

# **W.E.A.R. Bot – Wrist-Elbow Automated Rehabilitation Robot**

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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**Abstract**—The W.E.A.R. Bot is a wearable wrist-elbow automated rehabilitation robot. The significance of the design is in its ability to enhance flexion and extension in both the wrist and elbow for patients with neuromuscular diseases. The wrist utilizes a servo motor to activate the motion and the elbow’s motion is created from a pneumatic actuator with one bladder.

**Keywords**— *exoskeletons, elbow, wrist, pneumatic actuators, servo motors, rehabilitation*

## I. INTRODUCTION

Neuromuscular disorders, strokes, and spinal cord injuries can lead to patients experiencing varying degrees of paresis or paralysis. Through extensive physical therapy, some patients can regain their lost motor skills by activating the muscle-brain connection. One technique used in physical therapy is passive movements, where the therapist manually moves the targeted limbs of the patient to induce neuroplastic changes [1]. Alternatively, robotic exoskeletons have been designed to help patients achieve these movements without direct assistance from a physical therapist. However, exoskeletons have not been widely adopted in clinical settings and they are typically rigid, heavy, and expensive. There has been an increase in the development of soft wearable exoskeletons that could be used by individual patients outside of the clinic [2]. Stroke survivors typically experience reasonable recovery of the proximal upper limb muscles but limited recovery of the distal upper limb muscles, which play an important role in fine motor control [3]. Wrist exoskeletons are a promising tool to aid in the rehabilitation of these skills [4]. This project will focus on creating an affordable and portable exoskeleton to aid patients in regaining upper limb mobility, in particular, the flexion and extension of the elbow and wrist joints.

### A. LITERATURE REVIEW

Exoskeleton robots with multiple degrees of freedom for upper limb movement vary in method and application. In [4], a rehabilitative robot was developed with three dual-acting air cylinders for shoulder abduction and adduction, shoulder flexion and extension, and elbow flexion and extension. It was designed to be mounted onto a wheelchair and used pressure sensors and potentiometers to monitor movement. It lacked external programmability and required that the patient be confined to a wheelchair. In [5], a wearable assistive robot for elbow flexion and extension was developed using sEMG control and twisted string actuators. Although lightweight, the use of cables for actuation limited the addition of degrees of freedom to the shoulder, and the sEMG-controlled movement confined its application to able-bodied individuals with strong muscle signals.

Assistive technology for wrists has been increasingly developing. For the design [3], a portable wrist exoskeleton featuring a DC motor as the actuator assisted the wrist with flexion and extension. It was designed to be fully portable, with the power supply mounted to the upper arm and electronics housed on the forearm. The motor was triggered by an sEMG sensor (a Myo armband) to add mechanical support based on the amount of muscle activation. Though this design was notable for its portability and independence, its design was a little heavy and took up the entire arm.

The most effective forms for improving upper extremity movement are muscle-strengthening exercises, constraint-induced movement therapy, mirror therapy, and botulinum toxin. These methods work in terms of rehabilitating impairments. Several rehabilitation methods are recommended as adjuvant therapy. These include but are not limited to mental practice with motor imagery, passive neuromuscular electrical stimulation, repetitive transcranial magnetic stimulation, and virtual reality. There is a lack of evidence to support the efficacy of robot-assisted therapy for task-oriented movements [6].

A common side effect after strokes is auditory overload. The brain receives too much sensory stimulation and can’t keep up with it. Auditory overload results in an inability to concentrate on a task and fidgeting which can affect rehabilitation exercises [7]. Sounds at 70 decibels or below are considered safe, but long-term exposure can be damaging. Background noise is at 60 decibels [8].

### B. OUR CONTRIBUTION

W.E.A.R. Bot includes a unique combination of flexion and extension in the elbow and wrist to support fine and gross motor skills for patients. The elbow motion is achieved using a pneumatic artificial muscle (PAM) fixed onto a 3D-printed elbow hinge brace, while the wrist motion is achieved using a servo motor on a custom 3D-printed wrist brace (Figure 1). The elbow brace features foam padding for comfort and adjustable fit using velcro straps. The structure of the wrist mechanism is made with similar foam padding between the rigid components and the body, and the fit is easily adjustable using nylon straps. Soft materials ensure a more compliant and comfortable interface for the body.

The PAM connects to an air pump via a solenoid which is housed in a backpack. To control the flow of air from the pump, a feedback control system consisting of a potentiometer reads the position of flexion or extension

in the elbow which signals to either open or close the solenoid's valve according to the program. This provides users the ability to program angular position boundaries for progressive rehabilitation. The overall design is adjustable, comfortable, lightweight, and inexpensive.

The wrist portion uses a servo motor to move the wrist between flexion and extension. The servo is mounted on the top of the forearm. A metal wire is connected from the servo hand to the pivot mechanism. With the power source for the servo motor housed in a backpack, the wrist design is lightweight and portable. For both the elbow and wrist components of the design, patients and their doctors will be able to program specific rehabilitation routines to best suit their individual needs.

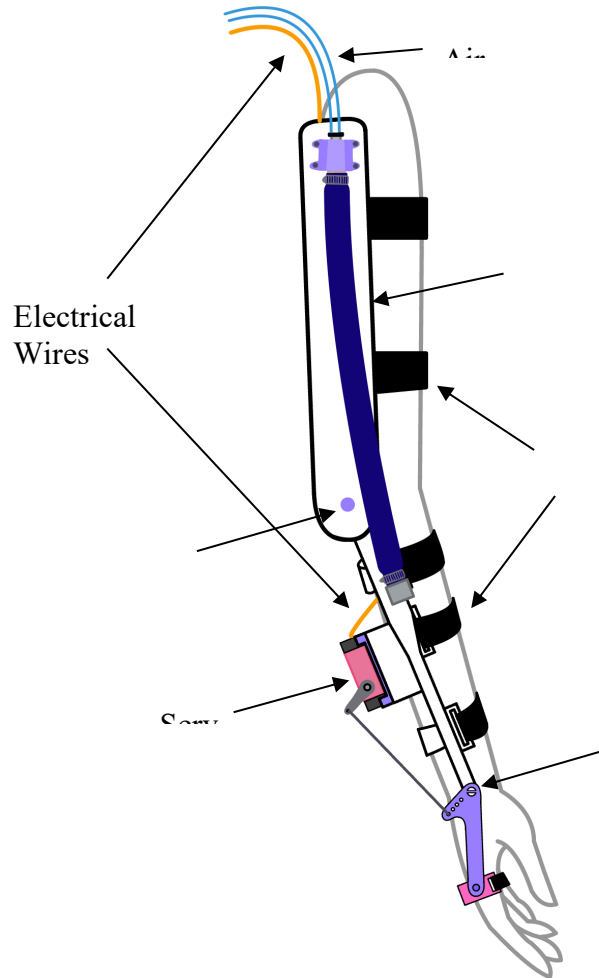


Figure 1: Overview of the W.E.A.R Bot Exoskeleton (Backpack Containing Air Pump, Solenoid, Arduino, and Power Supply Not Pictured)

## II. DESIGN PROCESS

### A. Methods

The human elbow bends due to the contraction of the bicep muscle from a straight position ( $180^\circ$ ) to about  $36.4^\circ$  (Figure 2). The wrist, however, uses a combination of muscles and tendons to flex and extend the wrist to  $145.6^\circ$  and  $131.5^\circ$  respectively (Figure 3). To mimic the contraction of the human bicep and generate the force required to lift the patient's arm, the W.E.A.R. Bot uses a McKibbins muscle. This type of PAM is low cost, low mass, and most similar to the human muscle. A 20 kg·cm servo motor raises and lowers the wrist. Using a servo motor allows for finer degrees of rotation in the wrist, which more accurately depicts the movement of a wrist.

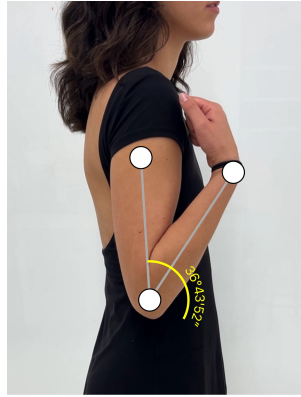


Figure 2: Natural Human Elbow Movement Due to Bicep Contraction

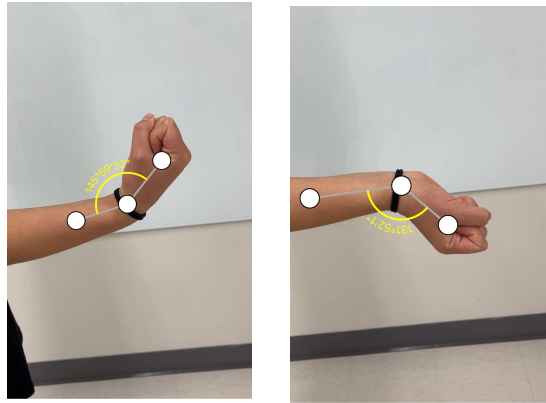


Figure 3: Natural Human Wrist Flexion and Extension

The maximum percent contraction of a PAM is dependent solely on the tube stiffness and mesh angle. W.E.A.R. Bot's PAM prototype with an initial length of 12 inches, contracted to 8 inches with an internal pressure of 3.5 bar, yielding a 33% contraction, which is on par with the expected maximum contraction for a standard McKibbins muscle [9]. The placement of the PAM on the elbow hinge brace is commensurate with a 33% contraction that will yield an angular range of motion between 20 and 120 degrees for elbow flexion. Based on the PAM placement, which is along the length of the arrow labeled  $F_T$  in Figure 4, the necessary force exerted by the PAM to move the forearm,  $F_T$ , was calculated using torque equilibrium in the following equations, where  $\tau_T$  and  $\tau_g$  are the torques exerted on the hinge by the PAM and gravity, respectively,  $F_T$  and  $F_g$  are the forces exerted by the PAM and gravity, respectively,  $L_T$  and  $L_g$  are the distances between the point of force application on the forearm and the hinge, respectively, and  $\theta$  is the angle between the forearm and the vertical. The length values were measured from the device and the force due to gravity was assumed to be 4.5 lbf based on the average forearm weight.

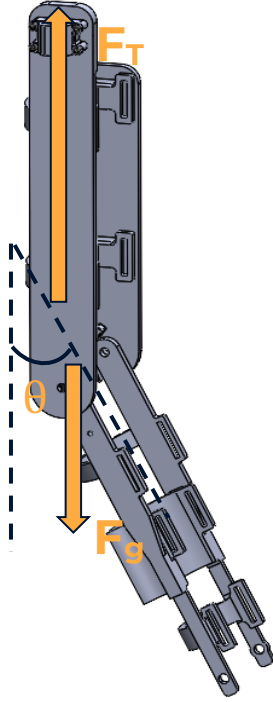


Figure 4: Free Body Diagram for Elbow Hinge Brace

$$\sum \tau = \tau_T + \tau_g > 0$$

$$\tau_T = F_T r_T \approx F_T (L_T \sin \theta)$$

$$\tau_g = -F_g r_g = -F_g (L_g \sin \theta)$$

$$F_T L_T \sin \theta - F_g L_g \sin \theta > 0$$

$$F_T > \frac{L_g}{L_T} F_g$$

Assuming that  $L_g = 3.5$  inches,  $L_T = 1.5$  inches, and  $F_g = 4.5$  lbf:

$$F_T > 10.5 \text{ lbf}$$

In order to determine the number of pneumatic muscles needed to provide a force of 10.5 lbf, the force of a singular pneumatic muscle must be calculated. The theoretical equation for modeling the force provided by a pneumatic muscle is shown below.

$$F = \left( \frac{\pi D_0^2 P}{4} \sin^2 \theta_0 \right) \left[ 3 \left( 1 - \frac{\Delta L}{L_0} \right)^2 \cos^2 \theta_0 - 1 \right] \quad (1)$$

For values of  $D_0 = 0.75$  inches = 0.01905 m,  $P = 3.5$  bar =  $3.5 \times 10^5$  Pa,  $\theta_0 = 23^\circ = 0.401426$  rad, and  $\Delta L/L_0 = 1/3$ , the force per PAM was found to be 1.46 lbf. This number was much lower than expected as most pneumatic muscles are able to produce much higher forces. To verify this result the force produced by one pneumatic muscle was then found experimentally using a spring balance as seen in Figure ##. The experimental results, as seen in Table I, show that a singular pneumatic muscle is able to provide a force of 10.12 lbf when inflated to a pressure of 3.5 bar. Based on this result it was determined that only one muscle was required to lift the forearm. Discrepancies between the theoretical value and the experimental value could be due to the unknown elasticity of the rubber bladder, complex braid patterns of the nylon casing, and other unpredictable factors. While

the force calculation may be incorrect, the theoretical equation does provide insight on the relationships the various factors have on the output force.



Figure 5: Spring Balance Used in Force Testing

TABLE I. Pressure Input vs Force of Muscle Table

Supply Pressure (Bar)	Average Output Force (lbf)
1.5	3.37
2	5.17
2.5	6.52
3	8.09
3.5	10.12

The 33% contraction of the pneumatic muscle will yield a range of motion of the forearm between 20 and 120 degrees, which means that the angle between the forearm and the upper arm will range from 160 to 60 degrees. A single-turn potentiometer connected to the hinge will turn as the forearm is lifted. This will vary a voltage-divider circuit providing a voltage to the Arduino that is inversely proportional to the potentiometer resistance value. The following equation for a voltage divider circuit, with  $R_1$  and  $R_2$  being the resistance values of the potentiometer and another resistor, respectively, and  $V_{in}$  being the input voltage, determines the output voltage  $V_{out}$ :

$$V_{out} = V_{in} \frac{R_2}{R_1 + R_2} \quad (2)$$

The input voltage for the voltage divider circuit will be 5V supplied by the Arduino. The 10-kOhm potentiometer will be aligned so that it is positioned at 0 kOhms for the forearm's resting position at 20 degrees clockwise from the vertical and about 2.8 kOhms for the forearm's maximum angular position at 120 degrees from the vertical. For a constant second resistor of 1 kOhm, the output voltage read by Pin A0 will vary between 5V and 1.3V. When the maximum angular position is programmed, the transistor enabling a 12V power source through the solenoid that is normally closed will only be activated until that angular position is reached according to the output voltage of the voltage divider circuit (Fig. 3).

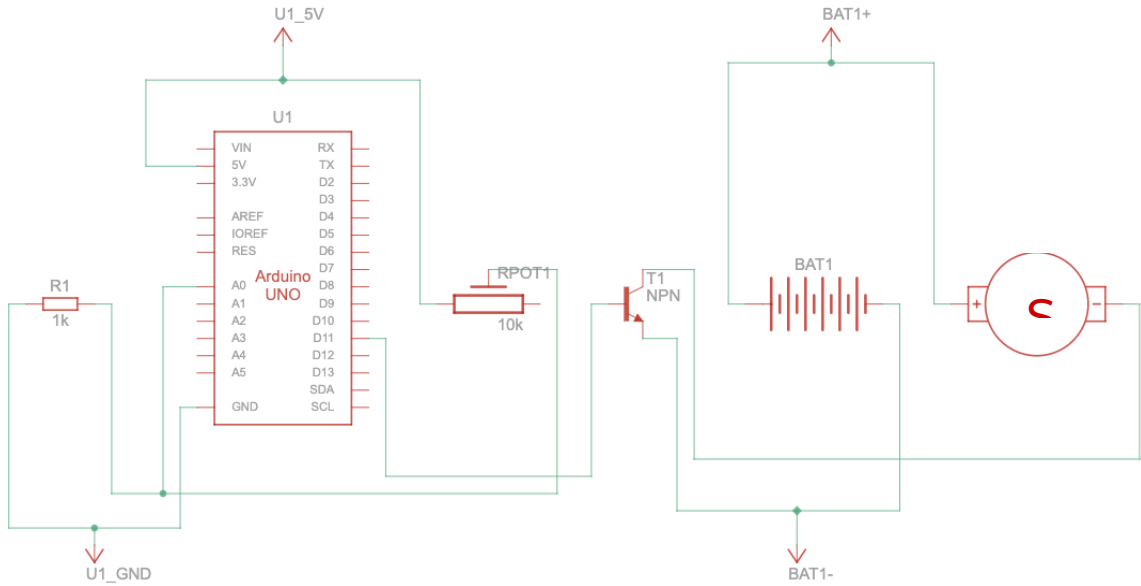


Figure 6: Circuit for Solenoid and Potentiometer

The wrist component design uses an RC Servo motor to rotate the wrist between flexion and extension. To calculate the required torque to move a person's hand, equation 3 can be applied. With the max torque occurring at  $\theta = 90$  degrees, the average hand weight is 3.924 N, and the average hand length is 0.193 m. The required torque to move the hand is  $\tau = 0.252 Nm$ .

$$\tau = rF\sin\theta \quad (3)$$

The typical ROM for an individual's wrist is 40 degrees in both flexion and extension. Our goal is to match this capability in our design to allow patients the most movement. To measure this ROM in our design, we will translate the analog signal from the voltage divider to the potentiometer's angular position.

The relationship between the analog inputs from the potentiometer voltage dividers and the real angular positions of the wrist joints will be determined experimentally. The angular position of each potentiometer (which is assumed to be equivalent to the angular position of the respective joint) will be incrementally increased, and the analog input will be recorded. The Arduino analog input pins read the signal using a 10-bit analog-to-digital converter, so the inputs will be mapped from 0 to 1023. A video will be taken with both the joint/potentiometer and the analog output given to the camera so that the angular position can be measured precisely, and the analog input will be plotted on a graph against the angular position for the full range of motion. Once this relationship is established, the control limits for the ROM for both joints can be set and customized.

### B. Design Specifications

TABLE II. Elbow and Wrist Range of Motion Design Goals

Joint	Flexion Angle (degrees)	Extension Angle (degrees)	Total Range of Motion (degrees)
Wrist	40	-40	80
Elbow	60	160	100

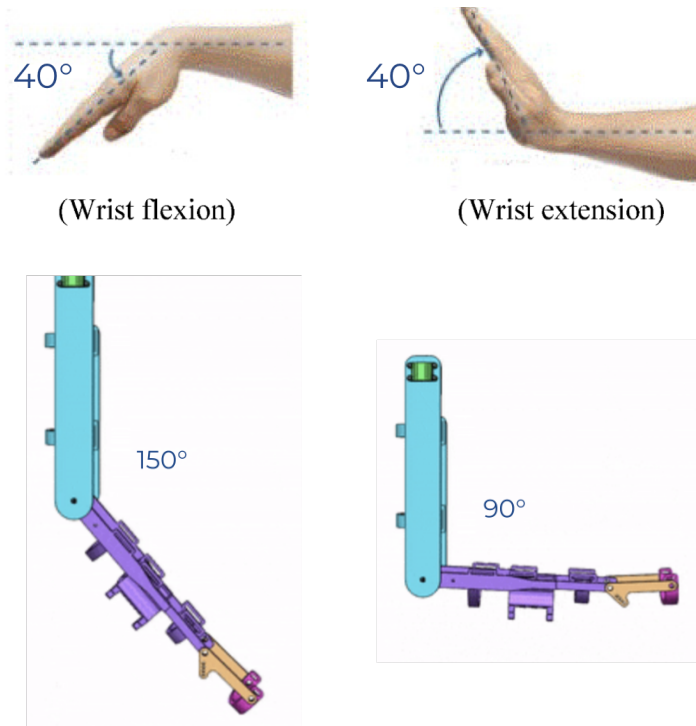


Figure 7: Elbow and Wrist Range of Motion Design Goals

The range of motion goals for this project were 40° above and below horizontal for wrist extension and flexion and between 150° and 90° for elbow extension and flexion. This was determined based on the range of motion found for normal human motion. If successful the device will achieve approximately 70% of the normal range. In addition to the range of motion goals, this project also had goals for the cost of materials and comfort to make the end product something affordable to most stroke patients and not cause them discomfort during rehabilitation. The economic goal was to keep the overall cost under \$300 and the comfort goal was to make the device using only soft materials.

### C. Materials

#### *Elbow*

The design features a 3D-printed hinged elbow brace with 100 degrees of rotation that attaches via Velcro straps to support the user's arm (Figure 4). The pneumatic actuator bladder has a diameter of 0.75 inches, a length of 12 inches, and is encased by an expandable mesh with an angle of 23 degrees. The end of the bladder is connected to the upper arm and forearm region using a 3D-printed mount and zip ties respectively. Air flow to the PAM is controlled by a 5/2 solenoid valve which is programmed using an Arduino. The air pump, solenoid, circuitry, and 12V rechargeable battery will be held in a small lightweight backpack for portable use (Figure 5). A single turn, 10 kΩ potentiometer will be placed at the elbow joint of the arm brace to provide feedback on the current elbow angle by varying the voltage signal to the Arduino through a voltage divider circuit.



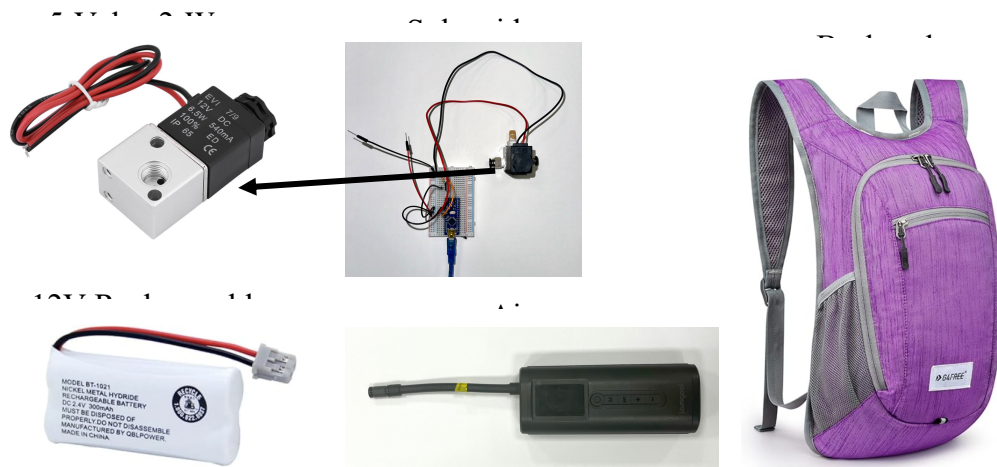


Figure 8: Backpack and Components

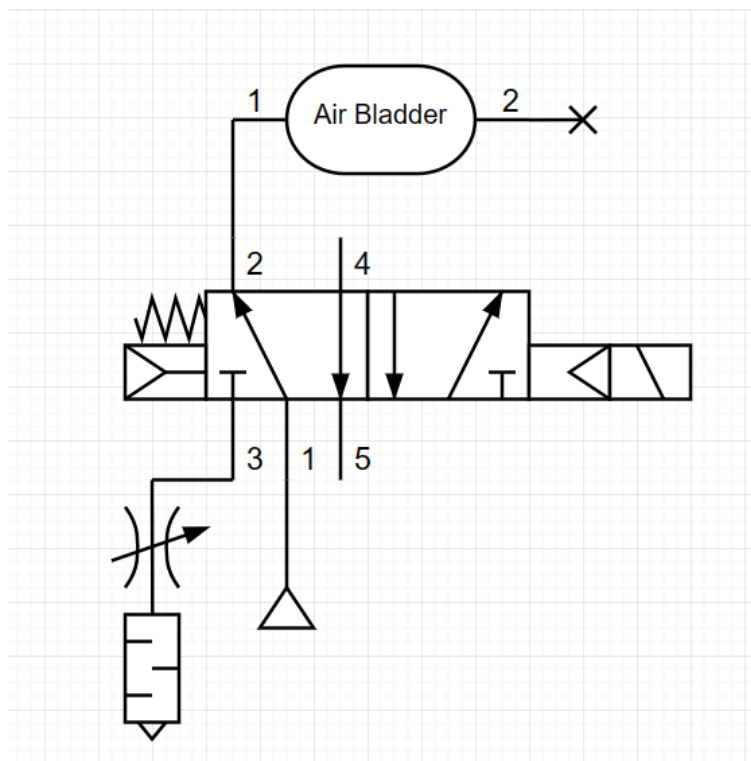


Figure 9: Schematic of Solenoid Pneumatic Design

### Wrist

The W.E.A.R Bot will also feature a custom 3D printed hinged wrist brace with a total ROM of 80 degrees (40 degrees flexion and 40 degrees of extension) (Fig. 6). The main actuator will be a digital servo motor with a stall torque of 19 kg-cm, and will require an external power supply to provide a minimum voltage of 5V and minimum current of 1.5A. The power supply and Arduino will be located in the backpack. The main forearm structure will be constructed of multiple 3D-printed components and secured to the forearm with velcro straps. The servo motor is fixed in place by a custom servo mount, and its rotational output is translated to the wrist via a control linkage (Fig. 7). This mechanism involves a steel wire that links the servo horn to a control horn at the wrist axis. Similar to the elbow system, A single turn, 10 kΩ potentiometer will be placed on the rotational axis and wired as a voltage divider to act as a rotary position sensor. Since the alignment of the motor, control horn, and potentiometer is crucial to the device's function, most of the structural components are rigid and made from

PLA and ABS plastic. The forearm structure, which extends from the elbow to the wrist, is secured to the forearm and the hand support is secured around the palm using nylon Velcro straps. Foam padding is attached with an adhesive to both the hand and forearm structures for better comfort and fit.

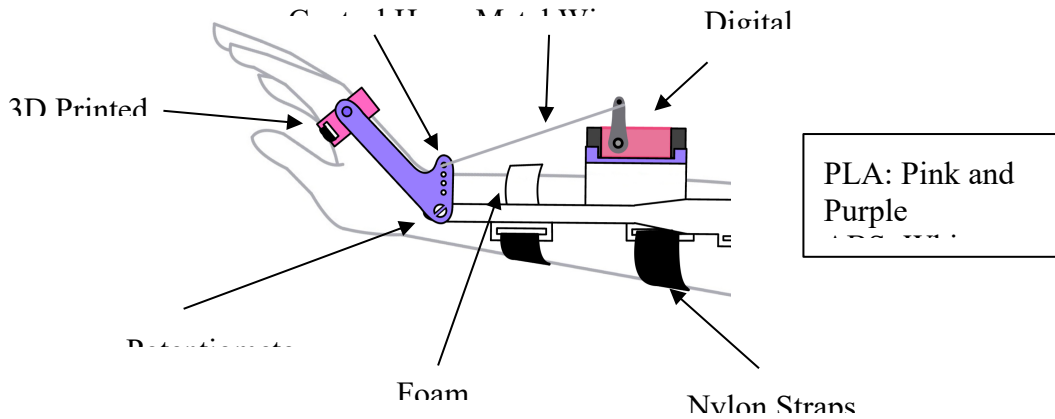


Figure 10: Wrist Exoskeleton Components and Materials

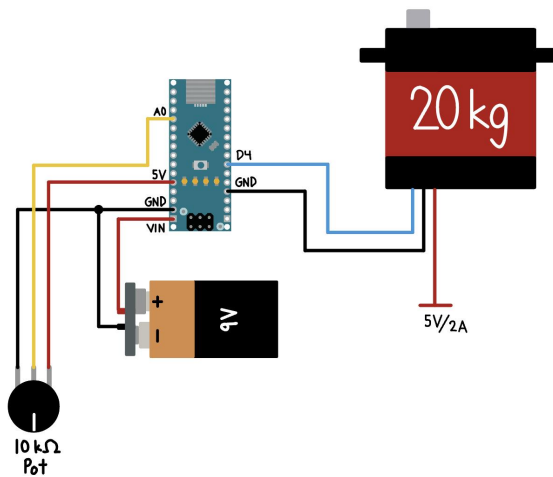


Figure 11: Basic Circuit Layout for Wrist Components

### C. Prototype Iterations

#### Elbow

In January, PAMs continued to be prototyped until airtight (Figure 13). Its percent contraction for varying internal pressures and weights was tested and compared to design calculations. The configuration depicted in the detailed design was tested while worn by each of the project members, with the maximum angle achieved measured by the dial on the elbow hinge (Figure 12). During the same month, the next iteration of code for the 3-way solenoid was developed, this time-varying actuation based on potentiometer and pressure data. In February, controls for the solenoid valve were tested by seeing its activation as a potentiometer increases and decreases in resistance, which

corresponded with the forearm angle once the system is fully built. Once these individual components were functional in April, the team integrated them and tested the whole system. The design iterations were continued until the final presentation in May.

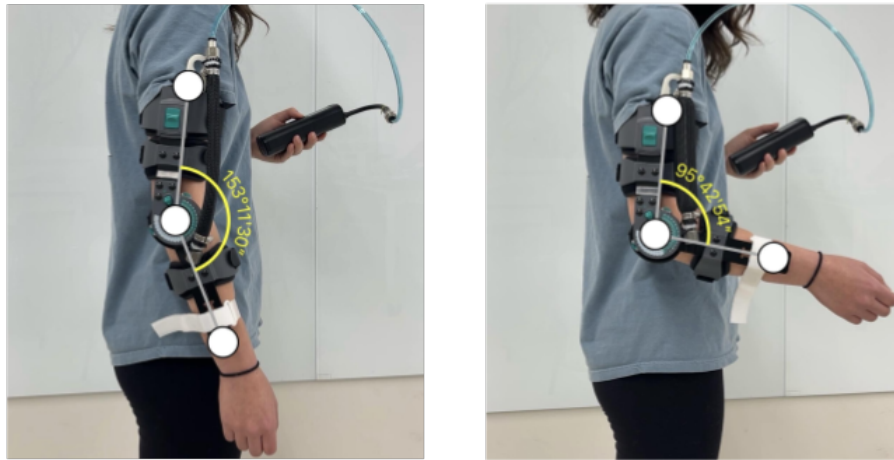


Figure 12: First Prototype of Elbow Design

PAM 12" in length, internal

PAM 9" in length, internal

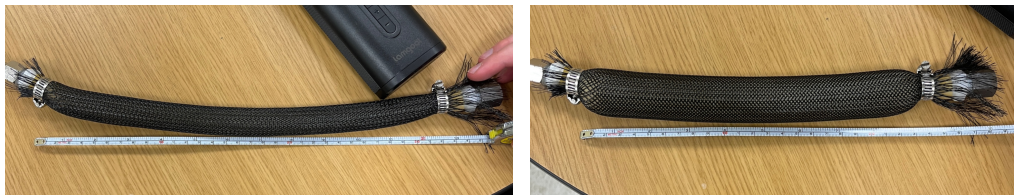


Figure 13: PAM Prototype

### Wrist

The necessary materials for the wrist component of the exoskeleton were ordered at the beginning of the semester. This will include the portable power supply, PLA/TPU filament, textiles for the padding and straps, Velcro, and ratchet lacing mechanism. The design of the 3D printed components will be completed in Solidworks and an initial print will be completed by the end of January. In February, the circuit for the wrist potentiometer, servo motor, and external power supply will be assembled. The code for servo motor control will be further developed and the torque output will be tested using the expected attached load, which includes the forces from the miter gears, lever, and hand. The first full prototype will be assembled by April, including the 3D printed components, padding, adjustable straps, and electrical components. Possible issues regarding the fit or alignment of the parts will be addressed. Further experimentation will be done with the assembled device to refine the code.

In our initial designs, we considered placing the servo motor on the side of the forearm and using miter gears to align the axis of rotation of the motor output with the natural wrist axis (Fig. ##a). To make the wrist components more balanced and avoid gear alignment issues, we decided to place the servo motor such that the axis of rotation of the motor output was parallel to the wrist axis. The control linkage mechanism used to achieve this was inspired by similar ones used to move the control surfaces in an RC plane. Our first prototype (Fig. ##b) was built primarily from soft materials, specifically nylon and velcro straps. The servo was placed on the inner forearm, with the wire linking the servo horn to the palm. However, this prototype only allowed for approximately 35° of flexion and no extension due to limitations in the linkage geometry. Additionally, controlling and securing the motor was challenging due to excessive slack in the system. We attempted to address these issues in our second prototype by 3D printing a rigid main body and only using soft materials for the straps (Fig. ##c). The linkage geometry was improved by relocating the servo motor to the top of the forearm and connecting the servo horn to a rigid control horn at the wrist axis, rather than to a loose strap at the palm. This prototype achieved approximately 37° of flexion and 24° of extension.

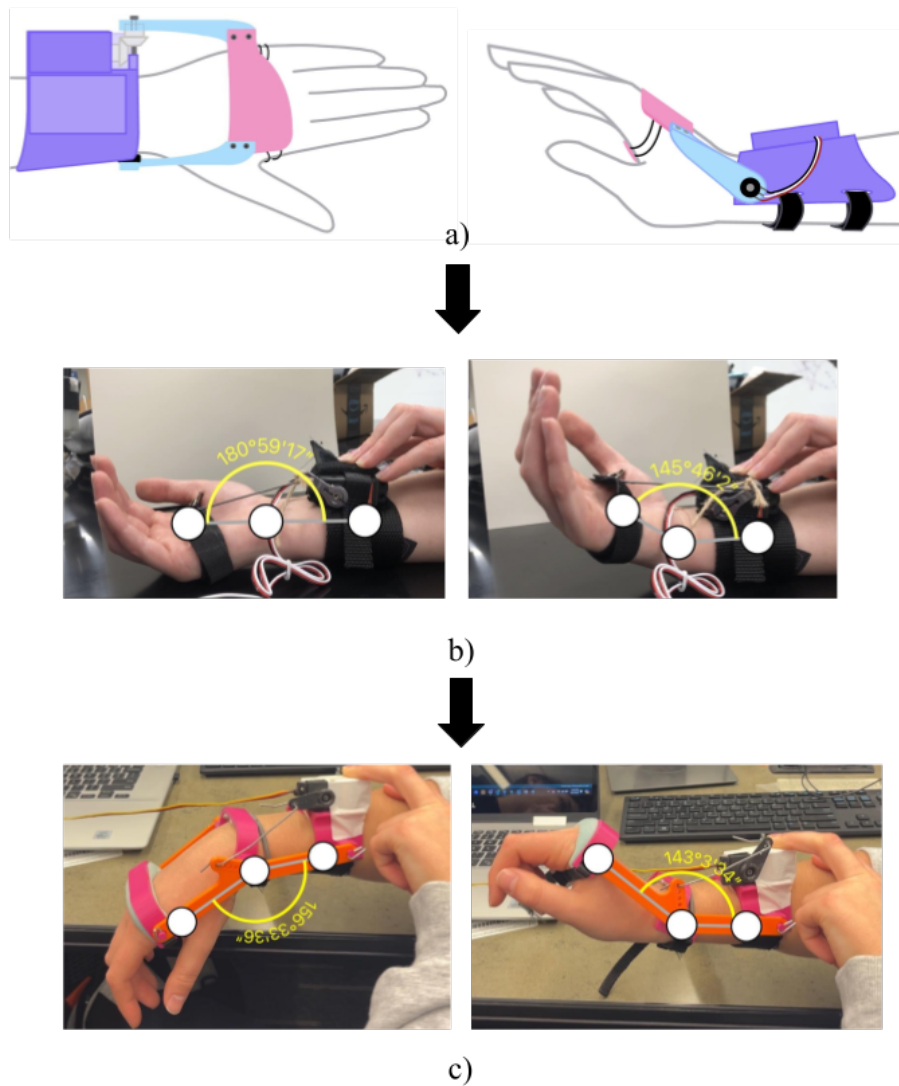


Figure 14: Wrist mechanism design iterations, a) initial design sketch, b) first prototype, c) second prototype

### III. RESULTS

As seen below in Table III, the project met three out of four of the range of motion goals and greatly exceeded that of both elbow flexion and wrist extension. The one range of motion goal that was not achieved was wrist flexion. While the servo motor was capable of lifting the weight of the hand to the desired degrees, the geometry of the control horn made it difficult to reach full rotation. In addition to range of motion, the design also met the affordability goal of \$300 with all material costs totaling \$215. The low cost of the design makes it accessible to most stroke patients. While the design does not cause discomfort for the person wearing it due to the adjustable straps and the foam padding along 3D printed edges, the design did not meet the goal for comfort as it was not constructed from all soft materials. As seen above in Figure 14, the first wrist design iteration was constructed from solely textile materials, however this allowed the degrees of freedom to increase beyond that of just flexion and extension and greatly limited the effectiveness of the device. For this reason it was decided rigid materials would be preferred.

TABLE III. Elbow and Wrist Range of Motion Results

Joint	Movement	Goal (degrees)	Achieved (degrees)
Elbow	Flexion	90	78
	Extension	160	155
Wrist	Flexion	40	23
	Extension	40	53

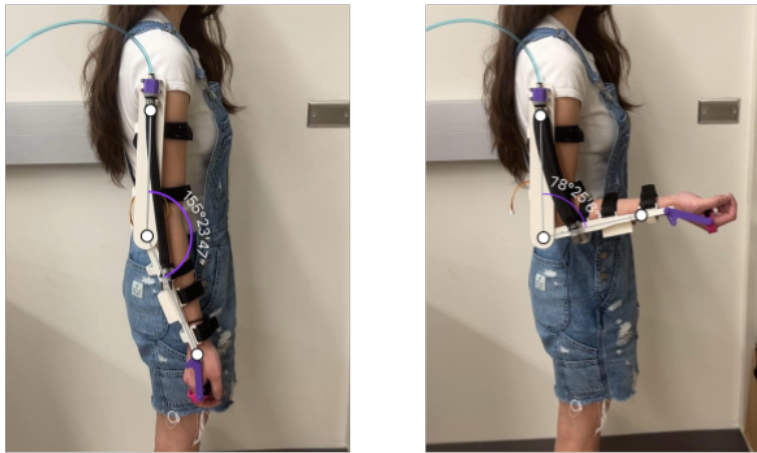


Figure 15: Elbow Range of Motion Results

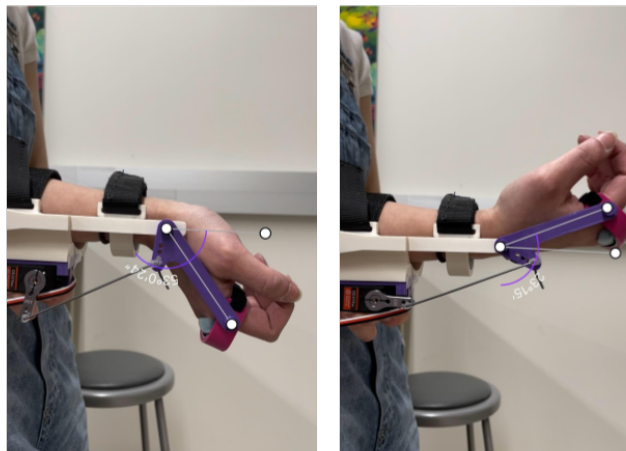


Figure 16: Wrist Range of Motion Results

#### IV. DISCUSSION AND CONCLUSIONS

### *Discussion*

Another concern in the elbow design is the loudness of the air pump required to inflate the PAMs. The pump currently operates at 80 decibels, but the goal is to reduce this to 60 decibels by creating a soundproofing box to house the pump. Currently, in the wrist design, the main concern is the comfort of the 3D-printed brace that will rotate the wrist and house the motor and circuitry. This issue will be addressed by having the brace be adjustable to fit the width of the patient's forearms and by lining the plastic with foam padding. Additionally, the hand support will be 3D printed using the more flexible thermoplastic polyurethane (TPU) plastic instead of the alternative polylactic acid (PLA) plastic.

### *Conclusion and Future Work*

The goal of this project is to design a highly customizable exoskeleton robot to assist patients who have suffered a neuromuscular injury in the rehabilitation of their arm muscles through repetitive movements of their elbows and wrists. By prioritizing an adjustable fit and allowing the user to customize the ROM limits and programmed movements, the W.E.A.R. Bot will be suitable for patients of a wide range of sizes and abilities, and will be easily implemented into personalized treatment plans. The design will improve upon current exoskeletons currently on the market by targeting muscles involved in both gross and fine motor skills while being portable, lightweight, and comfortable. The design consists of two systems: the elbow and wrist. The elbow system will use 3 pneumatic muscle actuators to create a contraction of 100 degrees. The PAMs will be controlled by a solenoid which will be programmed using an Arduino to perform a sequence of rehabilitation exercises. The wrist system will use a digital servo motor to rotate the wrist 40 degrees in both flexion and extension and will also use an Arduino to perform a sequence of rehabilitation exercises. The wrist will be enclosed in a 3D-printed structure that will house both the motor and circuitry. Possible future work for this design would be to sound proof the design, add additional degrees of freedom, which could include adding a shoulder component to target all three major joints of the arm.

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