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# Soft Pneumatic Exoskeleton for Wrist and Thumb Rehabilitation

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ABSTRACT

A huge population of the world is suffering from various kinds of disabilities that make basic daily activities to be challenging. The use of robotics for limb rehabilitation can assist patients to recover faster and reduce therapist to patient ratio. However, the main problems with current rehabilitation robotics are the devices are bulky, complicated, and expensive. The utilization of pneumatic artificial muscles in a rehabilitation system can reduce the design complexity, thus, making the whole system light and compact. This paper presents the development of a new 2 degree of freedom (DOF) wrist motion and thumb motion exoskeleton. A light-weight 3D printed Acrylonitrile Butadiene Styrene (ABS) material is used to fabricate the exoskeleton. The system is controlled by an Arduino Uno microcontroller board that activates the relay to open and close the solenoid valve to actuate the wrist. It allows the air to flow into and out of the pneumatic artificial muscles (PAM) based on the feedback from the sliding potentiometer. The mathematical model of the exoskeleton has been formulated using the Lagrange formula. A Proportional Integral Derivative (PID) controller has been implemented to drive the wrist extension-flexion motion in achieving the desired set-points during the exercise. The results show that the exoskeleton has successfully realized the wrist and thumb movements as desired. The wrist joint tracked the desired position with a maximum steady-state error of 10% for 101.45° the set point.



## 1. Introduction

The number of stroke victims is increasing every day. Many of them are left with disabilities that make basic daily activities to be very difficult [1]. As a result, they need to depend a lot on the caregiver [2]. Rehabilitation exercises can help the patients to recover and regain their limbs functionality [3][4]. Most of the current rehabilitation therapies are conducted manually by the therapists at the hospitals or rehabilitation centers. However, the ratio of the therapist to patients for manual rehabilitation exercise in Malaysia and many other countries all over the world is low. This means that there is a low number of therapists available to aid the high number of patients, which can lead to patients getting less treatment or skipping treatment and a high therapist workload. Rehabilitation devices or machines [5]-[14], including wearable exoskeletons, can help the health service provider in providing repetitive rehabilitation therapy more effectively. Some of the available commercialized rehabilitation devices include the Hand-Wrist Assisting Robot Device (HOWARD) developed by Takahashi et al., [15].

A rehabilitation device can be actuated by electric motors [16], hydraulic [17], pneumatics [18]-[20], smart materials [21]-[25], and passive elements such as springs. Pneumatic Artificial Muscle (PAM) is a pneumatic actuator consisting of an internal bladder that can stretch as the air enters and returns back to its original shape once the air leaves. When the internal bladder is pressurized, the PAM volume increases, and its length shortens. Its surrounding braided shell limits its expansion and so that its cylindrical shape remains. Using PAM, the designs for rehabilitation exoskeleton can be made to be compact and lightweight due to the high power to weight ratio nature of the actuator. It also provides an economical actuation solution and offers safe usage for the users [26].

Previous works on the PAM exoskeleton include the work by Chen et al., where the researchers developed the mathematical model of a new upper limb exoskeleton driven by cables and powered bay PAM using the Lagrange method. The mechanism performs passive exercises in rehabilitation therapy [27]. Merola et al. studied the control of a PAM actuated rehabilitation device to solve the nonlinearity and hysteresis problem in the pneumatic muscles, which can affect the system response [28]. The wrist rehabilitation system based on a soft parallel robot has been presented in [29], in which the design offers the advantages of parallel mechanism, and Nguyen et al. proposed an intelligent controller known as adaptive sliding controller and added a compensator for PAM actuated elbow rehabilitation device [30]. In work by Capace et al., a PAM actuated exoskeleton for "assist-as-needed" control strategy has been formulated [31]. Although many exoskeletons have been developed in past studies, many of the systems are bulky, complicated, and expensive.

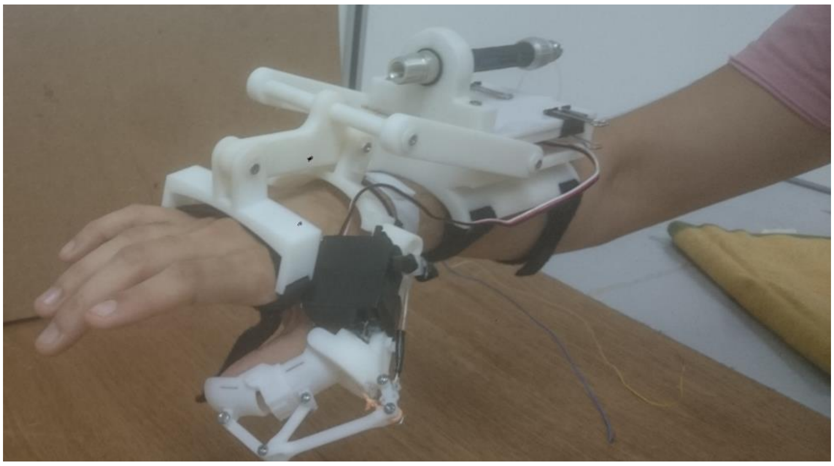
The contribution of this paper is the development of a new pneumatic exoskeleton for wrist rehabilitation that is a device simple, compact, light-weight, and low cost. The thumb movement is actuated by a servo motor. The rest of this paper is organized as follows. Section 2 presents the soft pneumatic, mechanical design, electronic configuration, and operational sequence. The mathematical modeling for the new wrist flexion/ extension mechanism and its PID controller are described in Sections 3 and 4, respectively. The results are presented and discussed in Section 5, and finally, a conclusion is drawn in Section 6.

## 2. Development of Soft Pneumatic Exoskeleton for Wrist and Thumb Rehabilitation

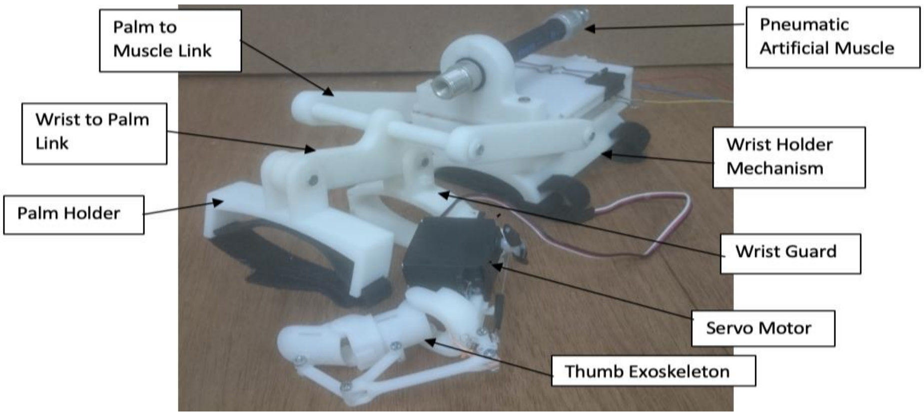
### 2.1 Mechanism Design

The prototype of the soft pneumatic exoskeleton for wrist and thumb rehabilitation is shown in Fig. 1. It is mechanical drawing, as shown in Fig. 2, has been drawn using Solidworks software. The dimension of the design is based on the average size of the hand. The design consists of a palm holder to secure the human palm while it is in motion, a wrist guard, a D-link, wrist holder mechanism, Pneumatic Artificial Muscle (PAM), a palm to PAM link, a thumb exoskeleton, servo motor, a solenoid valve, and PAM.

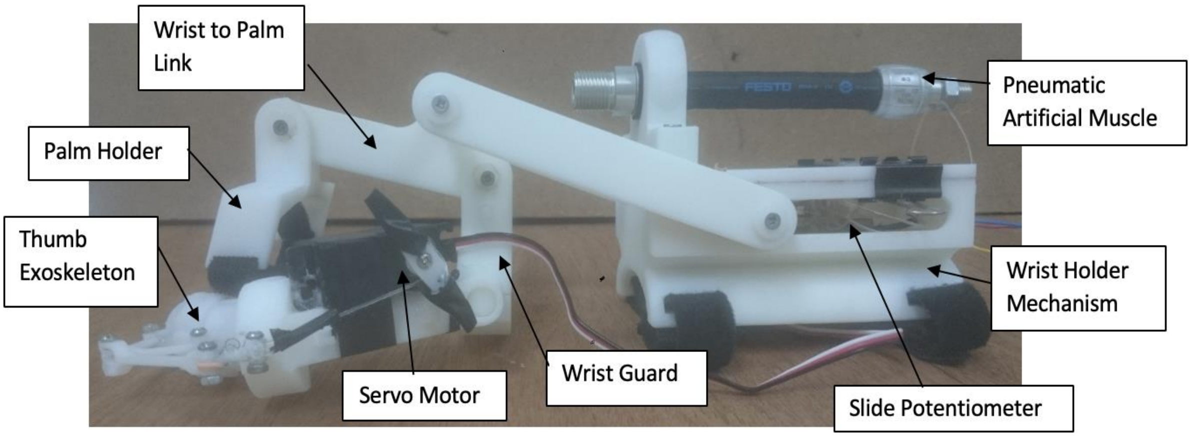
During the rehabilitation exercise, the wrist guard and the wrist holder are secured to the user's wrist. The user's palm is fastened to the palm holder with the help of Velcro straps, and the thumb exoskeleton is worn on the user's thumb. The wrist guard is attached to the thumb exoskeleton that is actuated by a servomotor, as shown in Fig. 1. The palm holder is connected to the wrist guard by a D-link that is attached to the Palm to PAM link. This link is connected to the PAM through a cable and converts the PAM's linear motion to the angular displacement of the patient's wrist joint (flexion/extension motion). A slide potentiometer is installed at the end of the link to measure the PAM's linear displacement. The PAM is connected to a solenoid valve which can be turned ON or OFF as commanded by the microcontroller through a relay. The end part of the solenoid valve is connected to the air compressor tank that supplies constant air pressure. The PAM is unidirectional, where it actuates the mechanism in one direction only by pulling the Palm to PAM link to realize the flexion motion of the wrist. A spring is used to return the Palm to PAM link to its initial position and counter the force from the PAM once it is empty for the wrist extension.



(a)




(b)




(c)

**Fig. 1.** Proposed soft pneumatic exoskeleton for wrist and thumb rehabilitation (a) worn on a human arm (b) isometric view (c) side view

In the mechanism operation, the PAM is filled with air, and as a result, it pulls the wrist to the maximum desired angle for flexion motion. Once this is achieved, it releases the air to return to the initial position and extends the wrist to its original position. The process is repeated for several cycles until the therapy session ends. In order to control the speed of the solenoid valves, their opening and closing time is set accordingly. By changing the time, the valve's movement pace per one cycle can be increased or decreased depending on the time chosen. As for the thumb motion, the servo motor rotates from the initial position to the final angle repetitively until the therapy session is completed. A delay is introduced in the Arduino programming to slow down or speed up the servomotor and thumb movement. The velocity of both the thumb and wrist are initially set to the lowest and then capped to the maximum value that is safe for the patients.

The whole structure of the exoskeleton has been developed using 3D printing with Acrylonitrile Butadiene Styrene (ABS) material. This method enables the fabrication of complex designs to be done in a shorter time compared to the techniques involving lathe and milling machines. The ABS material also is suitable for the exoskeleton design since it is lightweight, simple, and cheap. Arduino Uno is selected as the micro-controller since it is easy to use, cheap, and contains enough input and output ports for the exoskeleton mechanism requirement. The PAM utilized in the exoskeleton construction has an inner diameter of 10 mm with a nominal length of 80 mm. Its maximum permissible extension is 25% of its nominal length, and the operating pressure is between 0 to 8 bar. The solenoid valve chosen is the AQT15S model that allows airflow from the inlet or outlet when triggered electrically. Puma XN 2040 air compressor is used to supply constant air to the air muscle. The air flows from the tank to the PAM through an open solenoid valve. Another valve will open to exhaust the air from the PAM into the atmosphere when it is required to expand. A small hose barb is attached to the ends of the pipe and solenoid valve to ensure that the air is filled into the PAM smoothly. The RC servomotor (plastic gear) from Cytron Technologies is chosen to actuate the thumb movement since it is small, light-weight, easy to be programmed to reach the desired position, and able to provide sufficient torque for the prototype. A sliding potentiometer with resistance 10kΩ is installed in the wrist holder mechanism to measure the displacement of the Palm to PAM link. It is similar to a rotational potentiometer, but instead of having a rotatable shaft that changes its resistance, this type of potentiometer has a slider that moves in a linear motion to vary its resistance. The total cost for the complete exoskeleton excluding the air compressor tank is RM 837.00

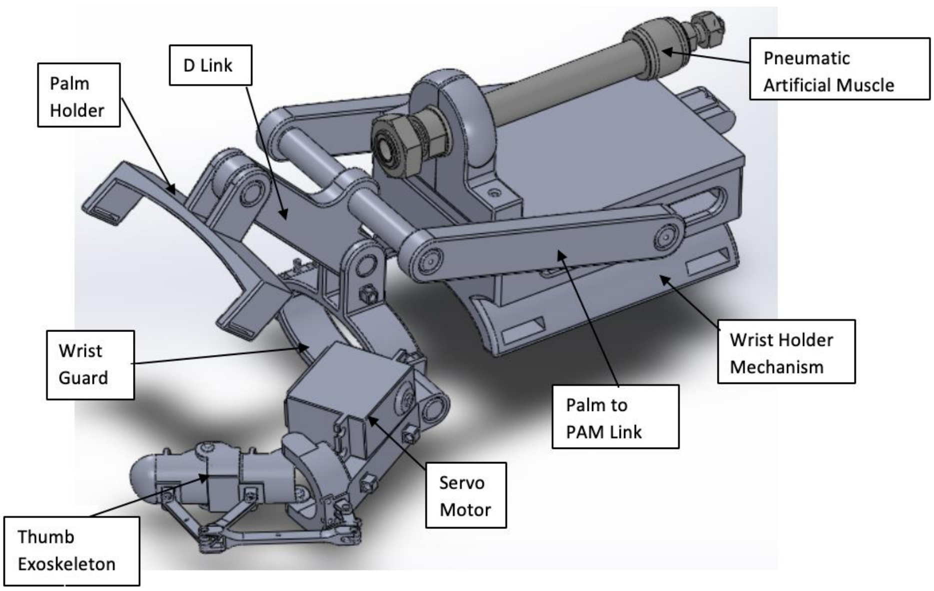



**Fig. 2.** Mechanical drawing of the proposed soft pneumatic exoskeleton in Solidworks

### 2.2 Electronic Configuration

The electronic configuration of the pneumatic exoskeleton is shown in Fig. 3. The Arduino microcontroller board is powered by a battery. The output ports of the Arduino are connected to a servomotor to actuate the thumb exoskeleton and to the relays that are connected to the solenoids to activate the wrist motion. The slide potentiometer is connected to the input ports of the Arduino, and it measures the displacement of the Palm to the PAM link, which indicates the displacement of the wrist joint. Push buttons are used to provide the option for the user to choose either the wrist rehabilitation or the thumb exercise. The Arduino switches the valve ON through the relay, and this allows the air tank to supply air to the PAM. As a result, the PAM expands and moves the Palm to the PAM link to flex the wrist, and the sliding potentiometer's resistance changes. The current link position or angular displacement of the wrist joint is sent to the microcontroller and based on this information. The microcontroller commands the valve to be opened or closed so that the desired angular displacement of the wrist joint is achieved.

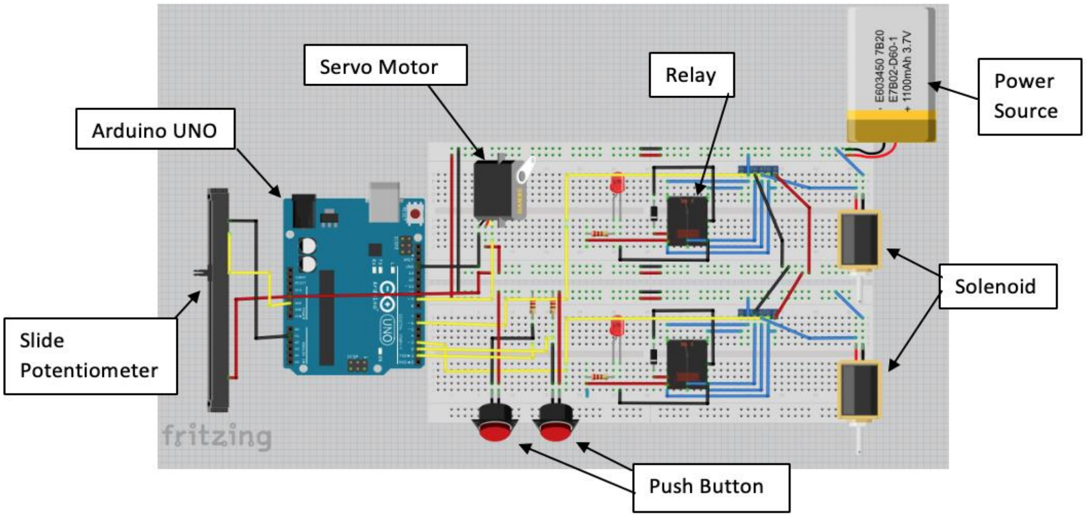



**Fig. 3.** Electronic configuration of the proposed pneumatic exoskeleton for wrist and thumb rehabilitation

### 2.3 Operational Sequence

The operational sequence of the proposed pneumatic exoskeleton for the wrist and thumb is illustrated in Fig. 4. The users have two options, either to choose the wrist exercise or the thumb therapy by pressing the respective pushbuttons. Under the wrist movement option, the user needs to set the two set-points, which are the initial position and the final position of the wrist. Then, under both wrist and thumb exercise options, the user needs to key in the duration of the exercise, and if the user chooses to increase the speed of the movement, the time delay will be decreased. On the other hand, if the user decides to decrease the speed of the motion, the time delay will be increased. The rehabilitation exoskeleton will continue moving until the therapy duration is completed.

## 3. Mathematical Model for the Wrist Motion

In the mathematical modeling of the exoskeleton wrist motion, the link and the palm guard are assumed as 1 DOF mechanical linkage for simplicity, as shown in Fig. 5. The kinetic energy $k_1$ of the link rotating about a fixed point can be written as [32]

$$k_1 = \frac{1}{2}[\frac{1}{3}m_1 l_1^2 \dot{\theta}_1{}^2] \quad (1)$$

Where $m_1$, $l_1$, and $\dot{\theta}_1$ are the linkage's mass, length from the origin to its center of gravity, and angular velocity, respectively.

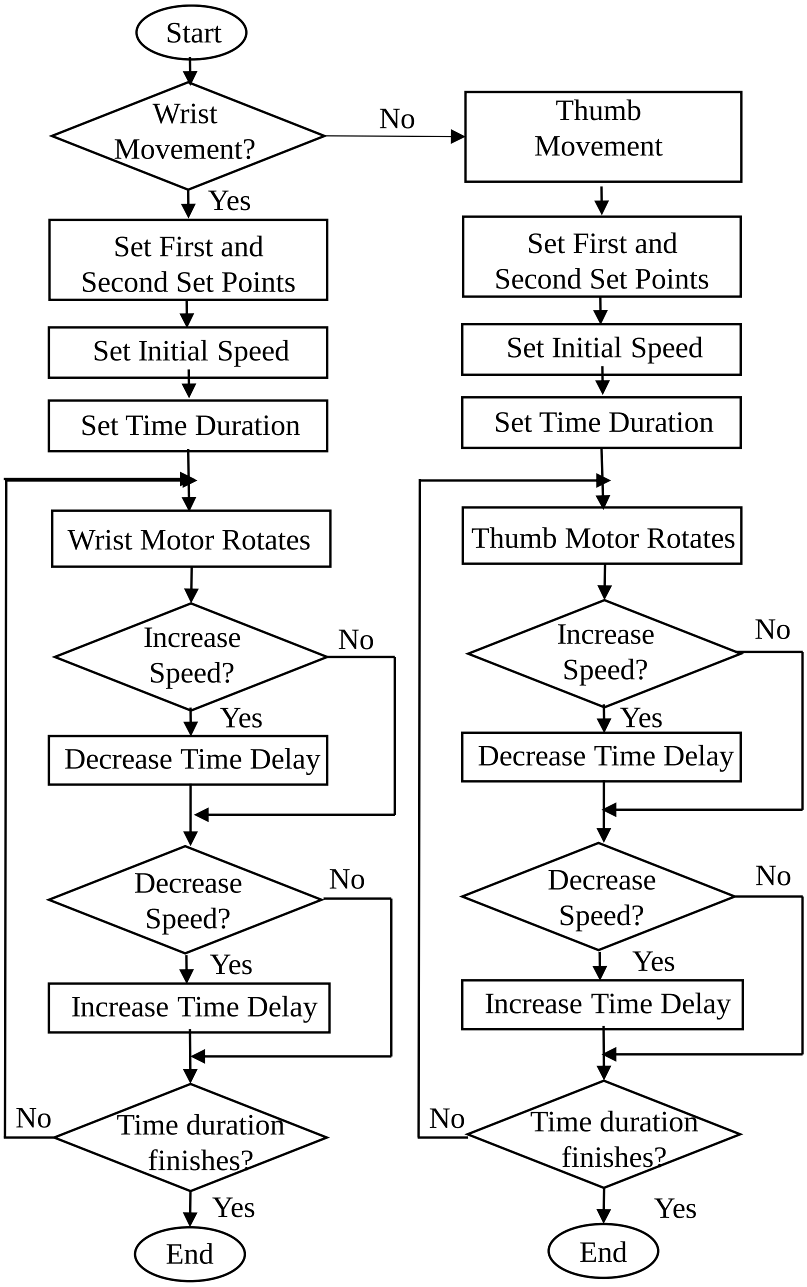



**Fig. 4.** Operational sequence of the proposed pneumatic exoskeleton for wrist and thumb rehabilitation

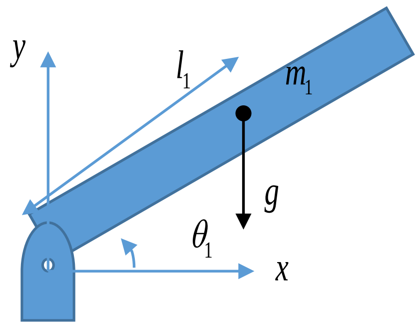



**Fig. 5.** Wrist linkage free body diagram

Then the potential energy, $p$ of the system can be represented as [32]

$$p = m_1 g \frac{l_1}{2} \sin\theta_1 \tag{2}$$

where $g$ is the gravitational acceleration. Once the kinetic and potential energy is obtained, using the Lagrange equation for the link, $L$ can be described as [32]

$$L = k_1 - p = \frac{1}{6} m_1 l_1^2 \dot{\theta}_1^{\,2} - m_1 g \frac{l_1}{2} \sin\theta_1 \tag{3}$$

The derivatives in the Lagrange equation, $L$ with respect to angular displacement, $\theta_1$ can be obtained as [32]

$$\frac{dL}{d\theta_1} = -m_1 g \frac{l_1}{2} \cos\theta_1 \tag{4}$$

Differentiating (4) with respect to time gives

$$\frac{dL}{d\dot{\theta}_1} = \frac{1}{3} m_1 l_1^2 \dot{\theta}_1 \tag{5}$$

Taking the derivative of (5) with respect to time yields

$$\frac{d\left(\frac{dL}{d\dot{\theta}_1}\right)}{dt} = \frac{1}{3} m_1 l_1^2 \ddot{\theta}_1 \tag{6}$$

Using Eqs. (4) – (6), the Lagrangian equation of the system with the external torques for the rotational motion of the wrist, $T$ can be determined as [32]

$$T = \frac{1}{3} m_1 l_1^2 \ddot{\theta}_1 + m_1 g \frac{l_1}{2} \cos\theta_1 \tag{7}$$

## 4. PID Controller

For simplicity, at this stage of the study, the well-known PID controller is used in controlling the angular displacement of the PAM actuated the wrist joint. The equation for PID controller can be written as

$$u(t) = K_p e(t) + K_d \frac{de}{dt} + K_i \int_0^t i(\tau) d\tau \tag{8}$$

where $u(t)$ is the input to the PAM, $e(t)$ is the feedback error between the desired and actual angular displacement of the wrist joint. $K_d$, $K_i$ and $K_p$ are the derivative, integral and proportional gains, respectively. The controller continually calculates the error, and this value is then integrated and differentiated before being multiplied with the respected gain and summed up.

## 5. Results and Discussion

### 5.1 Thumb Exoskeleton Motion Experimental Test

Fig. 6 shows the thumb's servo-motor motion with respect to the time. The graph is linearly rising from 90 degrees to 180 degrees then linearly dropping from 180 degrees to 90 degrees. As the servo motor rotates, it turns the exoskeleton joint together with the user's thumb attached to it.

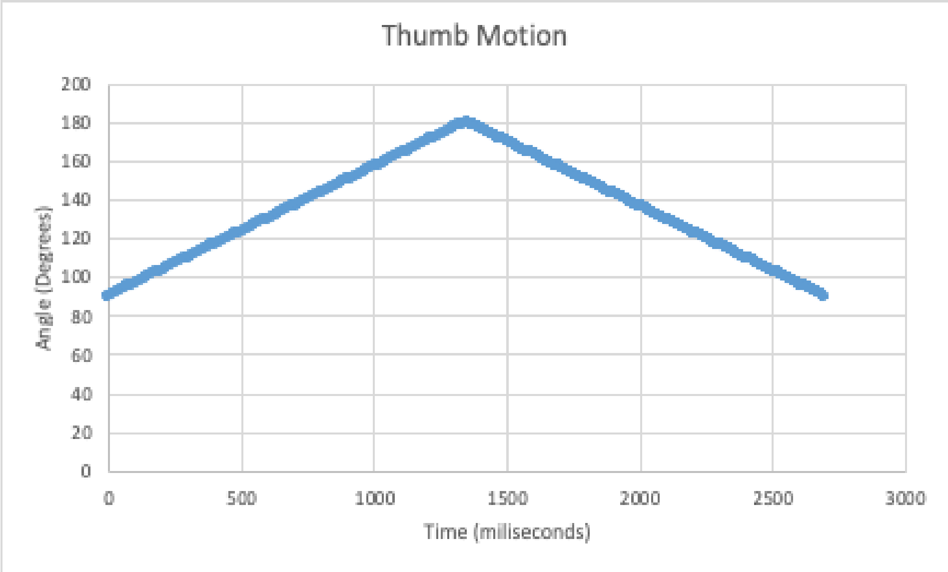



**Fig. 6.** Thumb's servomotor motion

### 5.2 Potentiometer Calibration for Wrist Rehabilitation

The displacement of the Palm to PAM link is varied, and the respective angular displacement of the wrist joint and potentiometer reading is recorded to determine the relationship between the potentiometer measurement and the respective angle produced by the wrist joint. These values are illustrated as in Table 1, and a graph is plotted based on the table.

**Table 1.** Potentiometer resistance with respect to linear and angular displacement

| Displacement [cm] | Angle [degrees] | Potentiometer Resistance [ $\Omega$ ] |
|---|---|---|
| 4.5 | -25.82 | 44 |
| 5.0 | 2.69 | 148 |
| 5.5 | 14.23 | 240 |
| 6.0 | 26.57 | 329 |
| 6.5 | 36.95 | 408 |

The mean gradient and the constant for a linear function have been obtained to be approximately 7.6 and 129.37, respectively, from the potentiometer versus angular displacement graph. Therefore, using the equation of a straight line, the relationship between the corresponding angle with respect to the potentiometer reading can be written as

$$Angular\ displacement = \frac{Potentiometer\ Resistance - 129.37}{7.6} \qquad (9)$$

### 5.3 Wrist Exoskeleton Motion Experimental Test

In the wrist exoskeleton motion, the reading from the potentiometer is compared to the set-point. Then, this error is fed into the PID controller, which drives the relay to either turn ON or OFF, or in other words, releasing or holding the air from the compressor. The linear displacement of the PAM leads to the angular displacement of the wrist joint. When the wrist angle changes, the Palm to PAM link, which is connected to the sliding potentiometer, moves and changes the potentiometer resistance. This process continues until the program is stopped.

Fig. 7 and Fig. 8 show the resulting wrist joint motion under the PID controller when the setpoints are set to be 48.8° and 101.45° respectively. Whenever the resulting output is greater than the set-point, the solenoid valve turns ON and releases the air from the muscle, which drops the potentiometer's resistance. On the other hand, if the output is lower than the set-point, the valve turns OFF and lets the air fill in the pneumatic muscle to move the exoskeleton to achieve the desired set-point, which then increases the resistance of the potentiometer.

From the result obtained in Fig. 7 and Fig. 8, it can be seen that the maximum steady-state error for the 48.8° and 101.45° setpoints are 21.7% and 5.89%, respectively. In Fig. 7, it can observe that the system takes a longer time to converge to the desired position with a high percentage overshoot of 90% and starts to settle down at 5.58s. This problem may occur because of the lower setpoint value, in contrast to the high speed of the PAM that makes it exceed the setpoint and takes a long time to reach the desired value. The position system response for the 101.45° set points in Fig. 8 shows a better result where the steady-state response is achieved at 0.5 s with a lower percentage overshoot of 10%. From both Fig. 7 and Fig. 8, it can also be seen that the results fluctuate around the desired set point due to the utilization of the solenoid valve that switches between ON and OFF positions in maintaining the desired joint displacement. However, both experimental test results show that with the aid of the PID controller, the system managed to converge to the desired position at the time increases.

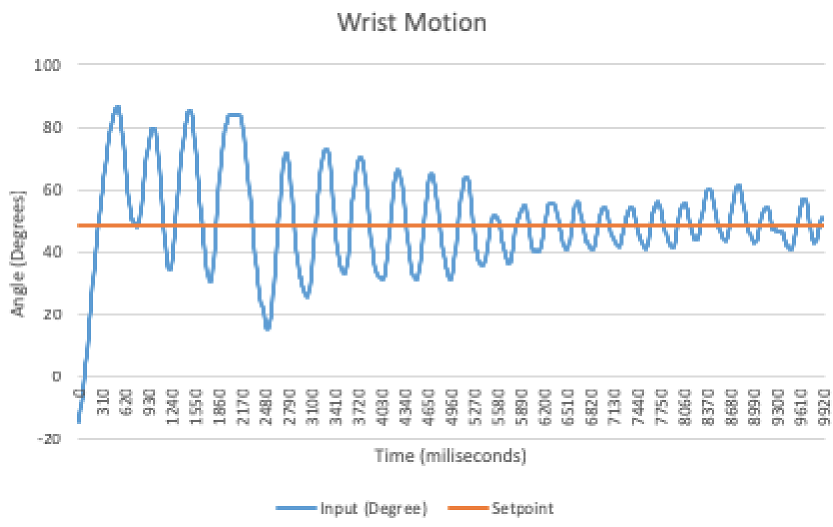



**Fig. 7.** Position Response of the wrist with set-point at 48.8 Degrees

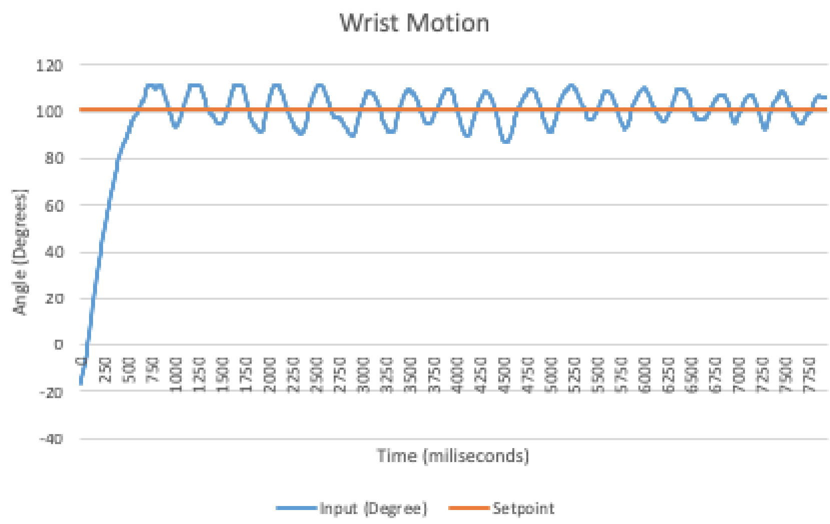



**Fig. 8.** Position Response of the wrist with set-point at 101 Degrees

Fig. 9 illustrates the system response for wrist rehabilitation when it is desired for the wrist joint to move between 48.8° and 101.45°. The controller turns ON the relay once the first set-point (48.8°) is reached. Once the position is above this first set-point, the air flows into the PAM, which increases the angular displacement, and this continues until it reaches the second set point (101.45°). Whenever the second set-point is attained, the relay is turned OFF, and the position returns to the first set-point (48.8°), and the solenoid valve is closed to fill the PAM. The result shows that the proposed exoskeleton has successfully provided the wrist and thumb rehabilitation motions as desired. However, the accuracy of the system may be improved with the application of a more advanced controller.

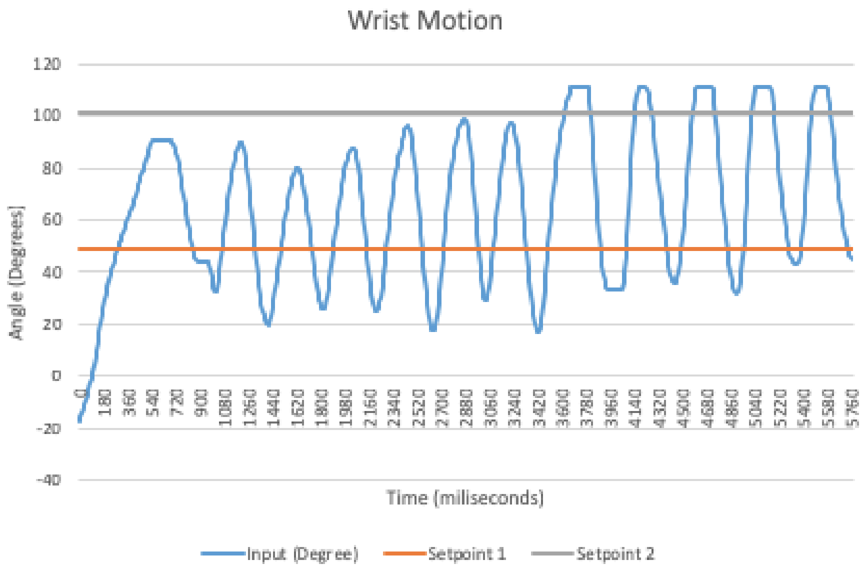



**Fig. 9.** Wrist motion between two set points

## 6. Conclusions

The development of a pneumatic exoskeleton for thumb and wrist rehabilitation has been presented in this paper. The device is simple, lightweight, portable, and low cost. A new mechanism has been presented, with Arduino Uno is used as the microcontroller and sliding potentiometer providing the angular displacement of the wrist joint. The results show that PAM has successfully actuated the exoskeleton with PID control to reach the desired set points. The system is able to realize both the thumb and wrist rehabilitation as required. However, there are some limitations in the design that can be improved in the future version of the device. It has been discovered that a link is needed between the wrist guard and wrist holder to avoid any discomfort at the human wrist. The solenoid used in the system frequently leaks, and this makes it hard to hold the muscle at a certain position. For future work, it is recommended to use an electric pneumatic regulator, where the pressure of the air can be controlled, no leakage will occur, and the results can be improved. It is also recommended to build the entire prototype from aluminum to ensure that the links are not broken when they are pulled by PAM. Future works also involve the inclusion of the human arm in the mathematical model of the wrist rehabilitation subsystem and the development of a more advanced controller to cater for the uncertainties in the variety of the human arm's physical parameters and a more complicated desired trajectory.

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