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

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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— exoskeleton, elbow, wrist, pneumatic actuators, servo motors, rehabilitation, passive movement therapy

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 non-paralyzed 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 movement [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 both fine and gross motor skills for patients. Most robot-assisted therapy devices for the upper extremity focus primarily on shoulder and elbow movements, and there is a notable scarcity of devices designed to target wrist and finger movements [6]. 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.

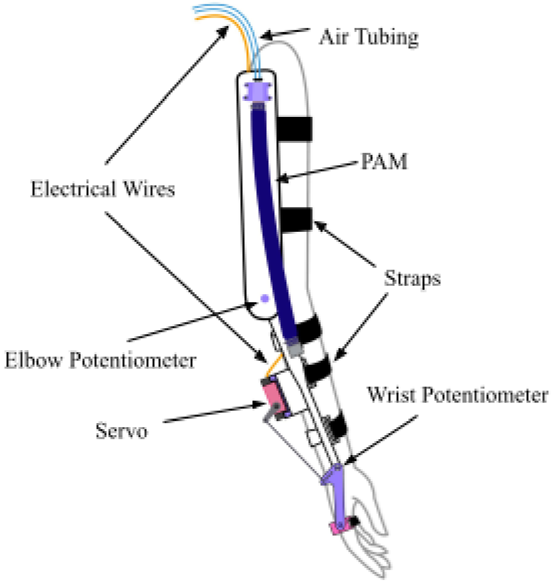


Fig. 1. Overview of the W.E.A.R Bot Exoskeleton (Backpack Containing Air Pump, Solenoid, Arduino, and Power Supply Not Pictured)

II. Design Process

A. *Methods*

The human elbow bends due to the contraction of the bicep muscle from a straight position (180°) to about 36.4° (Figure 2). The wrist, however, uses a combination of muscles and tendons to flex and extend the wrist to 145.6° and 131.5° 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.

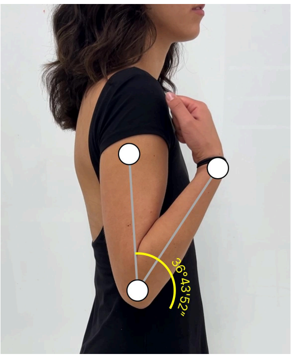


Fig. 2. Natural Human Elbow Movement Due to Bicep Contraction

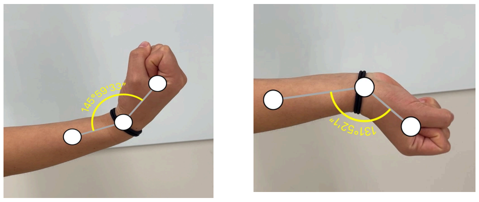


Fig. 3. Natural Human Wrist Flexion and Extension

The maximum percent contraction of a PAM is dependent solely on the tube stiffness and mesh angle. W.E.A.R. Bot's PAM 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 τ_T and τ_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 θ 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.

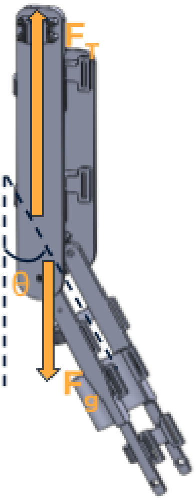


Fig. 4. Free Body Diagram for Elbow Hinge Brace

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

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

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

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

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

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.

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

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 PAM was then found experimentally using a spring balance as seen in Figure 5. 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 sleeve, and other unpredictable material or environmental factors. While the force calculation may be incorrect, the theoretical equation provides insight on the relationships the various factors have on the output force.

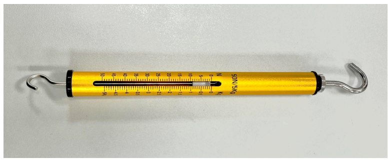


Fig. 5. Spring Balance Used in Force Testing

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 (Figure 6).

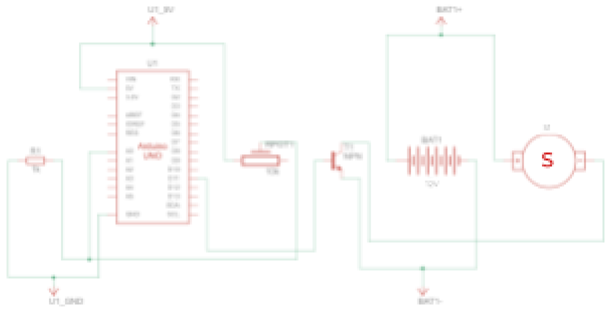


Fig. 6. Circuit for Solenoid and Potentiometer

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 range of motion (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

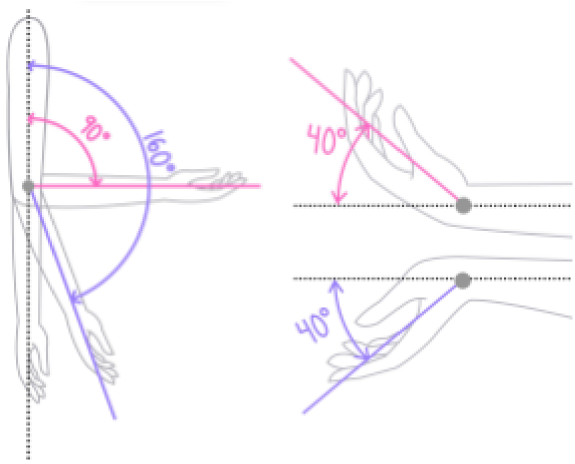


Fig. 7. Elbow and Wrist Range of Motion Design Goals

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

I. Elbow

The design features a 3D-printed hinged elbow brace with a maximum of 125 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 8). The pneumatic design of the solenoid is shown in Figure 9. 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.

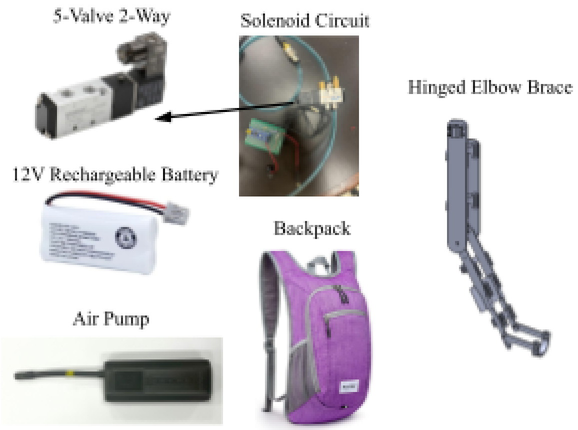


Fig. 8: Backpack and Components

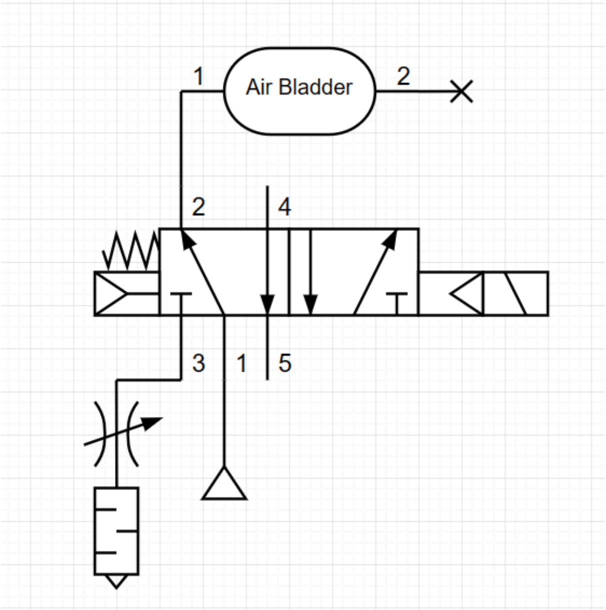


Fig. 9. Schematic of Solenoid Pneumatic Design

II. 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) (Figure 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 circuit layout for the servo is shown in Figure 11. 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 (Figure 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).

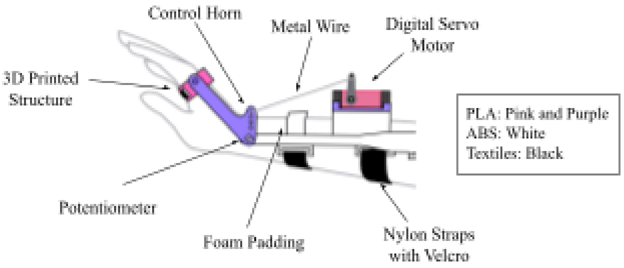


Fig. 10. Wrist Exoskeleton Components and Materials

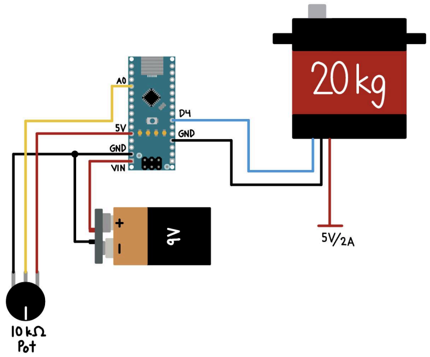


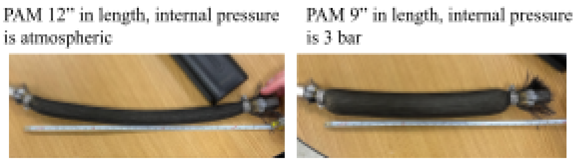
Fig. 11. Basic Circuit Layout for Wrist Components

D. *Prototype Iterations*

I. Elbow

The PAMs continued to be prototyped until airtight (Figure 12). Its percent contraction for varying internal pressures and weights was tested and compared to design calculations. In our first prototype, we attached the PAM using zip ties to a commercially available elbow brace (Figure 13). This prototype was tested on each of the project members, with the maximum angle achieved measured by the dial on the elbow hinge. The code for the 3-way solenoid was developed to be a time-varying actuation based on the potentiometer and pressure data. Next, 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.

Based on observations made during the testing of our first prototype, we determined that the ideal placements of the fixed ends of the PAM were not compatible with the commercial brace geometry, so the PAM length and ROM were limited. We decided to design a custom brace that extended closer to the shoulder so that we could use a longer PAM and have more control over where the PAM was attached. We also found that the upper end of the PAM had to be fixed but the lower end needed to be free to move a small amount as it contracted. To account for this in our new design, we designed a linkage to securely fix the upper end of the PAM to the brace using four screws (Figure 14a). Next, we measured the dimensions of the split knob of the potentiometer so that we could use the potentiometer as a revolute joint (Figure 14b), with the knob fixed to the upper arm component and the base fixed to the lower arm component of the brace. This would allow the knob of the potentiometer to rotate in tandem with the real elbow joint and act as a rotary position sensor. In order for the PAM to actuate sufficient elbow flexion, the θ value in Equation (1) must be greater than zero. We designed the new brace to restrict the elbow extension to 160° (Figure 14c), which would correspond to $\theta = 20°$. Once these individual components were functional, the team integrated them and tested the whole system.


PAM 12" in length, internal pressure is atmospheric

PAM 9" in length, internal pressure is 3 bar

Fig. 12. PAM Prototype

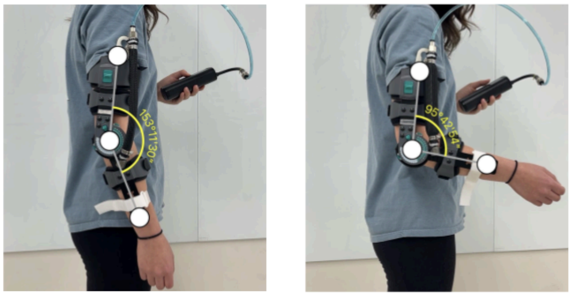


Fig. 13. First Prototype of Elbow Design

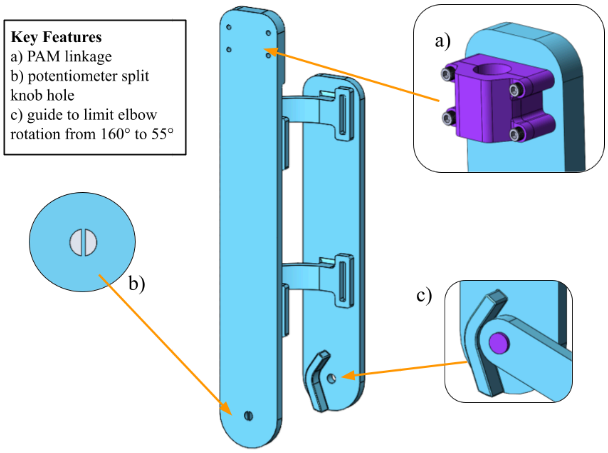
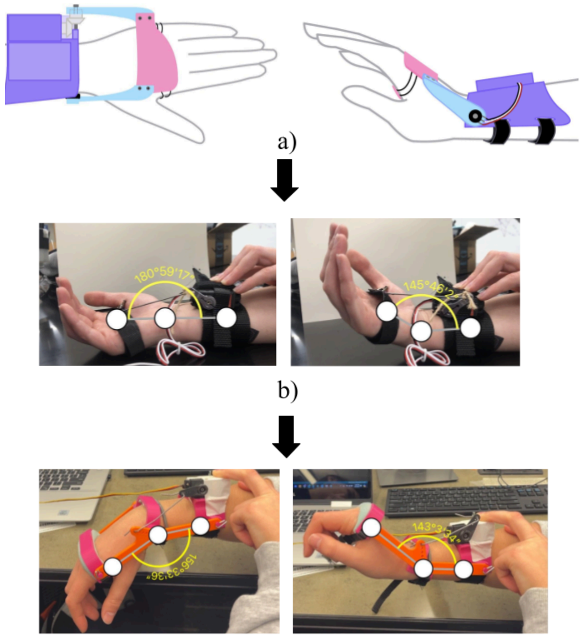


Fig. 14. CAD of upper arm/bicep components of our final W.E.A.R. Bot brace, highlighting key features related to the elbow mechanism

II. *Wrist*

The necessary materials for the wrist component of the exoskeleton were ordered at the beginning of the semester. This included the portable power supply, nylon straps, and velcro. The circuit for the wrist potentiometer, servo motor, and external power supply was assembled, and the code for servo motor control was further developed The first full prototype was assembled by April, including the 3D printed components, padding, adjustable straps, and electrical components. Possible issues regarding the fit or alignment of the parts were addressed after the completion of the first prototype. Further experimentation was 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 (Figure 15a). 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 (Figure 15b) 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 of the soft material. 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 (Figure 15c). 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. Further experimentation was done with the new assembled device to refine the code. This prototype achieved approximately 37° of flexion and 24° of extension.


a)

b)

c)

Fig. 15. Wrist mechanism design iterations, a) initial design sketch, b) first prototype, c) second prototype

III. *Final Prototype*

In our final iteration, we integrated both the elbow and wrist mechanisms into a singular wearable device (Figure 16 and 17). We opted to develop a single device for ease of use, rather than two separate modular ones. This decision aimed to streamline functionality and enhance the overall user experience. Utilizing nylon and Velcro, we constructed straps to securely fasten the device to the user's arm. We also incorporated foam padding to create a cushioning layer between the brace's rigid structure and the user's body, which enhanced both the fit and comfort. The pump and electrical components were able to be stored in a small backpack.

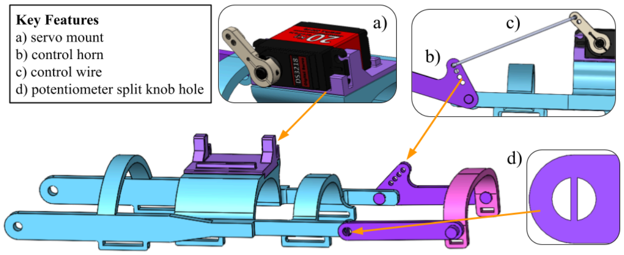


Fig. 16. CAD of forearm and hand components in our final W.E.A.R. Bot brace, highlighting key features related to the wrist mechanism

Fig. 17. Final Prototype Design

III. Results

As seen below in Table III, the project met three out of four of the range of motion goals and greatly exceeded those of both elbow flexion and wrist extension. To measure these results, the device was tested on a single group member, as shown in Figures 18 and 19. 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 the 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 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	160
Wrist	Flexion	40	23
	Extension	40	53

*measured from neutral axis, see Figure 7

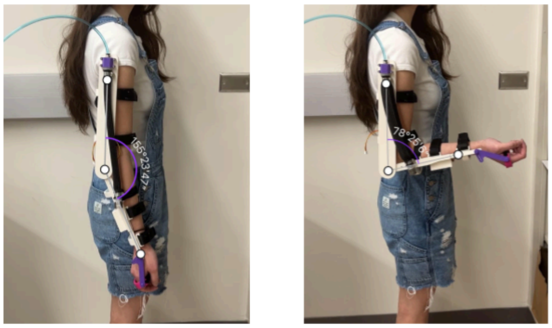


Fig. 18. Elbow Range of Motion Results

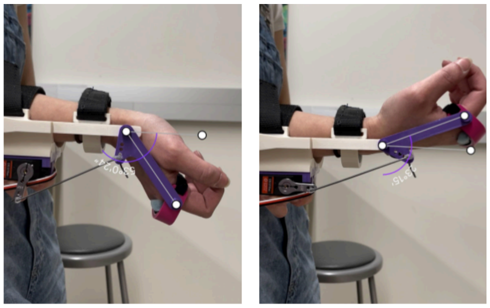


Fig. 19. Wrist Range of Motion Results

IV. Discussion and Conclusions

A. Discussion

Three of the four range of motion goals were achieved highlighting the effectiveness of a lightweight customizable design. The pneumatic muscle and servo had great strength-to-weight ratios, however, there was a drawback of the contraction of the muscle being at a nonlinear velocity. We were able to incorporate padding to make the design more comfortable but were unsuccessful in achieving desirable ranges of motion with the mostly soft designs of the first iterations. The 3D-printed elbow and wrist brace fit well for our arms and hands. The straps helped with the level of fit, however, there needed to be more adjustability of the brace to fit different arms/hand sizes. The solenoid for the PAM was successful in previous testings, however, there were difficulties when incorporating the finalized soldered circuit that led to the manual usage of the solenoid for final testing.

B. Conclusion and Future Work

The goal of this project was 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 is suitable for patients of a wide range of sizes and abilities and will be easily implemented into personalized treatment plans. The design improves upon current exoskeletons currently on the market by targeting muscles involved in both gross and fine motor skills while being portable, lightweight, and relatively comfortable. The design consists of two systems: the elbow and wrist. The elbow system uses one pneumatic muscle actuator to create a contraction of 90 degrees. The PAM is controlled by a solenoid which is programmed using an Arduino to perform a sequence of rehabilitation exercises. The wrist system uses a digital servo motor to rotate the wrist 23 and 53 degrees in both flexion and extension and also uses an Arduino to perform a sequence of rehabilitation exercises. The wrist is enclosed in a 3D-printed structure that houses both the motor and circuitry. Possible future work for this design would be to soundproof the design since currently the air pump used to inflate the PAM operate at 80 decibels and the goal would be to get this level down to 60 decibels. The brace could be made more adjustable and easier to don and doff by integrating adjustable ratchet lacing mechanisms for the closures rather than solely Velcro straps [10]. Additionally, to improve the comfort level, we suggest reducing the bulkiness of the rigid components and replacing the non-flexible nylon straps with a more elastic textile material. The wrist design could further be improved by integrating a mechanical stop to restrict the ROM. This would prevent the hand from being forced into unnatural positions, reducing the risk of injury. Another possibility for future work would be to add additional degrees of freedom which could include adding a shoulder component to target all three major joints of the arm. A final suggestion for future work to improve upon this design would be to incorporate an interactive user interface that would allow the patient to directly set the number of repetitions in the exercise sequence and control the range of motion. This would allow the user to quickly adapt the design to fit their specific needs instead of having to reprogram the Arduino.

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