphs show the support phase (percentage of the cycle up to the vertical line) and the swing phase (percentage of the cycle past the vertical line).

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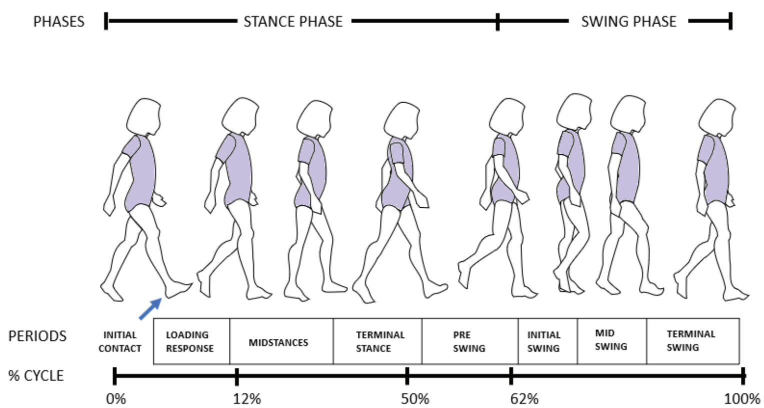

FIGURE 1. Gait cycle phases

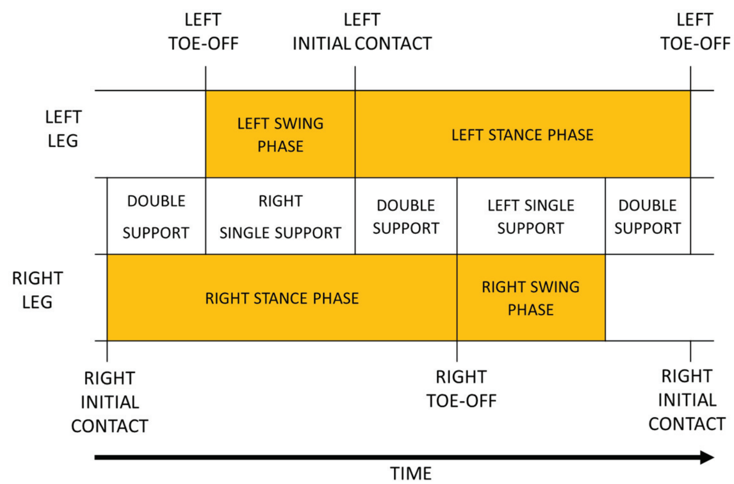

FIGURE 2. Support and double support during walking

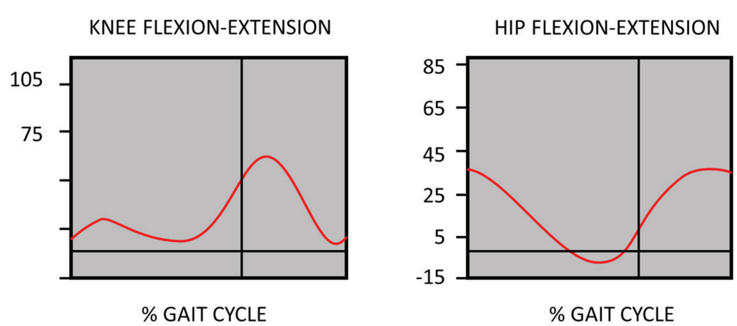

FIGURE 3. Graphs of angular kinematics across the gait cycle

From the graph in Figure 3, the normal gait range of motion can be stated in Table 1 below :

TABLE 1. Range of normal gait motion (hip and knee)

Joints	Motion	Range of Motion (degree)
Knee	Extension/flexion	10 to 55
Hip	Extension/flexion	-10 to 35

Gait Impairment

A stroke is a medical condition in which the brain cannot function normally due to inadequate blood supply. If there is no oxygen or nutrition in the blood, brain cells will perish quickly. Typically, the infected individual loses one or more limb functionality, while the affected brain region becomes dysfunctional. After an injury to the lower limb, therapy is necessary to rehabilitate the body and restore normal walking. Numerous rehabilitation treatment experiments have been conducted on persons who have lost their walking ability [7]. Gait therapy is a critical component of stroke rehabilitation [8]. While robot-assisted walking trainers are now available, their price remains unreasonably high [9]. There are robot-assisted walking trainers available, such as Lokomat and Gait Trainer, although they are still expensive (€ 330,000 for Lokomat and € 30,000 for Gait Trainer GT1). When resources are scarce, healthcare practitioners frequently devise low-cost techniques to ensure the quality of care received by patients.

Classification of Gait trainer

As indicated in Table 2, there are four types of robots utilized in gait rehabilitation. The motion that these gadgets apply to the patient's body can be categorized into several categories. For example, during gait phases exoskeleton control joints like the knee, hip, knee, and ankle. While "end-effector robots" simply move the feet during gait training, which are usually put on support (footplate) that enforces specific trajectories, duplicating the stance and swing phases [10].

TABLE 2. Different approaches to robotic gait trainers

Robotic Devices	Static	Dynamic
Exoskeleton	Lokomat	ReWalk
End-effector	Gait Trainer	i-Walker

EXOSKELETON DESIGN

System Design

The general closed-loop control scheme for robot-assisted gait trainers is illustrated in Figure 4. Repeating voltage signals will be generated by the gait pattern generator. The position controller will provide output signals and amplify current to regulate the exoskeleton's dc motor using a custom control algorithm, while the positioning sensors (encoder) will read the actual value of the hip and knee position of the lower limb exoskeleton.

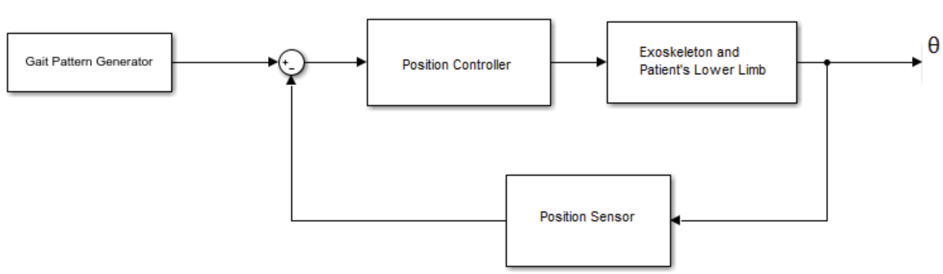

FIGURE 4. The closed-loop control system of a robotic gait trainer

Mechanical Design

Exoskeletons are mechanical structures that resemble the skeletal structure of a limb or body part [11,12] Figure 5 depicts the results of a comprehensive assessment of exoskeletons conducted to date [12] which divided them into two categories based on uses and needs: medical and non-medical systems.

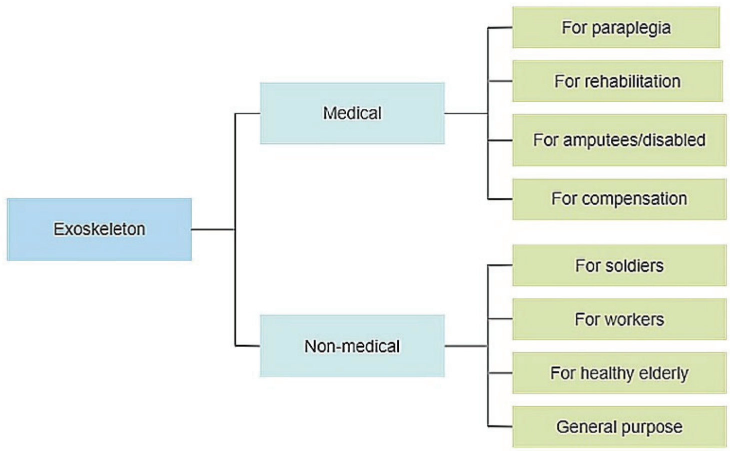

FIGURE 5. Classification of exoskeletons according to their usage

For example, the lower limb exoskeleton resembles the hip and knee. The biological models of hip and knee joints are depicted in Figures 6 and 7 [13], while the similarities between the human and artificial knee joints are illustrated in Figures 8 (a) [6] and 8(b). When a human walks, the swing motion of the lower limb is mainly made through movements of the joints of the hip and knee. The flexion, extension, and internal and external rotation are shown in Figure 8 (a) [6] .

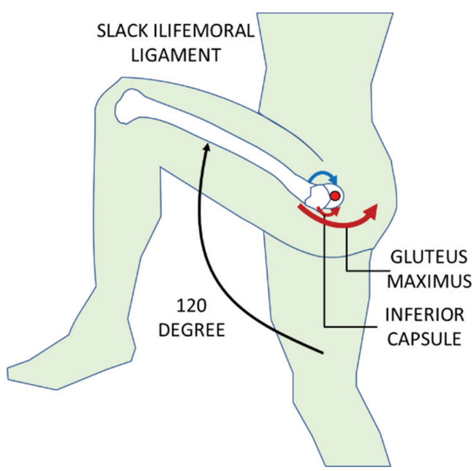

FIGURE 6. Hip flexion of knee joint

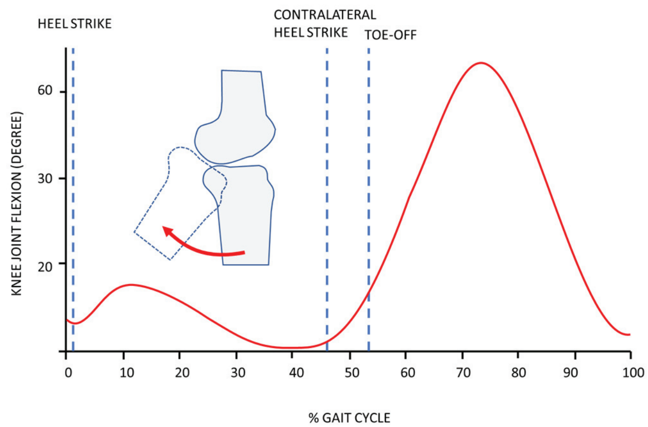

FIGURE 7. Kinematics of knee joint during gait

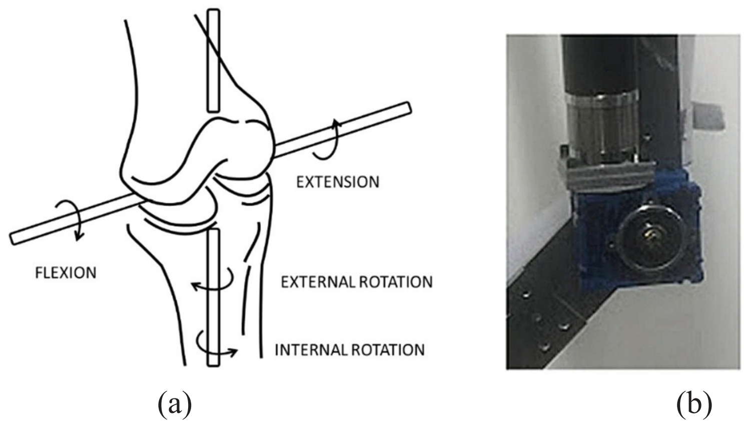

FIGURE 8. Similarities between knee joint (a) and exoskeleton joint (b)

The exoskeleton of a robotic gait trainer has four degrees of freedom (2 degrees of freedom for each side). The 3D (Solidworks) drawing of the lower limb exoskeleton is shown in Figure 9. The exoskeleton is made of aluminum to make it lighter [14]. The dc motors meet the performance criteria for a miniature solution contained within a portable device. Greater torque and lower speed are required to move the exoskeleton. This can be done by connecting the dc motor to the gearbox to increase torque and decrease speed [15]. Figures 10 and 11 show the 2D drawing of the gait trainer mechanical arrangement, while Figures 13a and 13b show a dc motor and a gearbox with a transmission ratio of 1:50.

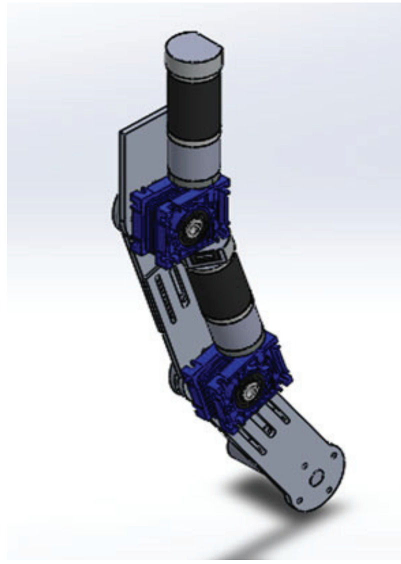

FIGURE 9. Solidworks drawing of lower limb exoskeleton

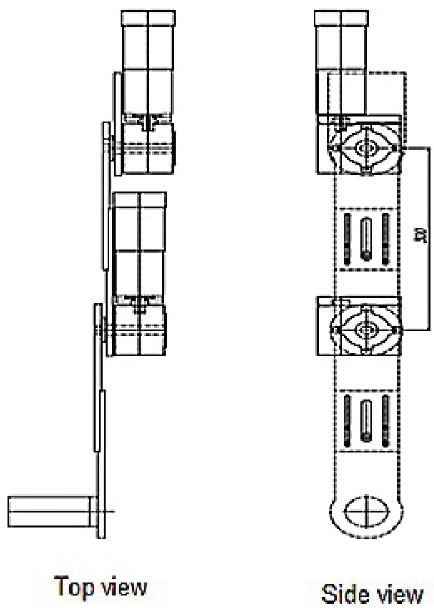

FIGURE 10. Exoskeleton (top and side mechanical illustration)

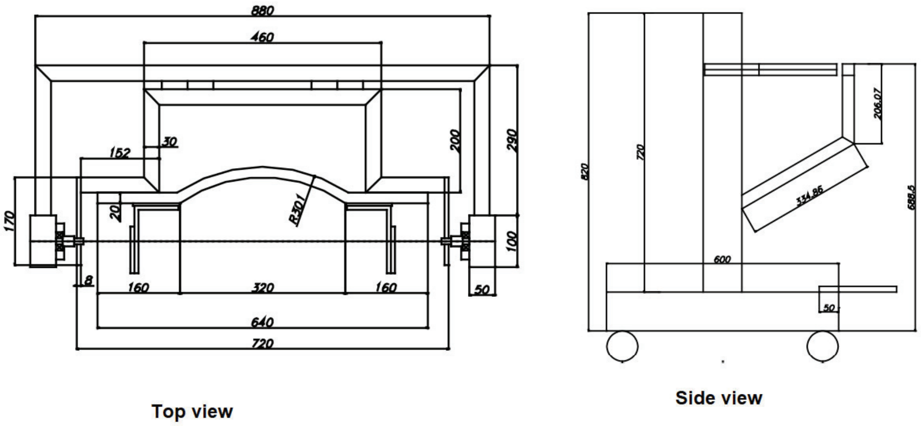

FIGURE 11. Exoskeleton support (top and side mechanical illustration)

FIGURE 12. PG56 encoder dc motor and the gearbox

As shown in Figure 13, there are four dc motors to drive four joints in this lower limb exoskeleton), two motors for the left side, and two motors for the right side. The dc servo motors control the joint motors (PG56) using PWM (Pulse Width Modulation) outputs from the microcontroller.

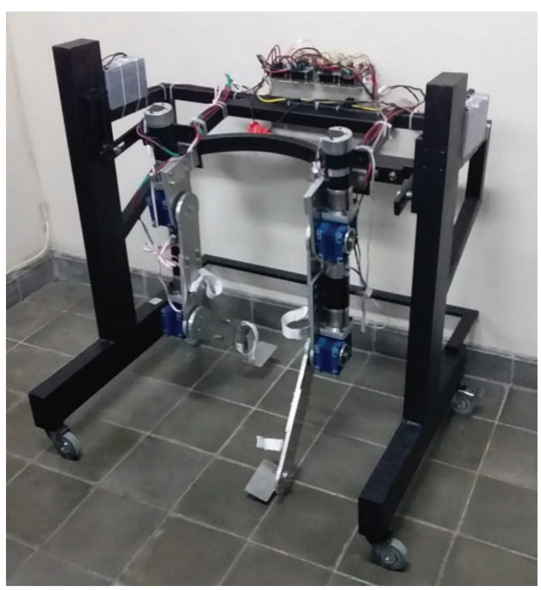

FIGURE 13. The physical appearance of the gait trainer

PID Control

PID stands for the proportional integral derivative controller. It is a classic control algorithm that uses the feedback-loop principle. The magnitude of a system's "error" is determined by the difference between the measured process variable and the setpoint generated by a PID controller. By altering the control process's output, the PID controller seeks and minimizes errors. The PID algorithm of the controller employs three distinct constant control parameters, P, I, and D represent proportional, integral, and derivative functions, respectively. (P=current error, I=sum of previous errors, D=prediction of future errors based on the error velocity's rate of change). The following formulation of PID control based on time error is used [16]:

$$u(t) = K(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d \frac{de(t)}{dt}) \quad (1)$$

(1)

where:
y = variable of measured process, r = variable of reference, u = control signal
e = control error $(e = y_{sp} - y)$, K = proportional gain, T_i = integral time
T_d = derivation time

Microcontroller and Actuator

The microcontroller being used as the controller of this robotic gait trainer is Arduino. Arduino is a user-friendly microcontroller platform that has an onboard microcontroller, and an integrated development environment (IDE) is used to program it. In robotics, Arduino is a valuable tool, because it is an open-source electronic devices platform based upon easy-to-use software and hardware [17].

This lower limb exoskeleton is using 4 dc motors as the actuators. There are many types of actuators, in which energy transformation takes place through multiple forms. Electric, hydraulic, and pneumatic actuators are the three types of traditional robot joint actuators. In recent decades, they have been successfully used for a variety of robotics. Shape memory alloys, electro-rheological fluids, electroactive polymers, and piezoelectric actuators are examples of newer actuators. However, most of them are ineffective due to their tiny forces or complexity. Electrical actuation is used in a variety of methods in most exoskeletons (e.g., gait restoration, rehabilitation, power increase, etc.). Electric actuators have the advantage of being inexpensive and simple to use and operate [18]. An overview map of the various technical options available to the design is shown in Figure 14 [19]. First and foremost, selecting an actuation concept is a crucial decision.

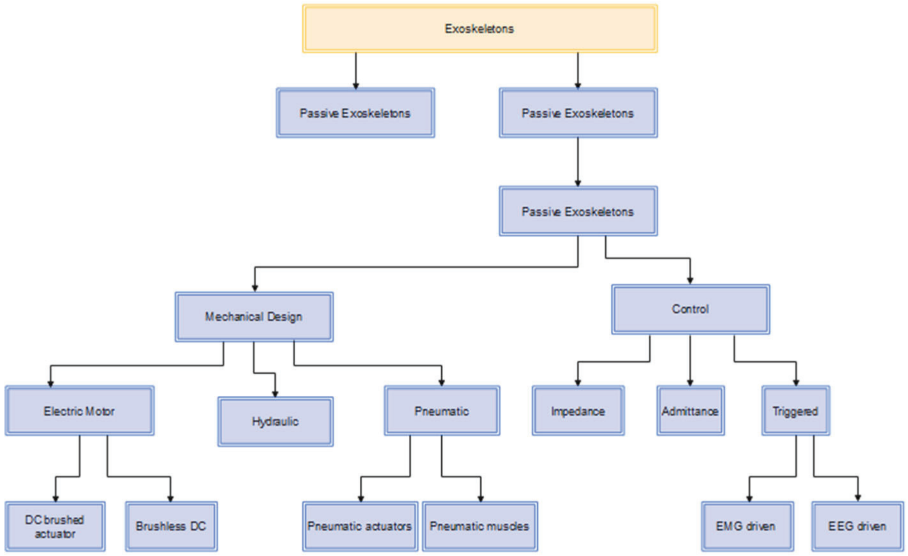

FIGURE 14. Exoskeleton concept solutions for actuation and power

RESULTS AND DISCUSSION

As seen in Figure 15, the dc motor for driving the exoskeleton of a robotic gait trainer is powered by a 24-volt battery. The control circuit requires a voltage of 5 volts, so the voltage from the battery is lowered first, from 24 volts to 5 volts, by the voltage regulator. Because the motor requires a large current, the BTS7960 driver is needed to amplify to run a dc motor. While the Encoder will read the actual position of the DC motor.

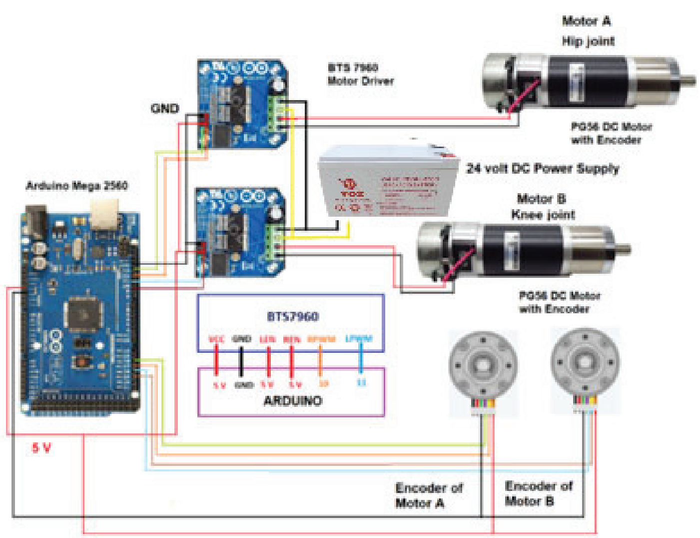

FIGURE 15. Wiring diagram of the robotic gait trainer

Data from a healthy population was used as a reference [20]. The graphs in Figures 16 and 17 depict hip and knee movements based on these data. The figures show that hip movement ranges between -18 and 25 degrees; knee motion ranges between 0 and 60 degrees. The reference path is stored in the memory of the microcontroller, then processed using a control algorithm in the microcontroller. The output of the microcontroller is sent to the driver to move the dc motor. Figures 15 and 16 show the movement of the knee and hip joints of the exoskeleton.

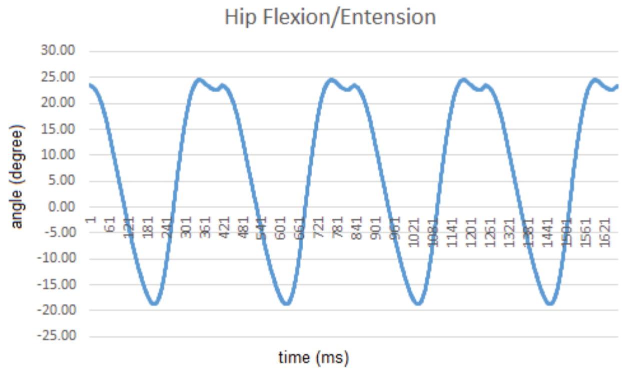

FIGURE 16. Hip range of movement of healthy people

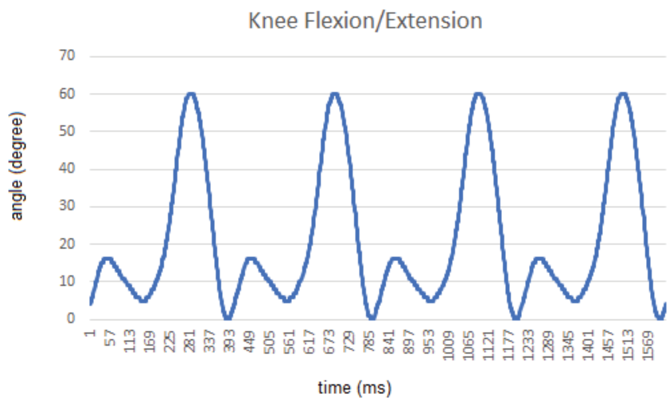

FIGURE 17. Knee range of movement of healthy people

Figures 18 and 19 show that PID results in a stable system with minor steady-state error. As illustrated in Figure 18, hip movement is controlled using a PID controller. Hip flexion/extension ranges from -15 to 20 degrees. The system is stable, but there are steady-state errors between 0 and 10 degrees. In Figure 19, the knee movement is controlled using a PID controller. The Knee flexion/extension range of movement is eight to 55 degrees. The system is also stable, but there are steady-state errors from 0 to 10 degrees.

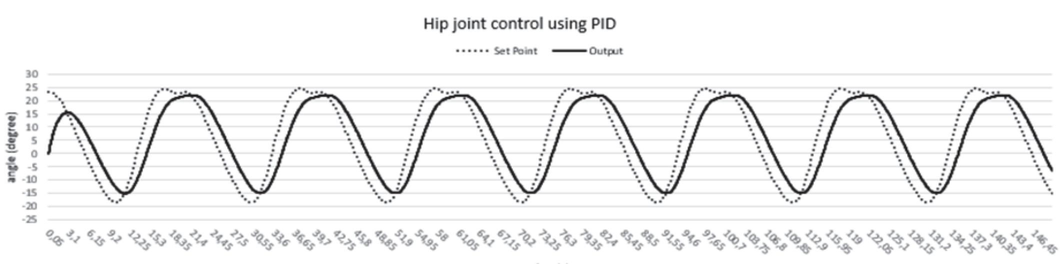

FIGURE 18. Movement of hip exoskeleton using PID

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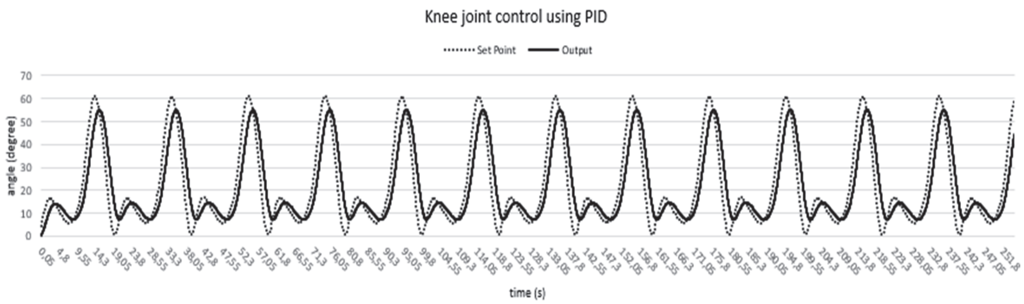

FIGURE 19. Movement of knee exoskeleton using PID

CONCLUSIONS

A lower-limb exoskeleton of a robotic gait trainer has been developed with a low-cost budget. this will be very helpful in the midst of rare and expensive robotic gait trainer devices. This robotic gait trainer uses a PID controller that enables tracking of the gait trajectory. The experiment has demonstrated that the exoskeleton controlled by PID is stable with error steady-state errors from 0 to 10 degrees. For future works, this PID controller can be improved by combining it with another control algorithm to minimize the steady-state error.

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