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Early Mobilization Therapy Robot for Medical Rehabilitation Purpose

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ABSTRACT

Impairments in ambulation may result from neurological dysfunction. The expense of therapy constitutes a substantial obstacle to recovery following neurological disorders. An uncomplicated and cost-effective two-degree-of-freedom early mobilization trainer robot has been conceived and constructed. This device is intended for early training or adaptation before ready for mobilization training on the ground. The early mobilization trainer assists persons with mobility impairments during their early therapy phase. This research analyses the design and construction of an early mobilization trainer positioned within the patient's bed. The experimental findings indicate that in the condition with load at the hip joint, the output of this device can follow the trajectory input precisely. For the knee joint, the output of this device can follow the trajectory input, but with 0.9 degree of a steady-state error. This amount of steady state error does not affect the therapy because it is too small in term of knee movement precision during therapy.

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1. INTRODUCTION

Globally, 15 million people are affected by stroke every year, making it the leading cause of motor disability [1], [2]. Although a significant portion fully recovers, a tiny percentage does so [3]. One answer to the issue of medical rehabilitation is robotic rehabilitation, a quickly expanding area that sees the creation of numerous new items each. The lack of qualified medical professionals, lengthy and intricate procedures, and the high demand for quality healthcare all contribute to this problem [4], [5].

A stroke is defined as a neurological deficit attributed to an acute focal injury of the central nervous system occurring on a vascular basis [6]. A stroke occurs when blood arteries become blocked, resulting in bleeding and a lack of oxygen flow to the brain [7]. Stroke is historically termed cerebrovascular accident (CVA), however, Burns *et al*. [8] stated that the term "cerebrovascular accident" (CVA) is outdated and should be avoided as it implies that stroke is an accident. About ten minutes is the maximum time the brain can function normally without glucose or oxygen [9]. The paralysis of a limb or limb on one side of the body is a common symptom of this condition, which happens when the brain region on the opposite side stops working. When problems arise with the lower limbs, rehabilitation is key to getting back on the feet and walking normally. There are a variety of rehabilitation treatment options that aim to enhance walking abilities [10].

Many patients feel better within the first six months following a stroke. The road to recovery becomes more winding but not impossible [11]. Stroke significantly impacts Activities of Daily Living (ADL), with many patients experiencing dependency on personal care, mobility, and communication [12]. ADL dependency within the first two days post-stroke can predict dependency at 3 and 12 months [13]. ADLs in stroke patients refer to essential self-care tasks that are often impaired post-stroke. It is now possible to begin an intervention program to retrain the ability to do ADLs with forceful motions and functional trajectories. An actual task increases the likelihood of neuroplastic alterations (brain rewiring) in which the relearned movement is integrated [14].

Lokomat [15], [16] costs €330,000 and Gait Trainer GT1 [17] costs €30,000; both are considered to be among the costliest robot-assisted gait trainers now on the market [18]. There are active and passive robot systems available for gait rehabilitation. The patient's limbs must provide enough effort for the passive device to move [19].

The kind of motions that walking rehabilitation robots can do for patients are also distinct. In the gait phase, an "exoskeleton" controls the movement of the hip, knee, and ankle, but a "robot end-effector" controls the movement of the foot, which is often supported by a footplate, and follows a predetermined trajectory, allows one to practice their gait without really walking. According to one definition, an exoskeleton is a dynamic anthropomorphic mechanical apparatus donned by the user, securely fastened to the body, and responds to the user's movements [20], [21]. Robots with end-effectors and those with exoskeletons each have uses and benefits. Fig. 1 compares various devices [22].

There are examples of commercially available walking trainers that include robots such as RehaStim [23] of Berlin, Germany, ReWalk [24], [25], [26] and Lokomat (Hocoma, Switzerland). Lokomat moves along a treadmill following a set of predefined paths. End-effector robots, like the G-EO System, made by Rehabilitation Technology AG in Switzerland follow the natural gait pattern by balancing on movable supports.

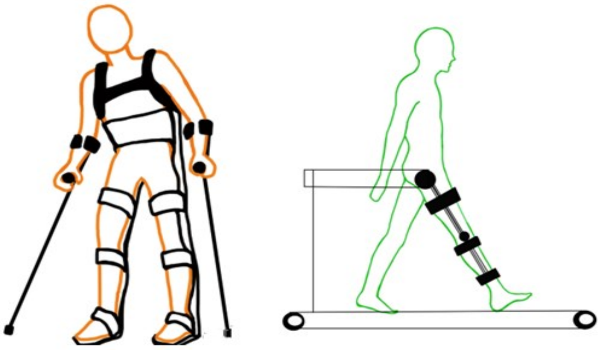

Fig. 1. Examples of walking movement trainer robot devices with different approaches [27]

Other than gait trainers, there are early mobilization therapy robots, for example, VEMOTION from Reactive Robotics (Germany). The VEMOTION robotic system was developed to assist with early mobilization in intensive care units, demonstrating feasibility in initial trials [28]. Therapy of early mobilization is a systematic method for increasing physical activity and mobility [29]. Early mobilization after stroke is believed to improve outcomes associated with stroke unit care [30]. It can improve functional capacity, muscle strength, and health-related quality of life [31], [32]. Many robotic systems facilitate (initial) mobilization [33], [34]. Fig. 2 illustrates that the VEMOTION® robotic assistance system is designed to increase the ease of (initial) mobilization operations [35], [36].

Fig. 2. Robot-assisted early mobilization with VEMOTION [37]

The device being developed in this research has a unique selling point. It automates and modernizes a medical rehabilitation system while utilizing many local components, resulting in much lower production costs than other goods on the market. Research is currently concentrated on designing mechatronic items and developing medium-tech medical equipment. This research aims to contribute to the solution to Indonesia's worldwide challenge of health independence [38]. The production of domestic medical devices is expected to reduce medical costs.

Making walking aids for medical rehabilitation significantly less expensive than imported manufactured items is now the biggest challenge. Therefore, the research question is how to design and manufacture a prototype for this hardware.

Therefore, this research contributes to the medical community by generating a new concept of low-cost robot-assisted physical therapy which will be very helpful for the world of physiotherapy. Secondly, this research provides less complicated hardware design and control algorithm software. In terms of the effectiveness of therapy, the use of this equipment will guarantee consistency of position and speed compared to human therapists. Especially if the therapist has to work the whole day.

2. METHODS

Frugal innovation is a comprehensive word that includes diverse efforts delivering efficient functional solutions to prevalent issues faced by the majority, utilizing minimal resources [39], [40], [41]. Fig. 3 shows that this research demonstrates the innovation process. Accurate mechanisms are known to be more expensive. However, the device might not be perfect if we utilize inexpensive mechanisms or electrical parts. Because of this, we need to employ a new procedure for optimization: optimization with a control algorithm.

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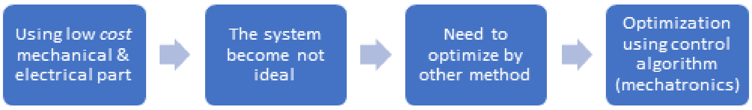

Fig. 3. Mechanical compensation using a control algorithm

Fig. 4 shows the overall framework for closed-loop control in early mobilization trainers. The gait pattern generator is designed to produce voltage signals that happen repeatedly. The exoskeleton's DC motor will be controlled by a position controller that amplifies current and provides output signals based on a proprietary control algorithm. The encoders and sensors that measure the exoskeleton's knee and hip positions will supply the actual values.

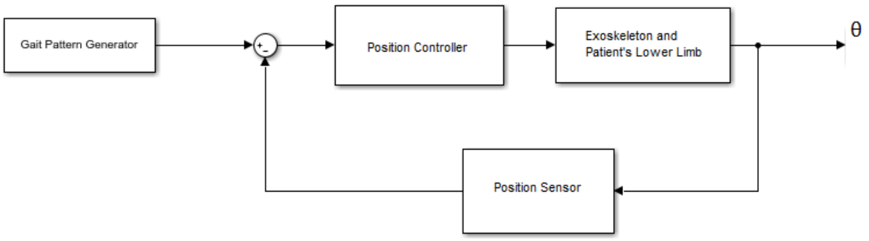

Fig. 4. The closed-loop control system of a robotic early mobilization trainer

2.1. Mechanical Design

The links of this device mimic the skeletal framework of a limb or other bodily component. A thorough evaluation of these links has been carried out up to this point [42], as shown in Fig. 5. The exoskeletons were classified into two groups: medical and non-medical systems. The system being constructed and investigated is included in the medical exoskeleton. Consider how similar the exoskeletons of the lower limbs are to those of the knee and hip. Fig. 6 presents the biological models of the hip and knee joints [43]. The lower limbs' motion when people walk is shown in Fig. 7 [44].

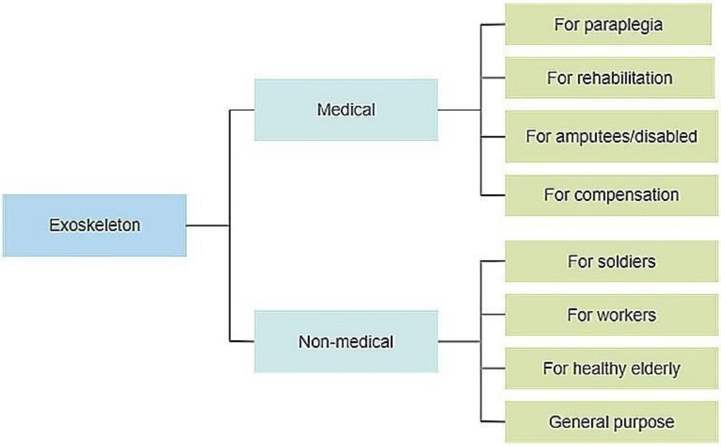

Fig. 5. Classification of exoskeletons according to their usage [32]

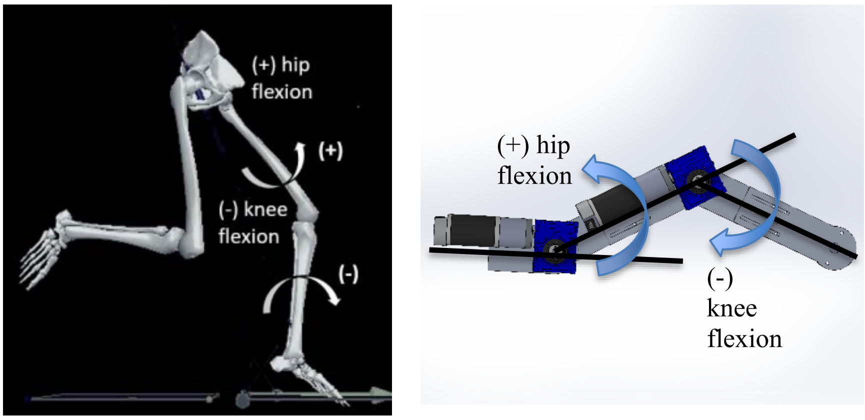

Fig. 6. (a) Model and (b) mechanical design of hip and knee in sagittal plane [33]

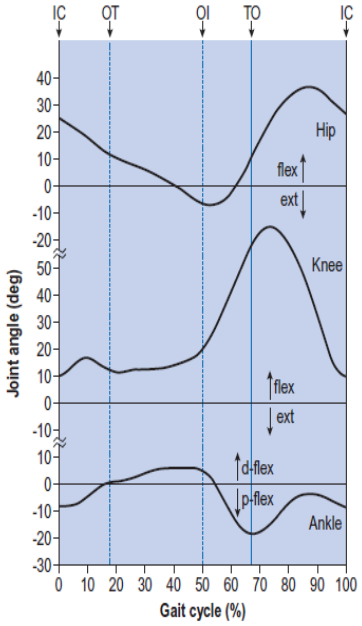

Fig. 7. Kinematics of lower limb joints during gait [34]

2.2. Electronic circuit

Fig. 8 illustrates a streamlined closed-loop control system that will be implemented on the robot Fig. 9. depicts the wiring schematic of this system. The 24-volt battery will supply power to DC motors and electronic circuits. The voltage regulator will transform 24 volts into 5 volts for the electrical circuit. The trajectory of the manipulator's movement is stored in the memory of Arduino Mega [45] The microcontroller then incessantly relays positional data to the motor. The BTS7960 will amplify the current [46] motor driver to ensure that the PG56 dc motor [47] is suitably powered. The encoder will relay the exact position to the microcontroller as input. The calculated voltage value will be sent to the driver circuit.

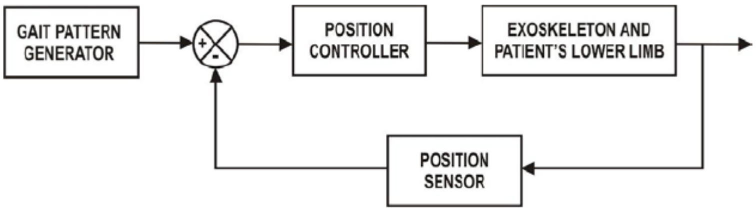

Fig. 8. Closed-loop control block diagram of an early mobilization trainer robot [48]

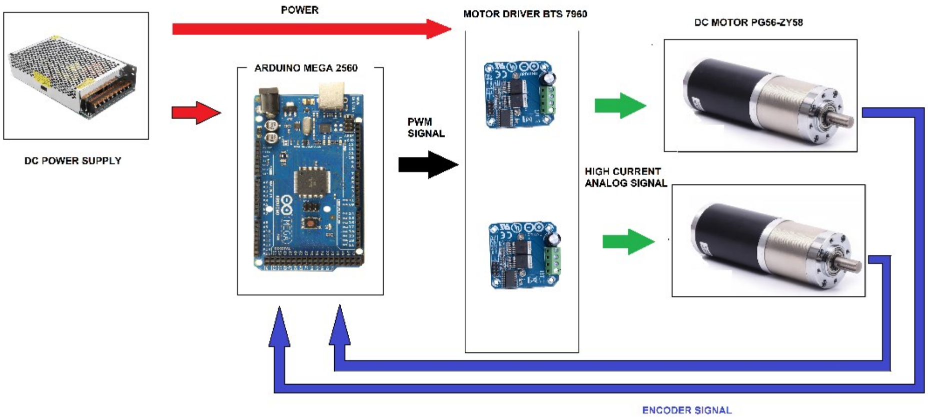

Fig. 9. Microcontroller connection diagram and motor drive system [48]

2.3. Control Algorithm

PID controllers are widely used in rehabilitation robotics due to their simplicity and effectiveness. They have been applied to various rehabilitation devices, including upper limb exoskeleton [49] and lower limb exoskeleton [50], [51]. The PID controller is the most prevalent choice because of its exceptional durability and straightforward installation. PID denotes the Proportional Integral Derivative controller [52]. PID is a traditional algorithm that employs the notion of feedback loops. The PID controller is already popular in the field of medical rehabilitation [53], [54]. The "error" is ascertained by the disparity between the set point and the measured output. The PID controller adjusts the output of the control process to seek and reduce the error. The controller's PID algorithm employs three distinct constant control parameters: P, I, and D, which denote the proportional, integral, and derivative functions, respectively. P represents the current error, I denotes the cumulative sum of prior errors, and D signifies the anticipated future error. The subsequent equation (1) predicated on temporal error is employed:

$$u(t) = K_p(e) + K_i \int_0^t e\,(t)\,dt + K_d \frac{d}{dt}\,e\,(t) \tag{1}$$

where y is output, r is set point, u is control, e is error, K is proportional constant, Ti is constant of integral time, Td is constant of derivative time.

During the test, the PID constants are tuned when the system has a nominal load that represents the average of a human leg. The control signal $u(t)$ will be sent as a PWM signal to the DC motor.

3. RESULTS AND DISCUSSION

Fig. 10 shows the prototype of the early mobilization therapy robot. It can be easily placed on the bedside. The length of the links can be modified based on the dimensions of the leg and thigh.

Fig. 10. Prototype of the early mobilization therapy robot

The prototype of this device has been tested for its control performance both manually and automatically. Even though the movements designed are still simple, considering that the rehabilitation supported is initial, this research focuses on movement precision. Control algorithm testing has been carried out. Due to the choice of large motor torque and supported mechanical transmission with a large speed ratio, even though this device moves slowly, it is very strong and precise. This can be seen in the following pictures where the movement of the tool can follow the trajectory of the command given. For this experiment, the trajectory pattern is a triangle wave.

Fig. 11 and Fig. 12 show the precision of movement in the hip joint with and without load. When used without load the resulting trajectory follows the programmed trajectory. However, there is a steady-state error when used with the load. Meanwhile, Fig. 13 and Fig. 14 show the stability (response) of the resulting movements in the hip joint, with and without load. When a load is applied the resulting response is quite good because there is no overshoot, and it follows the setpoint.

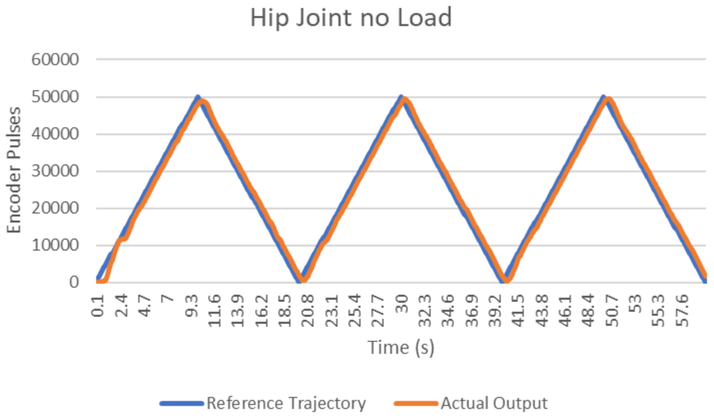

Fig. 11. Movement trajectory in the hip joint without load

Gaps between the setpoint trajectory and the actual system tracking do not affect the effectiveness of the therapy because it is just a response delay. The system tracking can follow the trajectory reference. A small gap on the corner when the system changes direction also does not affect the therapy. It is just a changing direction for testing purposes only. In real therapy, the speed of changing direction is not that fast.

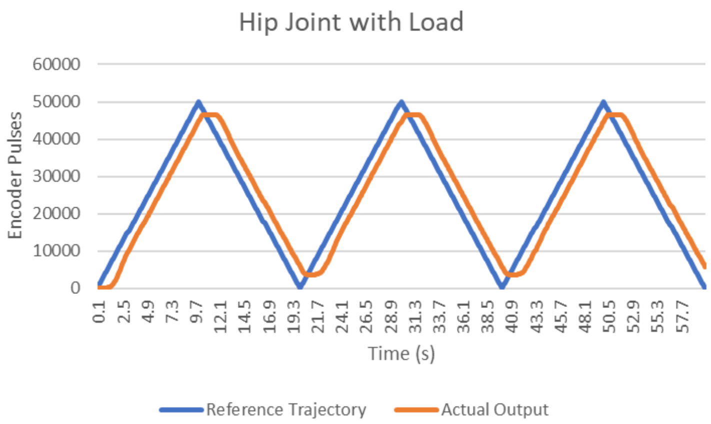

Fig. 12. Movement trajectory in the hip joint with load

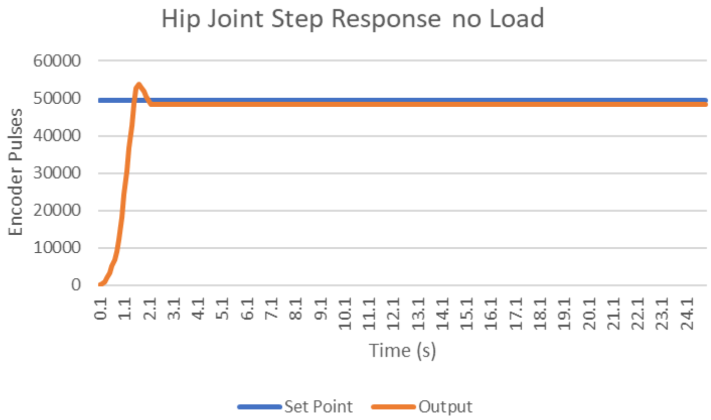

Fig. 13. Response to a Step input in the hip joint without load

Fig. 13 shows a response system without load. Since the system was tuned using a nominal load, it shows a small overshot. The amount of the overshoot is 4 degrees, and the steady state error is 1 degree. However, the test was conducted in high-speed mode. In the therapy mode, the speed will be much slower.

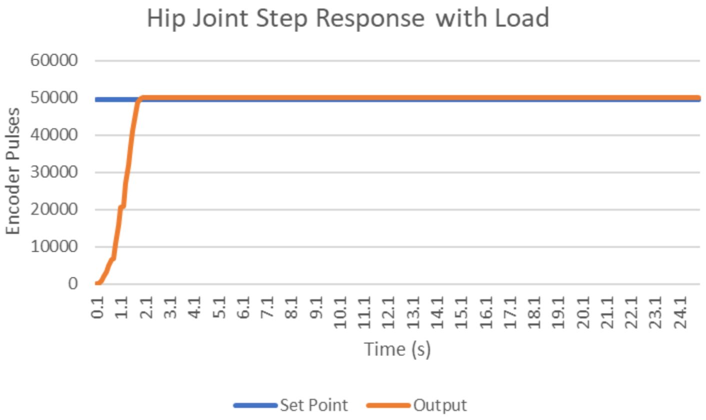

Fig. 14. Response to Step input at the hip joint with load

Fig. 15 and Fig. 16 show the precision of movement in the knee joint with and without load. When there is no load, the resulting trajectory follows the programmed trajectory. However, when a load is applied there is an error (the difference between the programmed path and the output position). Meanwhile, Fig. 17 and Fig.

18 show the stability (response) of the resulting movements in the knee joint, with and without load. When a load is applied the resulting response still has overshoot, and there is a steady-state error. The performance of this movement is summarised in Table 1. The RMSE analysis above shows that the control system without load performs better. Even so, when given a load, the system performs quite well in following the predetermined target trajectory.

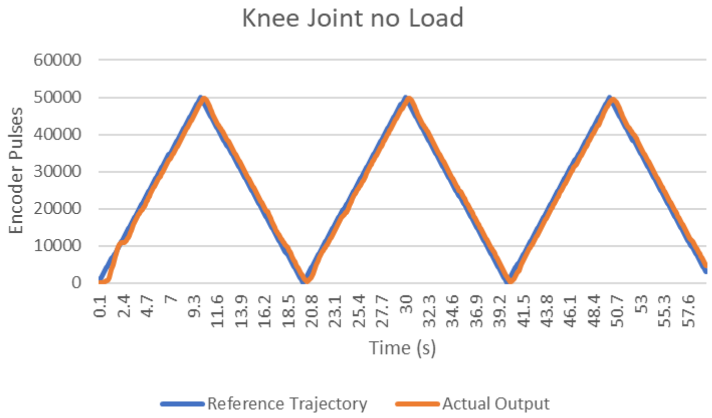

Fig. 15. Movement trajectory in the knee joint without load

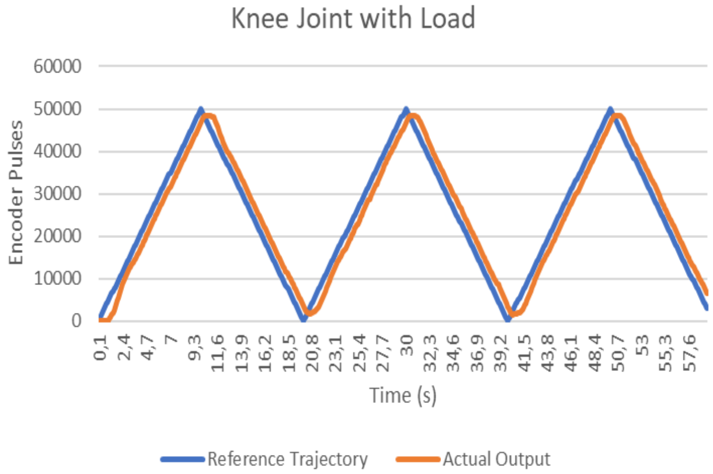

Fig. 16. Movement trajectory in the knee joint with load

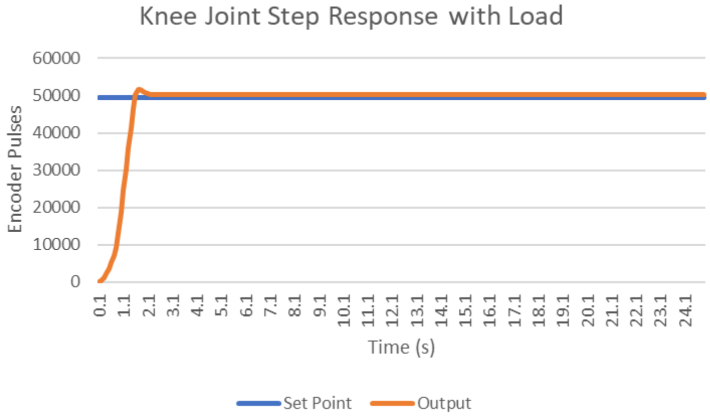

Fig. 17. Response to Step input at the knee joint with load

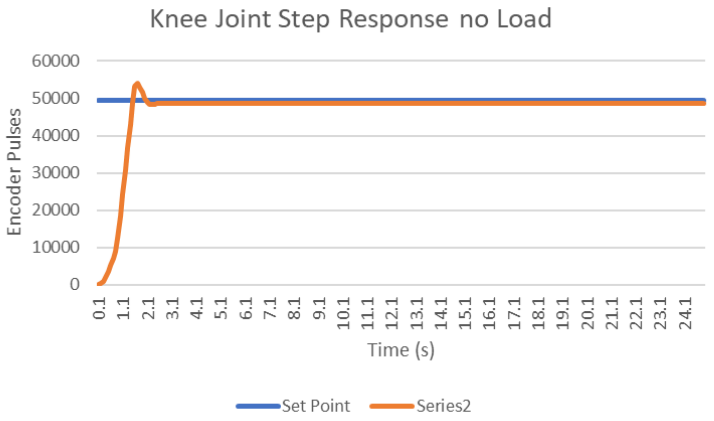

Fig. 18. Response to a Step input in the knee joint without load

Table 1. Root Mean Square Error (RMSE) of the movements

Joint	Error (RMSE)
Hip joint with load	5279.361
Hip joint no load	103.9663
Hip joint step response no load	8666.336
Hip joint step response with load	7011.209
Knee joints have no load	1617.791
Knee joint with load	3296.765
Knee joint step response with load	7994.152
Knee joint step response no load	7989.721

4. CONCLUSION

A low-cost robotic early mobilization trainer has been developed. This will be exceedingly beneficial in the context of rare and costly robotic early mobilization training equipment. This robotic early mobilization trainer employs a PID controller to facilitate the tracking of the gait trajectory. The experimental findings indicate that in the condition with load at the hip joint, the output of this device can follow the trajectory input precisely. For the knee joint, the output of this device can follow the trajectory input, but with a small steady-state error. A 0,9 degree of steady-state error does not affect the effectiveness of the therapy. PID is enough for this system because it is a simple controller but enough to give such an effective movement for the therapy.

Future study is to add a look-up table setting button. A look-up table consists of some PID constants based on the weight variation of a human leg. Therefore, a load variation can be handled easily.

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