DESIGN AND CONSTRUCTION OF CONTINUOUS PASSIVE MOTION (CPM) FOR ARM REHABILITATION DEVICE

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ABSTRACT

This research aimed to design and construct a low-cost continuous arm rehabilitation device based on the Cascade Control principle. Without the need to disassemble the machine, this rehabilitation device highlights the highly flexible design of the machine structure, which can be easily scaled to suit the users' needs. Thereupon, this study provides a promising Continuous Passive Motion (CPM) arm rehabilitation device comprising four main components: 1) Hardware design refers to the highly flexible arm rehabilitation device for postoperative treatment in patients with stiff shoulders and elbows or either the left arm or the right arm. Without machine disassembly, this device is specifically designed and built to be stable and suitable for the body shape of Asian people; 2) Mechanical structure design including setting menu, which can be adjusted during physical exercises in four different positions. There is also a touch screen display, which can be used to set the low-high angles and the appropriate time allotment for physical therapy; 3) Controller algorithm known as the signal processing in the control unit for the operation of the entire system; and 4) A safety mechanism using an emergency switch that provides safety aspects for the machinery and for the person using the machinery. The test results have indicated that this device is able to perform speed, angle and time setting control accurately and can be further developed commercially. The results of the study will be of great benefit to the field by providing quality healthcare services locally and at lower costs.

Keywords: Cascade Control, Continuous Passive Motion (CPM), Arm Rehabilitation Device.

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1. INTRODUCTION

At present, a growing number of patients, especially the elderly, are being treated for adhesive capsulitis of the shoulder and elbow, also known as frozen shoulder. Such movement restriction could arise from the natural deterioration of bone tissue, genetic disorders, and shoulder arthritis. Adhesive capsulitis can cause bursitis of the shoulder and some blood diseases. According to [1], frozen shoulder can be mainly classified into two types, namely primary frozen shoulder and secondary frozen shoulder.

To elaborate, primary frozen shoulder refers to a painful contracture of the glenohumeral joint that occurs spontaneously without any preceding events, while secondary frozen shoulder occurs as the result of predisposing factors, such as the joint inflammation, muscle strains, bone fractures in the areas of shoulder and elbow, central nervous system diseases, cardiovascular diseases, diabetes, hyperthyroidism, and hypothyroidism [2]. Secondary frozen shoulder typically consists of two sub-categories. The intrinsic category includes the limitation of active and passive range of motion in association with shoulder joint disorders, whereas the extrinsic category refers to an identifiable abnormality outside of the shoulder. As such, to ensure that a fracture is properly detected and treated the same way as primary frozen shoulder, it is essential that an X-ray must be performed.

Typically, the treatment of frozen shoulder can be prescribed as both surgical and non-surgical treatment. For the non-surgical option, steroid injections can be highly effective when they are used in conjunction with other treatments such as pain-relief medications and physiotherapy, depending on the underlying conditions. Nevertheless, a more invasive procedure may be required in severe cases or patients who are unresponsive to non-surgical treatment.

With reference to the aforementioned differences, the frozen stage must thereupon be considered when planning treatment strategies. In the event that there is no proper movement or exercise for a period of 6 to 12 weeks, a tendency of joint stiffness could occur. Therefore, this period is imperative for the restoration of normal mobility. Patients experiencing shoulder and elbow stiffness, especially those undergoing surgery, will recover rapidly during the first six months. As such, a rehabilitation should be provided to patients on a daily basis in order to increase and restore the normal range of motion of the shoulder joint.

According to the state-of-the-art literature review, a continuous passive motion (CPM) machine allows for the restoration of normal joint mobility after surgery. A patient may use a CPM machine after undergoing a joint surgery such as hip and knee replacements. In addition, a CPM machine is commonly used for rehabilitation following the knee and shoulder surgical procedures. Empirical evidence has suggested that the use of a CPM machine in the immediate postoperative period can lead to a reduction in hospital observation and an increase in early range of motion. Moreover, a CPM machine can offer a variety of benefits: (1) the joint can receive needed nutrition, (2) the range of motion is maintained, (3) the associated pain is decreased, and (4) the recovery time is accelerated. The immediate use of a CPM machine after surgery seemed to be an effective method in expediating recovery and reducing the risk of early degenerative joint disease. Thus, a CPM machine has become particularly helpful in the initial phase of recovery.

Furthermore, there are a variety of popular technologies in the industry to improve motor-sensory disability for hips, knees [3, 4, 5, 6], ankles [7], shoulders [8, 9], elbows [10, 11,12], wrists [13, 14], fingers [15], and upper-limbs. To illustrate, Miyaguchi, Matsunaga, and Kawaji [15] proposed a CPM device for the elbow to suppress reaction force based on the musculoskeletal system. In their device, the flexion and stretching range could be set by the switch box, and the flexion and extension angles of the elbows were controlled via a DC motor and rotary encoder. Nonetheless, the treatment time could not be set, and the patients must always be in control of their own treatment.

In addition, Hung-Jung Ho and Tien-Chi Chen [6] developed a combined CPM/CAM device that could simultaneously operate both CPM (Continuous Passive Motion) and CAM (Continuous Active Motion) systems in one device. CPM/CAM physiotherapy devices are commonly used to promote rehabilitation of damaged synovial joints to help minimize stiffness and increase range of motion.

CAM devices use some forms of mechanical resistance to patient muscle activity. They are typically designed to move continuously without requiring patients to stretch and bend. The CAM system has been combined with the CPM system to help in the process of exerting and stretching. As such, these devices may be used after surgery to reduce joint stiffness and improve range of motion. Occasionally, they are also used after knee replacement, elbow, hip, or shoulder surgeries. The operation and remote treatment are usually controlled by a LAN and a network operation control. Nevertheless, the research into the development and use of these devices is normally complex, costly, and time-consuming.

With the use of PLC (Programmable Logic Control) as the open operating controller, Metan, Mohankumar and Krishna [8] designed and built a low-cost CPM machine with a stepper motor. The device was specifically developed with the lightweight design for the shoulder joints for the purpose of accelerating the recovery of shoulder joint injuries. The findings of the study revealed that the low-cost machine with a reduction by 40 percent was effective as proven by the successful treatment of 30 patients in a prestigious hospital in India. The significant reduction in cost as compared to other commercial machines has forced the large number of rehabilitation centers to use the CPM machine for the cost-effective treatment. Despite this, the stability of the machine is not as strong as expected.

In 2019, Antonius Hendro Noviyanto [9] designed and developed a CPM machine for shoulder physiotherapy. The machine was powered by a DC motor, which was driven by a PID microcontroller. In the machine, there were three speed levels with two physical movements – flexion and horizontal movements.

Generally, human joints are soft and flexible in nature. They also have hyperelastic properties, which change with respect to the muscle activities. Measurement and understanding of joint pain in the human body are crucial in several areas, such as rehabilitation engineering, biomechanics, bionics, human robotics, etc. Such thorough understanding of human joints and muscles enables humans to develop bio-inspired control strategies to be implemented in innovative ways in order to explore new therapy options for individual and group muscle behaviors in human joints. Even though there have been numerous initiatives taken to develop CPM devices, most of the available devices are expensive and complicated. They also have the heavy structure and too many mechanical parts linked to patients' arms, which can be rather uncomfortable for patients. In addition, certain devices are used in static platforms or designed for some specific applications. Many existing devices are also controlled by an external PC without the embedded control system.

In regard to Continuous Passive Motion (CPM), it is a machine that facilitates the restoration of shoulder or elbow movement to the normal pace, allows the shoulder or elbow joints to move in and out at a gradual speed, reduces swelling, prevents venous thrombosis, and decreases the need for pain medication [16, 17, 18].

Another benefit of a CPM machine is that it can reduce the recovery time and the burden of physical therapy expenses. Patients can do physical therapy on their own without any assistance from a physical therapist. This consequently helps patients save time since performing physical therapy with a physical therapist traditionally requires at least one hour for one patient. Visiting a healthcare unit on a daily basis undoubtedly requires a large amount of both time and financial resources. Hence, the health system falls under pressure with the greater demand for providing healthcare on an outpatient basis.

At present, as continuous arm movement devices have to be imported from overseas, the continuous arm movement aids in Thailand become extremely expensive. This consequently makes it difficult for small and rural hospitals to access such aids. Moreover, the imported machine is inconvenient and has the risk of complications. That is, with its redundant structure and complex mechanism, the regular maintenance of the machine becomes rather difficult to perform.

Considering the existing needs for locally developed technological CPM equipment designed for arm rehabilitation that could be used in hospitals, clinics, physician's offices, and residences, this paper thus contributes to the design of a CPM device for arm rehabilitation. The aim of this research was to design and build a continuous arm rehabilitation apparatus to do physical exercises in both elbow and shoulder parts without disassembly convenient for users. The machine is stable and strong, supporting the body weight of 150 kilograms. It allows physical exercises in four positions: (1) Vertical Abduction/Abduction (0° - 180 °), (2) Horizontal Adduction/Abduction (0° - 140 °), (3) Flexion/Extension (0° - 175 °), and (4) Lateral/Medial Rotation (0° – 180 °).

After the discussion about the introduction, the second section is relative to the definition of mechanical structure design, which is followed by the third section regarding the hardware design and implementation. Following that, the controller algorithm will be detailed in the fourth section. Finally, the last section is concerned with the results and discussions.

2. MECHANICAL STRUCTURE DESIGN

Among the different challenges and issues in utilizing the continuous arm physiotherapy machine, the high cost of the machine has become a major concern for its implementation in rehabilitation centers across Thailand. To elaborate, in many physiotherapy centers, the use of a CPM machine is limited by the cost of the equipment. In addition to the cost, the size of the machine with the limited scale is also not suitable for the body shape of Asian people. As the human shoulder has the maximum number of muscles with the maximum degree of freedom, proper care should consequently be given to the shoulder muscles. That is, to provide the proper care, the machine should be highly smooth, slow, and continuous in operation.

Thereupon, this research highlights the highly flexible design of the machine structure, which can be scaled to suit the users' needs. Without the need to disassemble the machine, this rehabilitation device can be adjusted for the usage with either the left arm or the right arm. Such a feature could be of particular benefit to physiotherapists since disassembling the rehabilitation device could be a problematic task for those who are not familiar with it.

The machine can be adjusted using both arms when doing physical exercises on both elbows and shoulders in four different positions. The angle of doing physical therapy can also be adjusted in 45-degree increments to suit the physiotherapist's needs. As illustrated in Figure 1, apart from four basic physical exercises (Vertical Abduction/Abduction, Horizontal Adduction/Abduction, Flexion/Extension, and Lateral/Medial, this device can further be adjusted for the patients to effectively perform a more flexible position called an eating food position. In the anatomical position, this increases more flexibility and mobility by incorporating dynamic stretching of the forearm. The machine is specifically designed and built to be stable, making physical patients feel safe and comfortable when using the machine. There is also a touch screen display, which can be used to set the angle and the appropriate time allotment for physical therapy. During the physical therapy session, the time limit can be paused, or the treatment can be instantly cancelled with one press. That is, there is an emergency switch to stop the machine operation, which is used in the event that a physical therapist feels pain. The details of the setting are as follows:

- d1 Adjust the arm length
- d2 Adapt to the elbow or shoulder
- d3 Adjust to the shoulder width
- d4 Adjust the height of the machine
- d5 Adjust the height of the chair
- d6 Adjust the chair backrest height
- θ1 Adjust vertically or horizontally. (It can be adjusted in 45-degree increments.)
- θ2 Adapt to the left arm or right arm
- β1 Adjust the chair angle (0 – 360 degrees)
- α1 Adjust the physiotherapy angle (0 – 180 degrees)

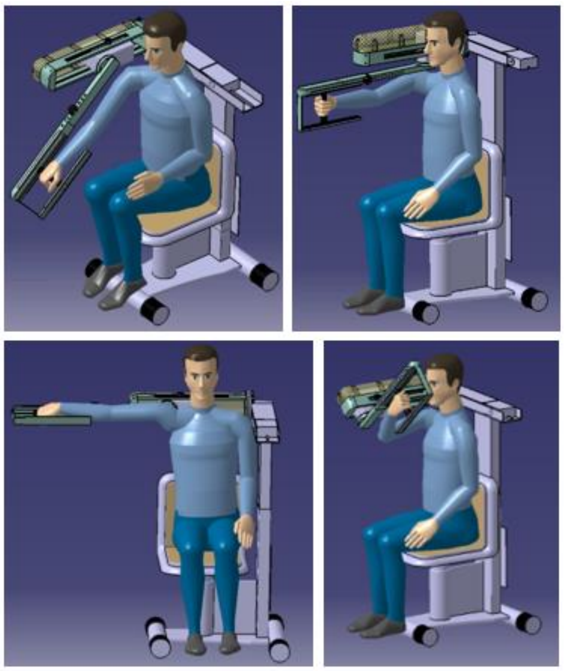


Figure 1. Examples of Machine Setup for Arm Rehabilitation

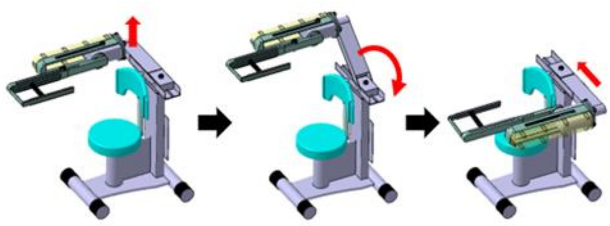


Figure 2. Arm Shift Operations (from left to right rotation)

The adjustment of the position of the machine from the right arm to the left arm is shown in Figure 2.

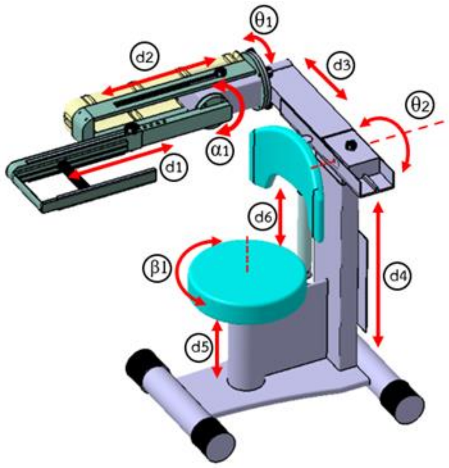


Figure 3. The Machine Setup Positions

Figure 3 shows the suitable setting of the machine for new users.

Table 1. Machine Settings at Different Parameters

Angle/ Link	Low angle (Degree)	High angle (Degree)	Distance (cm.)
d1	-	-	0 to 20
d2	-	-	0 to 30
d3	-	-	-35 to 0 to 35
d4	-	-	80 to 115
d5	-	-	40 to 45
d6	-	-	60 to 70
θ1	0	360	
θ2	0	180	
β1	0	360	
α1	-90	90	

Table 1 shows machine settings at different parameters. Different ranges and joints are adjustable according to linear ranges (d1-d6) and angle in degrees (θ, β, and α).

3. HARDWARE AND IMPLEMENTATION MECHANICAL STRUCTURE DESIGN

As portrayed in Figure 4, designing and constructing a continuous arm physiotherapy device comprises two main systems: (1) the master device as the main control with display and (2) the slave device receiving the initial values from the parameters. The four postures sent by the master device are Vertical Abduction/Abduction, Horizontal Adduction/Abduction, Flexion/Extension and Lateral/ Medial Rotation, respectively. There are also options for low angle, elevation angle, speed, and treatment duration. When the 'START' button is pressed following the setup process, all data are subsequently transmitted to the slave device using the 115000 b/s UART serial communication system. The master device contains the following main components as follows:

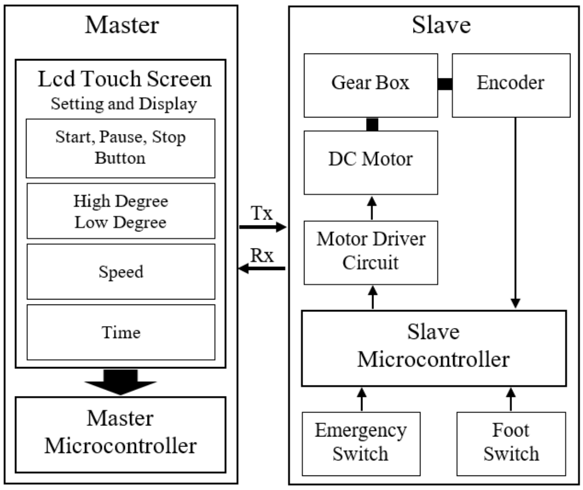


Figure 4. Block Diagram of Operating System

On the contrary, a slave device consists of a motor control for parameter input from the master controller, which is used for activating the motor. Furthermore, the motor moves at the set maximum speed in both the low and high angles as well as the back-and-forth directions. Upon the completion of the treatment, the motor will automatically stop and return to the starting point. Afterwards, the system will be reset. For the motor set, this study uses a DC motor, which was connected to a gear box.

As shown in Figure 5, a seven-inch crystal touch screen is practical for the CPM mode. For the CPM mode, there are four postures available for selection, namely Vertical Abduction/Abduction, Horizontal Adduction/Abduction, Flexion/Extension and Lateral/ Medial Rotation, respectively. The options of low angle, elevation angle, speed, and treatment duration are also available. In the design of the machine, a crystal touch screen was selected. In the CPM mode, three main buttons: the START, PAUSE, and STOP buttons are included as depicted in Figure 5.

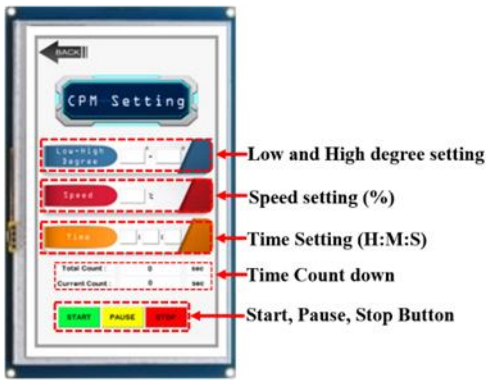


Figure 5. Display Screen and Settings Menu

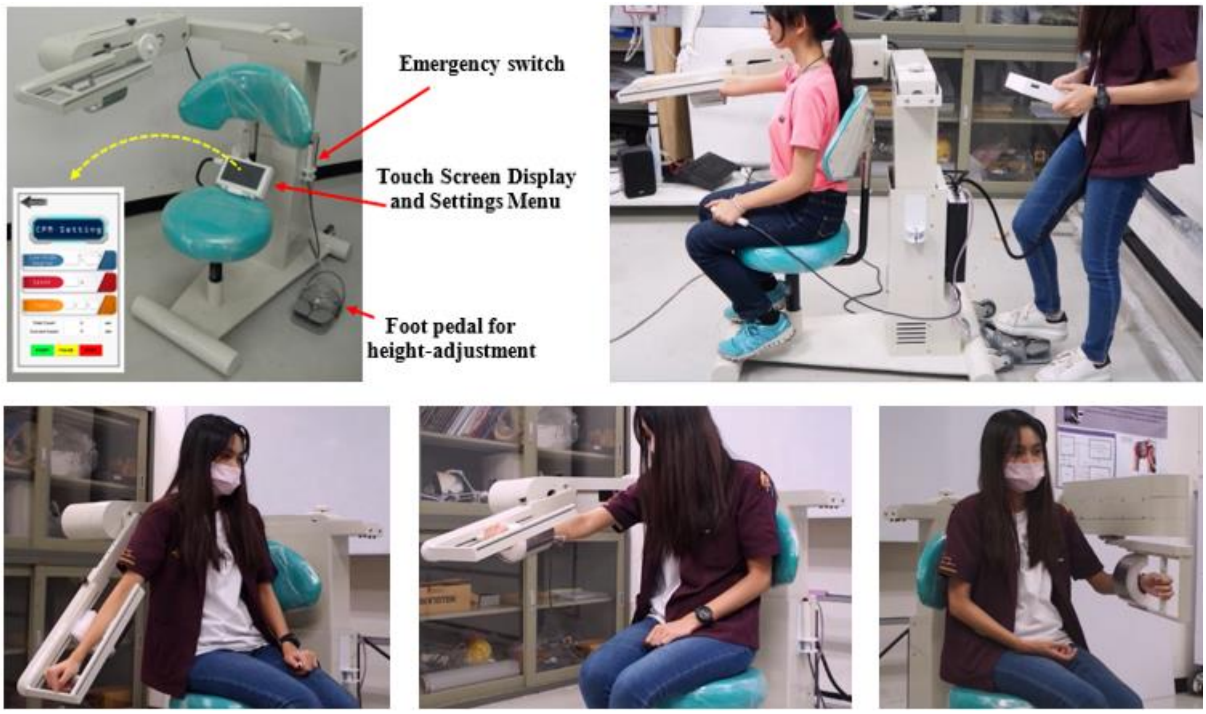


Figure 6. A Continuous Passive Motion Device for Arm Rehabilitation

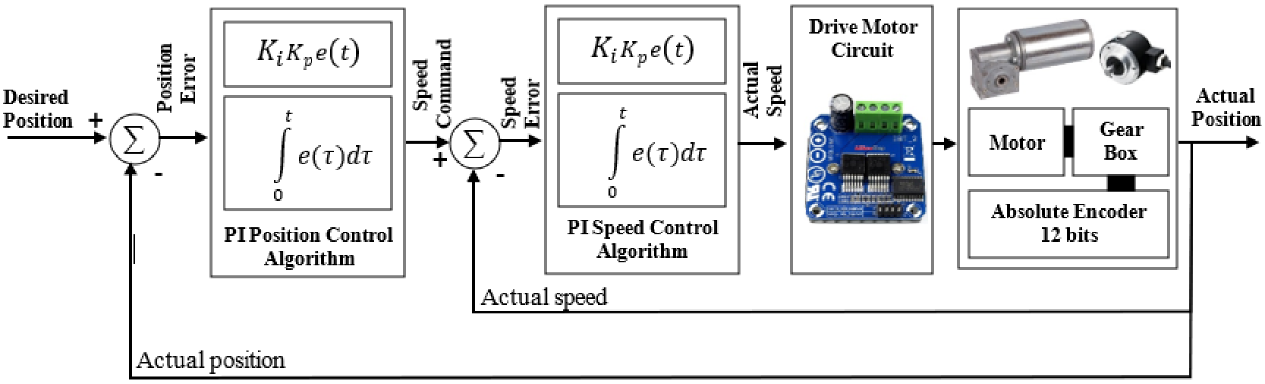


Figure 7. Structure of Cascade PI/PI Controller

Figure 6 illustrates the main components of a Continuous Passive Motion (CPM) device for arm rehabilitation, which can be effectively adjusted to suit the users' needs. Figure 7 shows the control system of the machine. The overall system is centered on the control panel and the touch screen display. This main controller is responsible for transmitting information that the physiotherapist has predetermined to the motor module via UART (Universal Asynchronous Transmitter Receiver) communication at 115200 bps. As for the display settings, the information includes the low angle, high angle, speed, and rehab time.

Following the machine configuration and the START button activation, the machine will start working to assist the patient with arm lifting. Regarding the predetermined procedures, the machine will accordingly operate at a consistent speed as previously programmed.

To temporarily pause the treatment, the PAUSE button needs to be pressed. The patient can resume the treatment by repressing the START button. Nonetheless, if the patient wishes to stop the treatment, the STOP button needs to be activated. Afterwards, the machine will automatically reset to its ready-to-use position.

4. CONTROLLER ALGORITHM

Drawing on the Cascade Control principle, the design approach presented in this paper guarantees the smooth control of the device. The rationale underlying the device operation is associated with the complete set of tuning parameters for the inner loop and the outer loop.

With a load capacity of 15 Nm, the torque required by the drive unit can be estimated from Equation 1 [20].

$$\tau = m \times g \times \frac{1}{2} l \quad (1)$$

where: τ = torque (Nm) W = force (N) l = length (m), m = mass (kg), g = acceleration of gravity (m/s2)

Assuming an average of 120 kilograms body weight, the arm weight of both women and men is 4.715% of body weight [19], so the arm weight will be equal to (100 ×4.715)/100=4.715 where τ = 4.715 × 10 × 1/2×0.5 = 11.78 Nm

Based on the preliminary calculation, it can be seen that the propellant can support the weight of a person weighing up to 100 kilograms. The information on the weight test is presented in the results section.

$$e(t) = SP - PV \quad (2)$$

$$u(t) = u_{bias} + K_c e(t) + \frac{K_c}{\tau_I} \int_0^t e(t) dt \quad (3)$$

A variation of Proportional Integral Derivative (PID) control is to use only the proportional and integral terms as PI control. The PI controller is the most popular variation, even more than full PID controllers. The value of the controller output u(t) is fed into the system as the manipulated variable input. The ubias term (equation 3) is a constant that is typically set to the value of u(t) when the controller is first switched from manual to automatic mode. This gives "bumpless" transfer if the error is zero when the controller is turned on. The two tuning values for a PI controller are the controller gain, Kc and the integral time constant τI. The value of Kc is a multiplier on the proportional error and integral term and a higher value makes the controller more aggressive at responding to errors away from the set point. The set point (SP) is the target value and process variable (PV) is the measured value that may deviate from the desired value. The error from the set point is the difference between the SP and PV and is defined as equation 2.

Digital controllers are implemented with discrete sampling periods and a discrete form of the PI equation is needed to approximate the integral of the error. This modification replaces the continuous form of the integral with a summation of the error and uses Δt as the time between sampling instances and nt as the number of sampling instances.

$$u(t) = u_{bias} + K_c e(t) + \frac{K_c}{\tau_I} \sum_{i=1}^{n_t} e_i(t)\, \Delta t \quad (4)$$

Common tuning correlations for PI control are the IMC method (Internal Model Control). IMC is an extension of lambda tuning by accounting for time delay. The parameters Kc, τp, and θp are obtained by fitting dynamic input and output data to a first-order plus dead-time (FOPDT) model. The first step in using the IMC tuning correlations is to compute the closed loop time constant. All time constants describe the speed or quickness of a response. The closed loop time constant describes the desired speed or quickness of a controller in responding to a set point change. Hence, a small closed loop time constant value (i.e. a short response time) implies an aggressive controller or one characterized by a rapid response. Values for the closed loop time constant are computed as follows:

AggressiveTuning : τc=max (0.1τp, 0.8θp)
ModerateTuning : τc=max (1.0τp, 8.0θp)
ConservativeTuning : τc=max (10.0τp, 80.0θp)

With the closed loop time constant and model parameters from the previous section computed, non-integrating (i.e. self-regulating) tuning parameters for a simple Ideal PI Controller can be determined using the following equation (5). Final tuning is verified on-line and may require adjustment. If the process responds sluggishly to disturbances and/or changes to the set point, the controller gain is most likely too small and/or the reset time is too large. Conversely, if the process responds quickly and is oscillating to a degree that is undesirable, the controller gain is most likely too large and/or the reset time is too small.

$$K_c = \frac{1}{K_p} \frac{\tau_p}{\theta_p + \tau_c} , \qquad \tau_i = \tau_p \quad (5)$$

In addition to a fast closed-loop response, this method prevents motor vibration during machining operation. The primary controller uses two parameters, namely Kvp and Kvi. It also establishes a set point for the secondary controller, which controls the motor speed. We uses two parameters is Kvp and Kvi to controls the motor speed. Moreover, the machine comprises a soft-start and a soft-stop operation to avoid the movement issues.

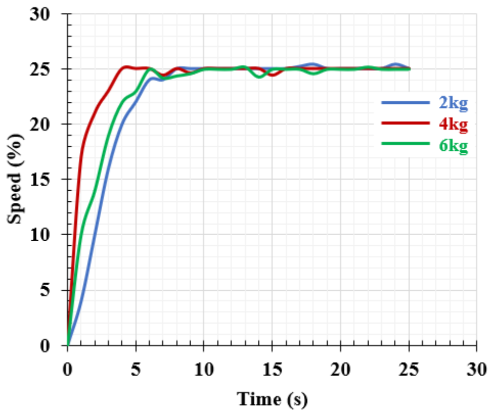
5. EXPERIMENTAL RESULTS

Initially, the test was performed using a one-kilogram weight arranged lengthwise according to the shape of the arms. The weights utilized in the test included two, four, and six kilograms, respectively. Such weight ranges were obtained by calculating the arm's weight per body weight percentage.

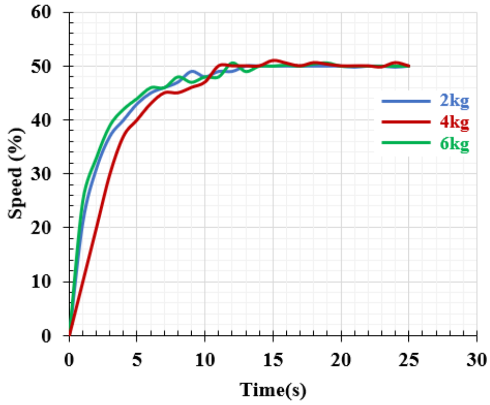
In terms of the men's weight, Upper Arm was reported at 2.71%, Forearm (1.62%), and Hand (0.61%). For women's weight, Upper Arm was at 2.55%, Forearm (1.38 %), and Hand (0.56%). On average, the weight of the arms for both women and men was at 4.715% of body weight [19].

Therefore, the researchers utilized the lowest weight of two kilograms for an individual weighing approximately 42 kilograms and four kilograms for an individual weighing roughly 85 kilograms. Simultaneously, the highest weight of six kilograms was used with an individual weighing approximately 128 kilograms.

Figures 8-10 present the results of the machine's usability test at 25%, 50%, 75% and 100%, respectively. The position was set at -30 degrees to 30 degrees and at -60 degrees to 60 degrees at 2,4 and 6 kilograms, respectively.



(a)



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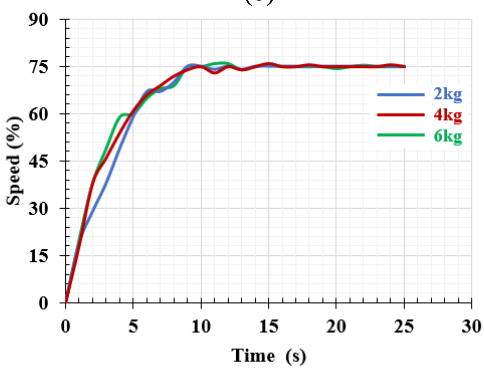

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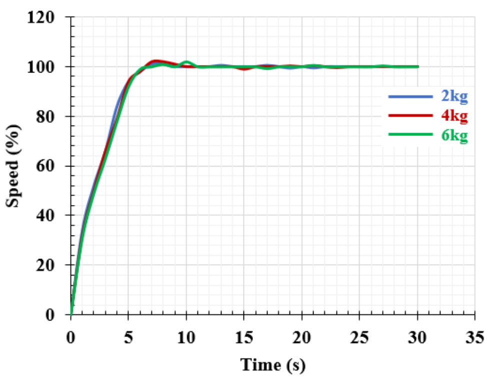
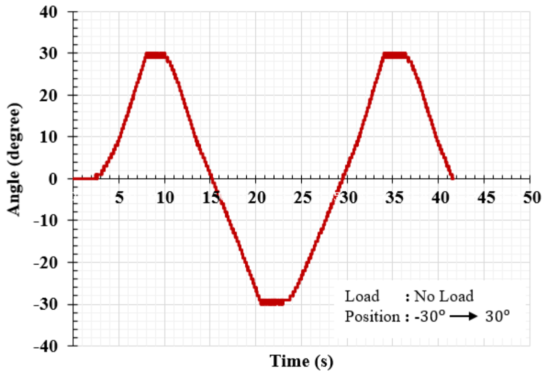
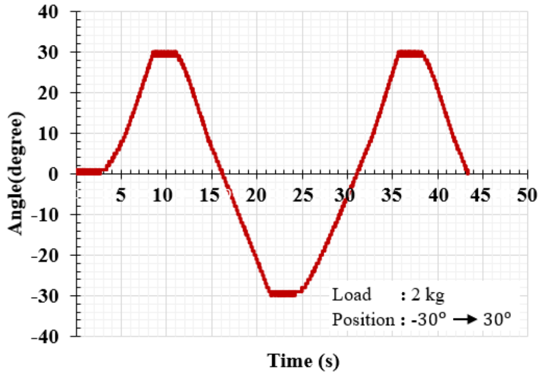


(d)

Figure 8. Speed Control Test Results (a) 25% Speed (b) 50% Speed (c) 75% Speed (d) 100% Speed



(a)



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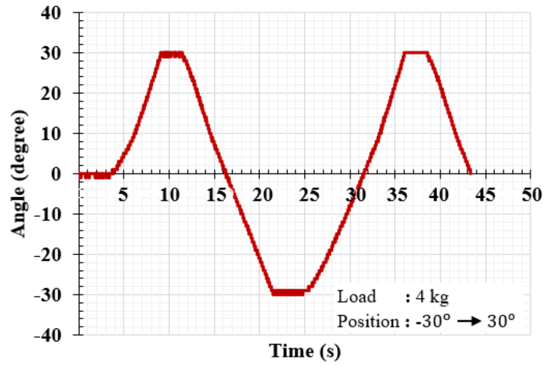

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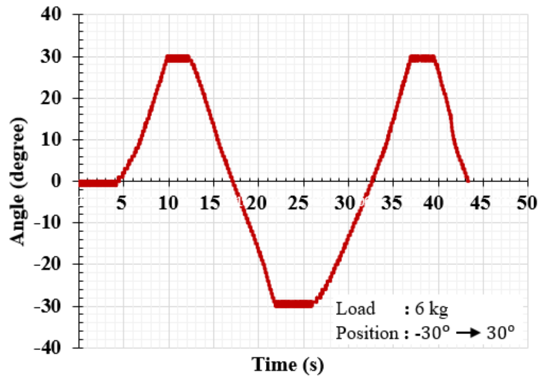
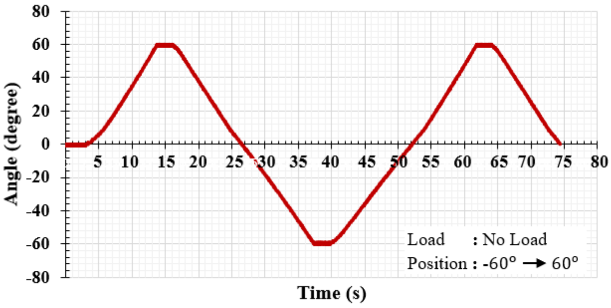
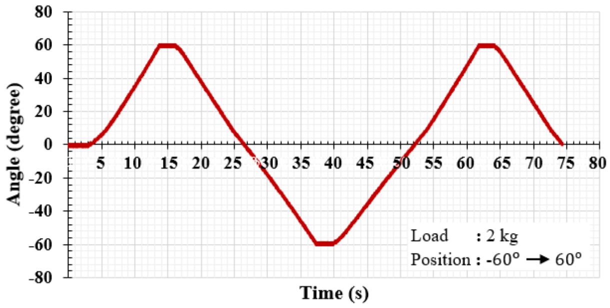


(d)

Figure 9. Results of Position Control -30 Degrees to 30 Degrees Figure (A) Tested Under No-Load Conditions (B), (C) and (D) Tested at Weights of 2, 4 and 6 kg, respectively.



(a)



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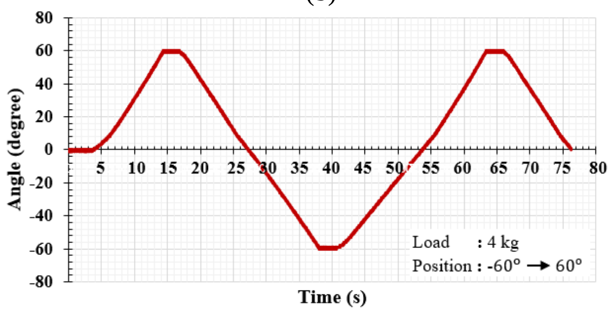

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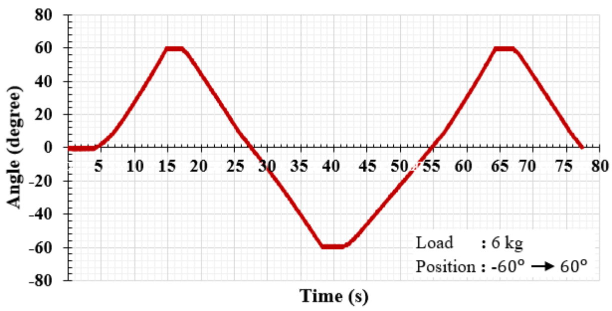

(d)

Figure 10. Results of Position Control -60 Degrees to 60 Degrees Figure (A) Tested Under No-Load Conditions (B), (C) and (D) Tested at Weights of 2, 4 and 6 kg, respectively.

6. DISCUSSION AND CONCLUSION

This research aimed to design and construct a continuous arm rehabilitation device for postoperative treatment in patients with stiff shoulders and elbows. This is intended to minimize the needs to import expensive medical devices from overseas and to ignite research on the development of rehabilitation devices. Stakeholders´ requirements were taken into consideration to determine the design features and an algorithm. Lastly, a working prototype was made to carry out all functional tests.

Upon the research completion, this study provides a promising result with the four physical posture adjustments: Vertical Abduction/Abduction (0° – 180°), Horizontal Adduction/Abduction (0° - 140°), Flexion/Extension (-50° - 175°), and Lateral/Medial Rotation. (0° – 180°). The speed can be adjusted from 1-100%, where 100% equals the speed of 1 rev/min (6 degrees/1 second). In addition, the angle can be adjusted up to 180 degrees according to the user's needs (low angle and high angle).

Furthermore, for the accurate time setting system, the treatment time allotment can be programmed as required. There is a 100% accurate safety system for the purpose of harm and injury prevention.

The test results have indicated that this device is able to perform speed, angle and time setting control accurately and can be further developed commercially. Based on such findings, this study will greatly contribute to the field by providing opportunities for provincial hospitals in rural areas to access proper and effective healthcare.

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