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Bio-Mechatronics Design and Manufacturing of Arm Exoskeleton with Electro-Pneumatic Mechanism for Passive Rehabilitation

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Abstract. Exoskeletons are crucial for providing intensive and consistent rehabilitation over a longer period and may be able to treat the patient without the presence of the therapist compared to manual therapy. This approach allows for frequent treatment reducing several costs. Therefore, this study aimed to examine the passive elbow rehabilitation of lateral epicondylitis patients, usability, and bioinspired design, to develop a mechatronics system with three rehabilitation positions. Regarding the biomechanical fundamentals of the elbow joint and as an engineering sustain, Computer-Aided Design (CAD) was made, consisting of Finite Element Analysis (FEA), anthropometric, ergonomic, and assembly analysis. The results showed that for the three rehabilitation positions, FEA showed von Mises stress less than the elastic modulus by a 10^3-factor resulting in no permanent deformation. Position 1, 2, and 3 produced angular displacements of 27°, 16.5° and 31° respectively with a total of 74.5°. An arm exoskeleton for passive rehabilitation of the elbow was developed using a pneumatic cylinder and an AD8832 electromyography (EMG) sensor, capable of detecting the EMG peak point to activate or deactivate the 24 V Arduino relay to flex or extend the elbow based on the positions. A total angular displacement of 74.5° was obtained instead of the simulated version 84.63°, with an error margin of 11.96%. The force during the three rehabilitation positions was 18 N exerted by the air compressor at a 6-bar constant pressure, and due to the use of choke valves.

Keywords: Arm Exoskeleton; Bio-design; Passive Rehabilitation; Robot-Aided Rehabilitation

1. Introduction

The upper limbs are associated with various important roles in daily activities. Therefore, a musculoskeletal and neurological disorder can affect the functions, reducing the patient quality of life, either due to a spinal cord injury, different disorders in motor

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neurons, or a Cerebrovascular accident (CVA) (Copaci *et al*., 2019). CVA is one of the main causes of mortality in the world because rehabilitation treatments have a special requirement for one or more therapists due to extended supervision time (Vargas, Cornejo, Correa-López, 2016).

A literature review on exoskeletons and robotic rehabilitation showed significant advancements in control and torque estimation. A Model Reference Adaptive Control (MMRAC) has proven effective for controlling soft robotic exoskeletons, enabling both passive and assistive control without the need for additional sensors, and showing robustness against uncertainties (Toro-Ossaba *et al*., 2024). Additionally, trend analysis showed that all analyzed exoskeletons use flexion/extension movements, with aluminum and 3D printing, as well as PID control algorithms and servomotors (Huamanchahua *et al*., 2021). The most common applications are assistance and rehabilitation (Cornejo *et al*., 2021). An adaptive controller based on artificial neural networks demonstrated high accuracy in gesture detection for wheelchair-mounted exoskeletons (Schabron, Desai, and Yihun, 2021). Twisted String Actuators (TSAs) have proven effective in lightweight, customizable assistive devices (Hosseini *et al*., 2020). Topological optimization of transtibial prosthetic sockets using Finite Element Analysis (FEA) demonstrated improvements in stress performance and weight reduction, although it may also contribute to material fatigue over time (Faadhila, 2022). Compared to manual therapy, exoskeletons have the potential to provide intensive and consistent rehabilitation over a longer period (Lo and Xie, 2012).

Other studies focused on the development and evaluation of innovative medical and rehabilitation devices aimed at enhancing patient outcomes. For instance, a study designed a Transforaminal Lumbar Interbody Fusion (TLIF) spine cage using reverse engineering, followed by simulated compression tests, which demonstrated the capability to withstand the forces typically encountered in spinal fusion surgeries (Norli *et al*., 2024). Another study addressed the challenge of maintaining motivation in pediatric rehabilitation, particularly for children with Developmental Coordination Disorder (DCD). This study discussed the iterative co-creation of Matti, a pressure-sensitive Tangible User Interface (TUI) for exergaming, which has shown potential as a tool to improve patient engagement and the effectiveness of therapy sessions (Ockerman *et al*., 2024). These devices can provide autonomous rehabilitation for patients, potentially reducing healthcare costs and increasing treatment frequency. The main focus is on the bio-mechatronics design and manufacturing of an arm exoskeleton with an electro-pneumatic mechanism tailored for passive rehabilitation.

Passive robotic rehabilitation aims to restore muscle and joint function by assisting the affected limb without requiring active participation from the patient (Juarez *et al*., 2021). Systems using electromyography (EMG) signals for rehabilitation are typically categorized as active (Tiboni *et al*., 2018), where movements from a functional limb are mirrored by the affected one (Gull, Bai, and Bak, 2020; Qassim and Hasan, 2020). However, this study focuses on a passive reflex rehabilitation method, where both arms are simultaneously engaged, enhancing recovery through synchronized motion. The classification for the device based on the type of assistance provided is passive reflex (Maciejasz *et al*., 2014) because it aims to assist the motion of the elbow extremity while mirroring the other arm (Khalid *et al*., 2023), The proposed exoskeleton assists in elbow movement, a critical function in daily tasks, and is designed to improve rehabilitation outcomes by mirroring the movements of the unaffected limb.

Upper limb exoskeletons are used to rehabilitate patients with various conditions, such as strokes (Cervantes *et al*., 2024), cerebral palsy (Sandoval *et al*., 2023), and neuromuscular diseases, helping to regain mobility of the arms, shoulders, hands, and elbows (Lo and Xie, 2012). The elbow is a hinge-type synovial joint located between the humerus with the ulna and radius formed by the humeral trochlea, the spheroidal condyle, the trochlear incision, as well as the head of the radius that allow flexion and extension movements at an angle of up to 170° (Rodriguez *et al*., 2022). The proximal radioulnar joint allows pronation and supination of the forearm (Molina *et al*., 2023a). Rotation occurs within a ring formed by the annular ligament and the radial incision of the ulna, and these movements are essential for everyday tasks (Rahlin, 2024).

Mechatronic virtual bio-design and biomechanics are key areas for developing effective arm exoskeletons for passive elbow rehabilitation (Cornejo, Cornejo-Aguilar, and Perales-Villarroel, 2019). Virtual bio-design allows the operation of these devices to be analyzed using computational models, which has led to significant advances in design (Cornejo, Vargas, and Cornejo-Aguilar, 2020). However, challenges such as improving comfort, portability, and efficiency remain. Elbow biomechanics, on the other hand, studies the physical and mechanical principles of joint movements, providing crucial information for the design of exoskeletons that adapt to the anatomy and natural movements of the elbow (Molina *et al*., 2023b). This study contributes to ongoing efforts by integrating mechatronic virtual bio-design with elbow biomechanics, creating a low-cost, more effective, and personalized exoskeleton for passive elbow rehabilitation. The objective is to enhance the design and performance of exoskeletons through FEA and dynamic simulations, offering a novel approach to rehabilitation technology.

The manuscript is organized as follows; Section 2 describes materials and methods for the bio-mechatronics design of the arm exoskeleton for passive rehabilitation, including simulation of the control system. Section 3, focuses on the system manufacturing and integration, while Section 4 describes the test and results, focusing on the angular displacement and performance of the system. In Section 5, the manuscript ends with conclusions and further work.

2. Materials and Methods

This started by defining the problem and proposing an innovative solution to the classic rehabilitation methods, with a robot-aided system intended to be accessible and easy to use for patients (Cornejo *et al*., 2023). To achieve this, the study problem consisted of assessing the passive elbow rehabilitation of lateral epicondylitis patients and clearly understanding the symptoms. As a next phase, the project was subjected to evaluation of the clinical background as well as the usability of bioinspired design, to develop a mechatronics system with the appropriate materials. The specific requirements and constraints were then defined to produce a conceptual design regarding the biomechanical fundamentals of the elbow joint. The material selection consisted of appropriate elements for the exoskeleton and the actuators. As an engineering sustain, Computer-Assisted Design (CAD) was performed, consisting of FEA, anthropometric, and ergonomic, as well as assembly analysis. Consequently, the mechatronics system design, simulation, and manufacturing were prepared. This passive elbow system can be used in rehabilitation and clinical centers, as shown in Figure 1.

2.1. Digital twin

A digital twin can be described as an integrated multi-physics, multi-scale, probabilistic simulation of a complex product that uses the best available physical models and sensor updates to mirror the life of corresponding twin according to Michael Grieves (Jiang *et al*., 2021). Although initially focused on industrial applications, digital twins have reached the medical sector, for robot-aided rehabilitation, where the main goal should be relatively simple mechanically. The structure must be easy to put on and training within the limited space, with an additional bio-signals tracking system (Falkowski *et al.*, 2023). Following the digital twin and the design methodology for rehabilitation robots (Martínez and Z.-Avilés, 2020), the mechanical, electronic, control, and programming system for a passive elbow rehabilitation exoskeleton station was developed.

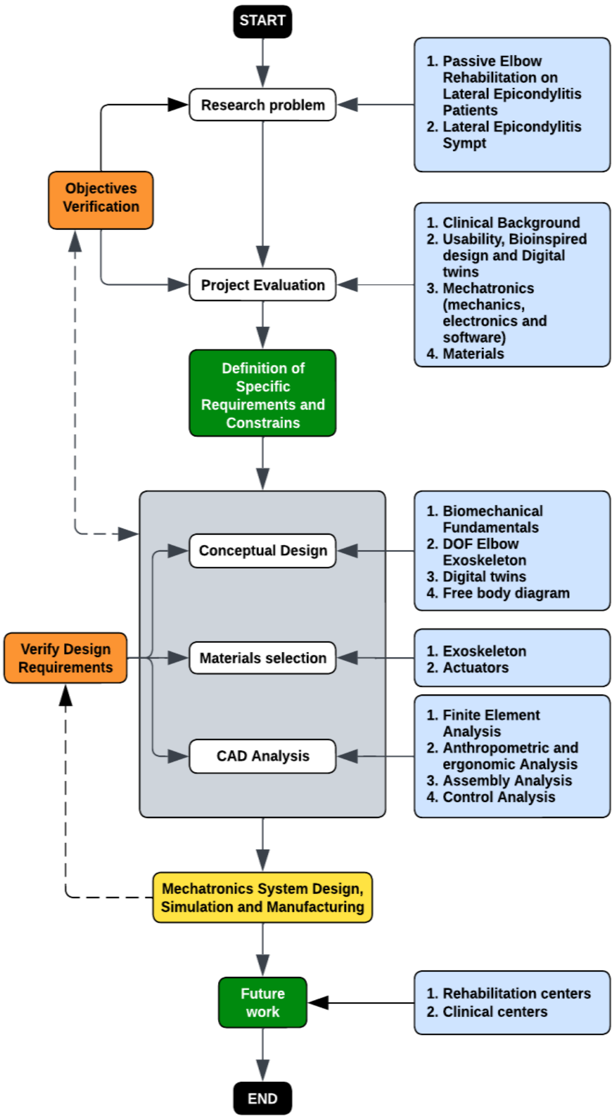

Figure 1 Experiment set-up and apparatus

2.2. Free body diagram

Initially, the system was encharged to transmit force to replicate the flexion and extension of the elbow, which naturally has a range from 0° to 150° (Martin and Sanchez, 2013). The functional range of movement is from 30° to 130° (Felstead and Ricketts, 2017), hence, a smaller range was considered to not damage the elbow joint, from 30° to 90°. To reach this point, three rehabilitation positions were considered due to the limitation of the pneumatic cylinder at 100 mm axial displacement. Each position produced a 30° angular displacement taking as a reference the position of the joint. As an initial phase, the free body diagram of the system was developed to understand how the system will behave as well as the kinematic and dynamic interactions. Equation (1) describes the geometrical restrictions:

$$l_2 \cos(\beta) + h = l_1 \cos(\theta) \tag{1}$$

Where l1 and l2 represent the lengths of the link that transmit the force to the revolute joint, θ, and β represent the angle formed with a vertical plane as shown in Figure 2. a., by modelling the dynamics of the system using the second law of Newton (Rojas-Moreno, 2001). The linear and rotational motion between the first link and the pneumatic coupling (Figure 2. b.) as well as between the elbow pad and the second link is described in equations (2), (3), and (4) while the variables are presented in Table 1:

$$(m_c + m_1)\ddot{x} - \left(\frac{m_1 l_1}{2}\right) sin(\theta) + \dot{\theta}^2 \left(\frac{m_1 l_1}{2}\right) cos(\theta)\,\ddot{\theta} = F - R\,cos(\beta) \tag{2}$$

$$\frac{m_1 l_1 g\, sin(\theta)}{2} - m_2 l_2 \ddot{x}\, cos(\theta) = J_1\ddot{\theta} - R l_1\, cos(\beta + \theta) \tag{3}$$

$$m_2 g d - R l_2 = J_2\ddot{\beta} + B_c\dot{\beta} \tag{4}$$

Table 1 Description of Variables and Model Parameters

Experiment	Container
l_1	Length of first link
l_2	Length of second link
θ	Angle of the revolute joint
β	Angle formed between the first and second link displayed in a vertical plane
h	Height of the pneumatic coupling to the base of the second link
m_1	Mass of the first link
m_2	Mass of the second link
g	Gravity (9.8 m/s^2)
R	Mutual reaction
m_c	Mass of the pneumatic coupling and the piston
F	Pneumatic cylinder force
J_c	Moment of inertia of the pneumatic coupling and the patient's arm
B_c	Rotary viscous friction

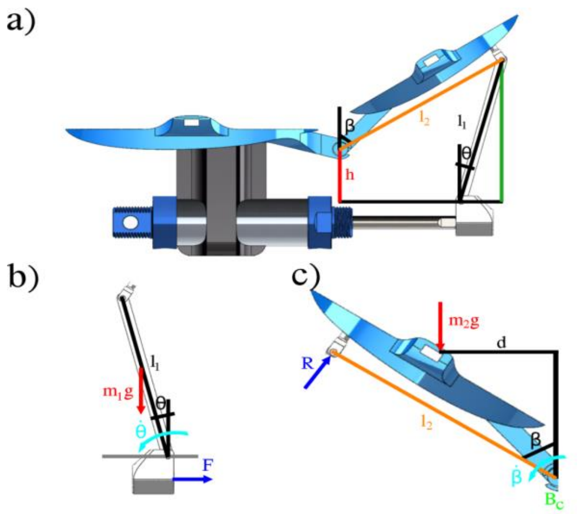

Figure 2 Free body diagram of the system to be developed: a) Geometrical relationships between the links that transmit force, b) Forces interaction on the link and the coupling of the pneumatic cylinder, c) Forces interaction between the link and the revolute joint

2.3. Mechanical design considerations

The mechanical design was carried out using ISO 7250-3:2015 (ISO, 2015), which standardizes the dimensions of the elbow to wrist (267 mm), and shoulder to elbow (340 mm). Half of the arm was taken to make the elbow pads considering ergonomics comfort

(Schiele and Helm, 2006), with one in the arm of 170 mm, and the other in the forearm of 134 mm. After several simulations, the appropriate link distance was 110 mm to achieve the three rehabilitation positions. For the table support, the proper distance was 50 mm, and when the user feels uncomfortable, regulating the chair height can solve this inconvenience. For the actuator, pneumatic cylinders were considered by offering a high force-to-weight ratio, being able to be stopped at any time without causing injuries, and requiring less maintenance, which is desirable for a potentially mobile rehabilitative exoskeletal system (Karanth and Desai, 2022; Burns *et al.*, 2020; Carvalho, Gopura *et al.*, 2016; Zhang *et al.*, 2008). As shown in Figure 3, the hole system can be assembled by the patient putting the table support stable and then connecting the elbow pad, the link mechanism to the pad, and pneumatic cylinder. The parts come with a tolerance of 0.15 mm, allowing a correct coupling, which needs only two ⅛" screws or the link mechanism. At the same time, the pneumatic cylinder can be introduced by pressure. To make the system accessible, polylactic acid (PLA) was considered, as 3D printing technology can be used to sustain the patient needs in short periods (Demeco *et al.*, 2023), by customizing the designs and maximizing the times of fabrication.

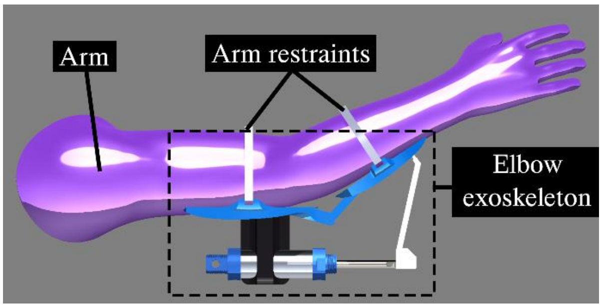

Figure 3 System developed for passive elbow rehabilitation: a) Isometric view, b) Exploded view

2.4. Finite element analysis

In the analysis, two groups were considered, one for the elbow pads, and the other for the rehabilitation station. A previous study developed human arm parameters (Speich, Shao, and Goldfarb, 2005), to simulate the weight distribution of the forearm and arm using FEA. As a reference point for the studies, the base of each elbow pad was considered a fixed geometry. A normal force of 150 N was applied to the face in contact with the arm in the elbow pads, by taking a median of 10 kg for the human arm mass, and a scale factor of 1.5 was used for the analysis. Furthermore, the material selected was ABS from the SolidWorks standard library, with an elastic module of 2 GPa. The maximum von Mises stress for elbow pad 1 was 56.234 N/m^2, and for elbow pad 2, it was 331.985 N/m^2. Under the material elastic limit, there is no permanent deformation.

The second group of FEM studies was made to the table support and the linkages. Figure 4a shows that l_1 receives a von Mises stress of 135 MPa in the bolted joint, hence, a ⅛" screw was considered as the maximum shear stress of 145 MPa according to the 'Structural Design of Stainless Steel' (BSSA, 2001). For the table support, Figure 4b shows a maximum von Mises stress of 8.567 MPa for the elbow joint, while Figure 4c shows a maximum of 6.287 MPa for the bolted joint in the pneumatic cylinder coupling. Figure 4d shows a maximum von Miss stress of 20 MPa in the joint to the elbow pad. However, these values are less than the elastic module by a 10^3-factor.

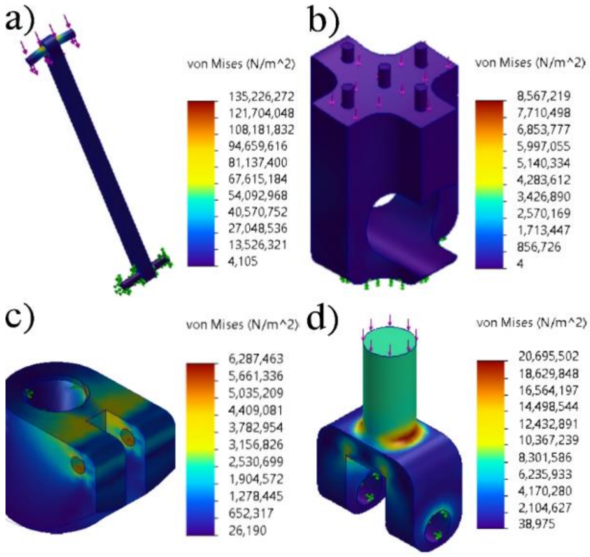

Figure 4 FEA studies for the elbow pads: a) l_1 under a 150 N load with a maximum von Mises stress of 135 MPa, b) Table support under a 150 N load with a maximum von Mises stress of 8.567 MPa, c) Pneumatic cylinder coupling under a load of 150 N with a maximum von Misses stress of 6.287 MPa in the bolted joint, d) Elbow pad coupling under a load of 150 N with a maximum von Misses stress of 20 MPa

2.5. Electronic design

The EMG circuit consists of three electrodes connected to the forearm that capture the electrical activity of the muscles, connecting to the (1) AD8832 sensor to amplify, filter, and digitize signals (Zaman *et al*., 2019). These signals were sent and processed by the (2) Arduino UNO, to control the (3) 24 V relay, with a (4) 24 V power supply that powers the relay and valve, while a separate 5 V supply powers the Arduino, to activate or deactivate the (5) solenoid valve 5/2, regulating the flow of air. Moreover, the Arduino UNO connects to an AD8832 configured with a bandwidth of 0.05 Hz to 200 Hz and a CMRR of 80 dB (Junior *et al*., 2023). The ECG electrodes were connected to the IN+ and IN- pins of the AD8832, and the amplified and filtered signal was sent to the OUT output, connected to an analog input pin (A0). The microcontroller (ATmega328P) processed and filtered out high-frequency noise and stabilized the signals. The electrodes detect voltage changes generated by muscle cells during contraction and transmit to the EMG circuit. Subsequently, the circuit read with the Arduino program to determine the readings when opening or closing the hand and moving the arm unidirectionally (Figure 5).

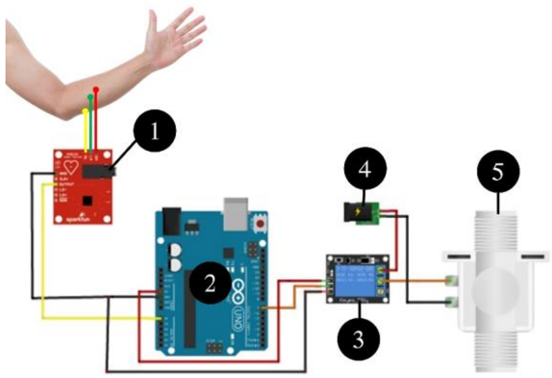

Figure 5 Circuit diagram of the electronic system. (1) AD8832, (2) Arduino UNO, (3) 24 V relay, (4) 24 V power supply, y (5) solenoid valve 5/2

2.6. Pneumatic modeling

A system model requires knowledge of the physical interactions between forces (Ogata, 2010). MATLAB offers Simscape as a tool to analyze directly the physical interactions between components (Xavier, Fleming, and Yong, 2020). For this study, a double-acting pneumatic cylinder was modeled using the fluids library (MATLAB, 2018b), with a reservoir established as a reference point. The gas properties included a constant of 0.287 kJ/(kg·K), compressibility factor of 1, reference temperature of 293.15 K, specific heat at constant pressure of 1 kJ/(kg·K), dynamic viscosity of 18 s·uPa, and a thermal conductivity of 26 mW/(m·K). The pressure source was in charge of regulating the flow through the pneumatic circuit, while a 4/3 directional valve was used to control the flow direction. To connect the load to the physical system, a translational multibody interface was considered. When the signal comes from Simulink, it must be converted to a physical signal using the Simulink-PS, and vice versa. For the EMG input signal simulated as a pulse, it was converted to a physical signal to activate the directional valve (Figure 6).

2.7. Multibody modeling

Simscape offers multibody links that act as an interface between CAD software and MATLAB (MATLAB, 2023; MATLAB, 2018a). For this project, it was used to pass the system developed in SolidWorks to the Multibody interface. An automatically generated model was made, and the position of the components was readjusted in Figure 7. The input force for this subsystem was the pneumatic force due to the EMG signal, which moved the cylindrical joint between the pneumatic cylinder and the piston rod, limited in the Z prismatic primitive (P_z) with a lower limit bound of -50 mm, and an upper limit bound of -25 mm. Gravity was established by the mechanism configuration block at the Y axis with a vector ([0 -9.80665 0]). Finally, the output of the signal was the angle between elbow pads 1 and 2 measured using a transform sensor in radians multiplied by a gain of 180/π in the angular displacement (in degrees).

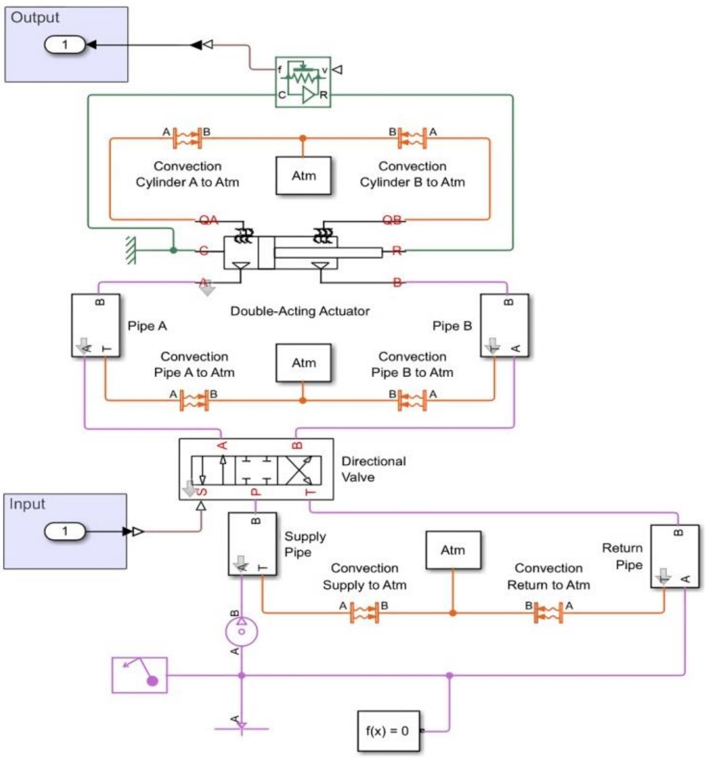

Figure 6 The EMG input activates the pneumatic circuit and changes the position of the 4/3 directional valve

2.8. Control system

For the simulation of the passive elbow exoskeleton rehabilitation system (Figure 8), MATLAB software was used together with the SimScape library from SIMULINK, which has been used for modeling prosthetic and rehabilitation systems (McGeehan *et al*., 2022; Wu *et al*., 2022; Pitre et al., 2021; Hoh, Chong, and Etoundi, 2020). By simulating the changes in the position of the 4/3 directional valve, the operation of an electromechanical solenoid button can be approximated by using a unit step signal that oscillates between -1 and 1. The arm motion was detected by the EMG sensor and established a peak point. This changed the position of the valve, extending or contracting the pneumatic cylinder. Subsequently, the pneumatic force was transferred to the exoskeleton, and, depending on the rehabilitation position, the angular displacement would be different.

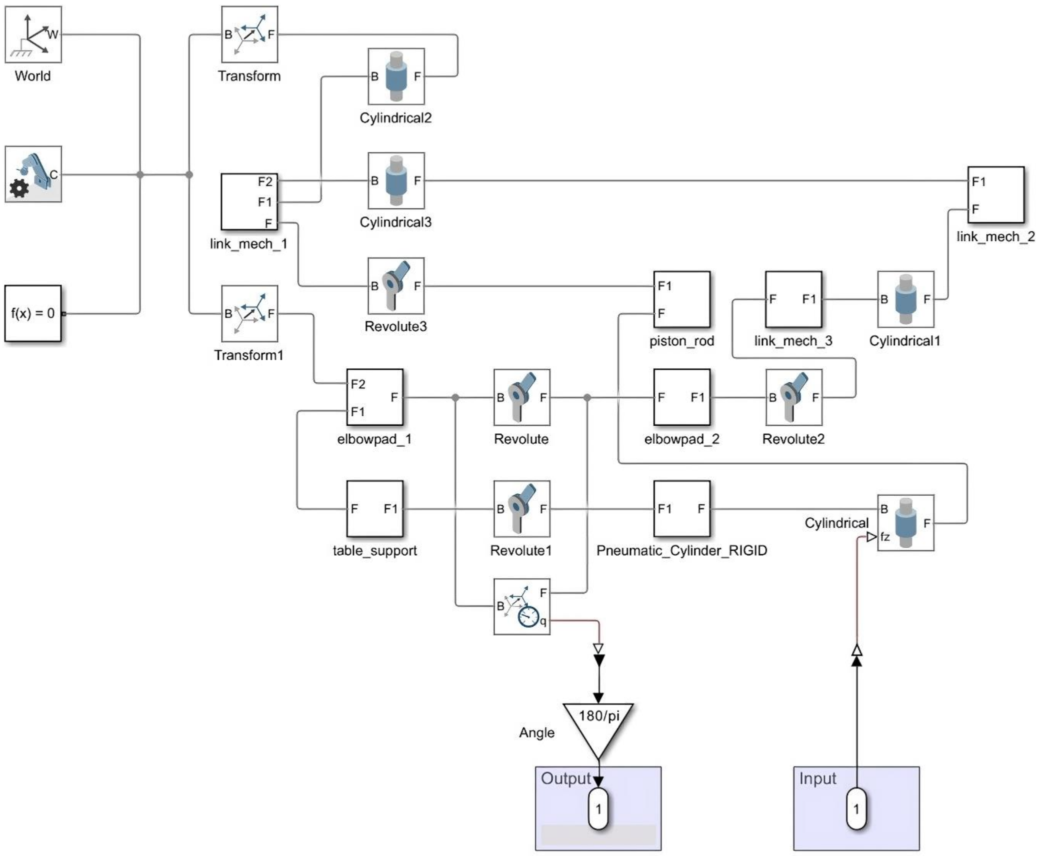

Figure 7 Scheme of the mechanical behavior of the system using SimScape Multibody

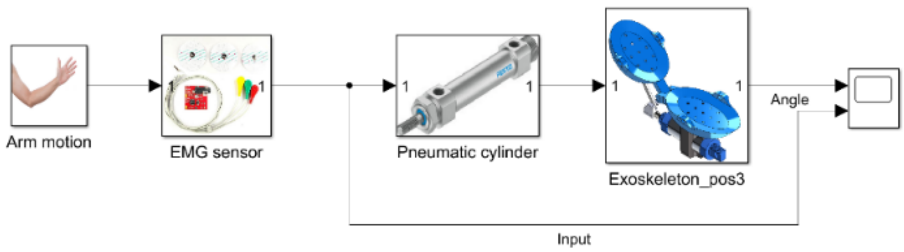

Figure 8 Control system for the Passive Rehabilitation Elbow Exoskeleton

For all the simulations, the input signal was computed for a period of 20 s with a duty cycle of 50% and an amplitude of 2. At position 1, the angle between the elbow pads had a minimum of 58.82° and a maximum of 93.33° with an angular displacement of 34.51°. At position 2, the angle between the elbow pads had a minimum of 26.38° and a maximum of

42.3815° with an angular displacement of 16°. Finally, at position 3, the angle between the elbow pads had a minimum of 0.016° and a maximum of 34.1287° with an angular displacement of 34.11° as shown in Figure 9. As a total displacement, the partial sum of the positions was 84.63°, falling within the safety range of motion defined previously. The simulated EMG signal ranged between 1 and -1 to mimic the elbow joint extension (1) and flexion (-1). When the patient does flexion, the pneumatic resulting force activates the pneumatic cylinder to achieve full displacement, contracting the elbow with a maximum pneumatic force of 18 N. To extend the joint, the force is gradually reduced over 5 seconds to a minimum of -18 N, as shown in Figure 10.

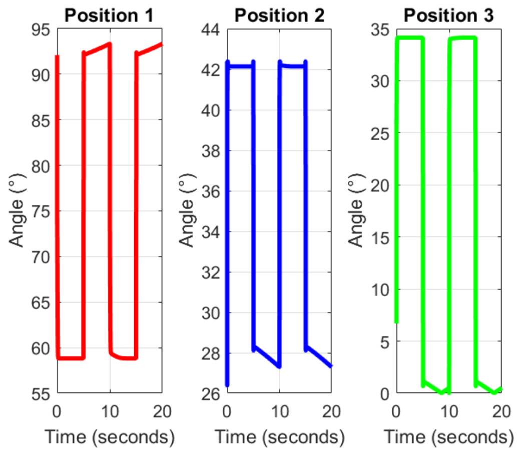

Figure 9 Change of angular position as a function of time

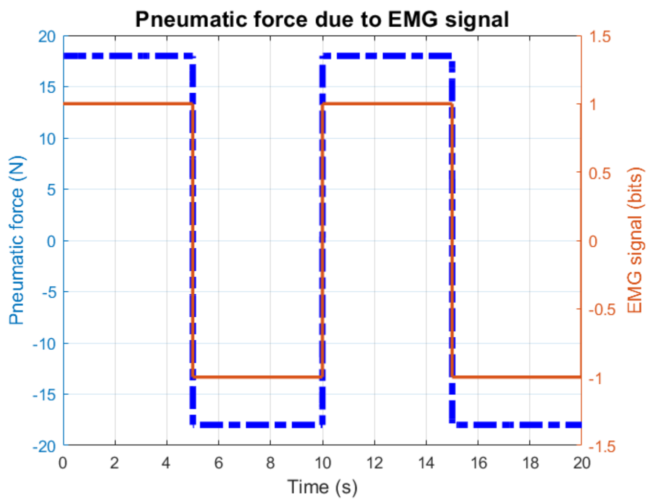

Figure 10 Pneumatic force is due to the EMG signal as a function of time

3. System Manufacturing and Integration

3.1. Mechanics Prototyping

As the next phase, physical integration of the system was made. Initially, the (1) elbow pad, (2) table support, and (4) linkage mechanism were exported from SolidWorks to FlashPrint5 for 3D printing (Cornejo *et al*., 2022). A previous study showed that PLA has the highest tensile strength (33.7 MPa) using a layer thickness of 0.27 mm and an infill of 78% (Camargo *et al*., 2019). To add more resistance, an infill of 100% was considered as well as tree supports for corners minor to 20°. By using the base for a correct addition with the heated bed, favorable results were achieved.

3.2. Electronics Prototyping

A FESTO 24 V DC supply was used to power the 5/2 solenoid valve. Due to the voltage and current requirements, a 5 V DC Arduino relay was used to close or open the circuit when the patient desired. The AD8832 EMG sensor powered with an 18 V battery, was responsible for receiving the muscular signals of closed and opened arms, with three electrodes placed in the forearm. The pneumatic cylinder that exerted motion to the elbow exoskeleton used an air compressor of 220 V connected to the outlet as a power supply. A constant pressure of 6 bar with choke valves in the cylinder was manually configured to reduce the velocity of the stem. For the control system, the Arduino UNO prototype board was used, which received the EMG signal and converted into bits to establish an activation point at the peak of the muscular activity of the arm, varying between 500, 800, and 900 for different patients. At this point, the microcontroller sends 5 V to the relay to close the circuit and the pneumatic cylinder exerts force to extend or flex the elbow exoskeleton based on the position of rehabilitation as shown in Figure 11.

3.3. Software Programming

Arduino IDE 2.3.2 software was used due to the advantages compared to previous versions, such as improvements in stability and performance. Initially, the EMG signal was defined in the analog pin A0, and the communication port of the relay was established in pin 8. To determine the readings of the EMG signal, a variable numReadings was defined to establish the maximum amount of sample. Subsequently, global definitions for the array that stores the sensor reading, the index of the reading, the sum of all readings, and the average were established. The configuration was set up using a communication to the serial port which had a value of 115200, with EMG_signal being the input, and the relayPin as an output. Readings were then computed and compared to the EMG_peak. The relay was activated when the value was greater than the average, or deactivated when the value was lower, as shown in Figure 12 and Appendix A Table A.

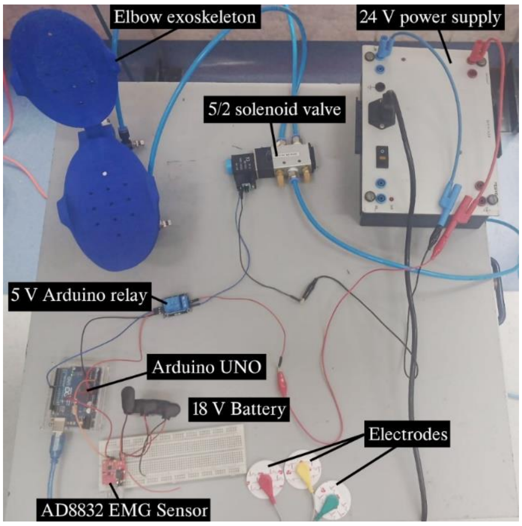

Figure 11 Electro-pneumatic prototyping of the system.

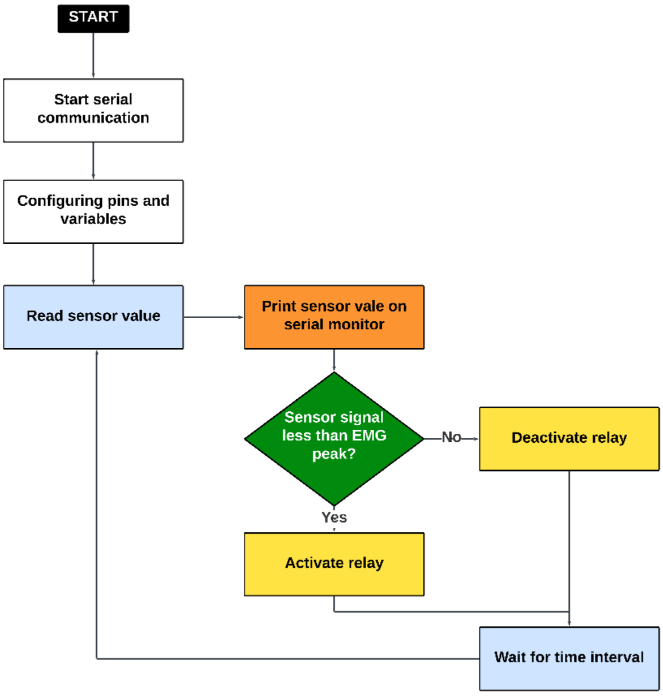

Figure 12 Arm Exoskeleton for Passive Rehabilitation of the Elbow Programming.

4. Results and Discussion

After the mechanical and electro-pneumatic prototyping, a test was developed to contrast the angular displacement on the simulations against the physical system. Initially, the configuration for the initial test was made by putting the electrodes on the arm with motion. In the right arm, three electrodes were placed on the forearm, one in the middle (green), one in two fingers forward than the middle (red), and one below the forearm (yellow). The left arm, which behaves as the extremity without motion, was placed on the exoskeleton. Before each test, a calibration of the EMG sensor is required to activate the system properly. For two patients, the muscular peak when making a fist received by the AD8832 EMG sensor was 500 and 800 bits respectively. This suggests that when the activation points are set the same for both patients, the sensor would not have worked well.

For position 1 (Figure 13a), the initial angular position had a starting angle of 87° and a final of 60°, with a margin of 6.45% error concerning the initial design and the digital twin made. For position 2 (Figure 13b), the initial angle was 25° and the final was 41.5°, indicating a 1.19% error. Finally, for position 3 (Figure 13c), the initial angle was 7° and the final was 38°, with a margin of error of 8.57%. This error can be acknowledged due to the cylinder position when it varies between the start or end point of the pneumatic actuator. The total angular displacement was 74.5° instead of the simulated version with 84.63°, and the error margin was 11.96% (Tables 2 and 3). The pneumatic cylinder exerted a force of 18 N due to the air compressor at a pressure of 6 kPa. The choke valves were used to reduce the velocity of the stem and not affect the patient arm.

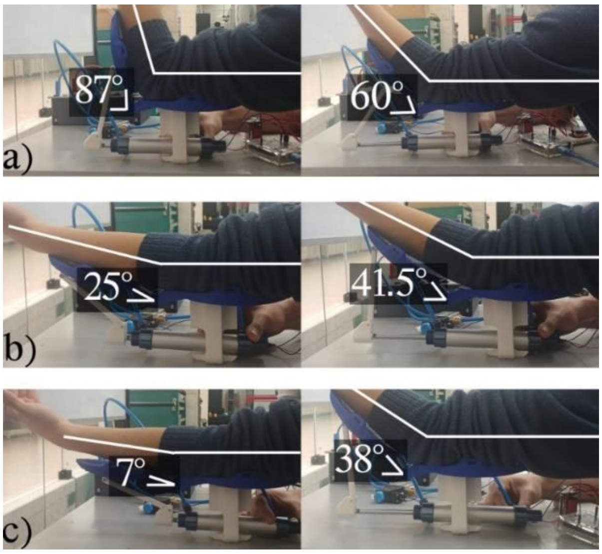

Figure 13 Comparison between the three rehabilitation positions: a) Position 1 with an angular displacement of 27°, b) Position 2 with an angular displacement of 16.5°, c) Position 3 with an angular displacement of 31°

Table 2 Test and Simulation Angle achieved for flexion

Position	Tested flexion (°)	Simulated flexion (°)	Absolute error (%)
1	87.00	93.33	6.78
2	41.50	42.38	2.08
3	38.00	34.12	11.3

Table 3 Test and Simulation Angle achieved for extension

Position	Tested extension (°)	Simulated extension (°)	Absolute error (%)
1	60.00	58.82	2.00
2	25.00	26.38	5.23
3	7.00	6.00	16.67

The results obtained can be compared with other related works. Irshaidat developed an exoskeleton soft robotic arm with various novel pneumatic Muscle Actuators (pMA) capable of bending (Irshaidat *et al.*, 2019). To control the bending angle, the pressure must be controlled by a solenoid valve through a balance of both tensile forces depending on load and existing air pressure in each muscle of the actuator arm. For the project developed, the angle was determined by the rehabilitation position, with constant pressure for the three positions (Rivera *et al.*, 2020). Burns developed HERCULES, a three-degree-of-freedom pneumatic upper limb exoskeleton for stroke rehabilitation (Burns *et al.*, 2020). The main advantage of this system is that it manages to rehabilitate the arm by having three degrees of freedom. However, the dimensions, portability, and costs are higher than those proposed in this project (Rivera *et al.*, 2024). Ma et. al. developed a soft wearable exoskeleton with a pneumatic actuator for assisting the upper limb (Ma *et al.*, 2020).

The assistive capability of the exoskeleton is deficient in comparison with existing devices manufactured with rigid materials. A pneumatic system was used for the linear transmission of movement instead of electrical rotational motors that use constant pressure. Therefore, there is no electrical energy consumption in the compressor until the pressure is below 6 bars. Using pneumatic linear transmission also keeps a clear working area and can be stopped under load without any damage (Gopura, Kiguchi, and Bandara, 2011). Compared to rotational transmission, other exoskeletons that use variable pressures require greater energy consumption. A proposed exoskeleton design was also assembled by modular pieces (Liu *et al.*, 2021), which allows the reconfiguration of the elbow pads to adapt in a more personalized way to each patient. This design complies with safety measures that do not exceed the elastic limit of the material (Zhou *et al.*, 2021). Finally, the open-access technology has great potential to be used and developed by the same user taking into account low-cost economic viability (Vargas, Cornejo, and Vargas, 2024).

5. Conclusions and Further Work

In conclusion, an arm exoskeleton for passive rehabilitation of the elbow was developed using a pneumatic cylinder and an AD8832 EMG sensor, capable of detecting the EMG peak to activate or deactivate the 24V Arduino relay to flex or extend the elbow based on the rehabilitation positions. A total angular displacement of 74.5° was obtained instead of the simulated version 84.63°, with an error margin of 11.96%. The force during the three rehabilitation positions was 18 N exerted by the air compressor at a 6-bar constant pressure, and due to the use of choke valves. The EMG peak point was established experimentally, which varied depending on the patient arm, reaching 500 or 800 bits respectively. Future studies should develop a system of filters for the EMG signal with the use of artificial neural networks to detect the peak point for each patient instead of experimental and manual configuration. Approval from the ethics committee of the Institute of Research in Biomedical Sciences (INICIB) would be requested to (1) take tests on healthy patients and receive feedback, (2) take tests on patients with lateral epicondylitis, (3) make improvements based on the results, and (4) patent this technology with the support of the Ricardo Palma University.

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Conflict of Interest

The authors declare that there are no conflicts of interest.

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