

Design and Development of a Low-Cost Upper Limb Exoskeleton for Rehabilitation and Strength Augmentation

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Abstract-

This paper presents the design and development of an untethered, powered exoskeleton system for upper limbs intended for rehabilitation, therapeutic applications, and occupational strength augmentation. Existing commercial exoskeletons are often bulky, expensive, and limited by tethered configurations. The proposed solution offers a low-cost, ergonomic, and wireless design actuated via onboard sensors that track user motion. The system is capable of collecting kinematic data—such as range of motion—which can assist in physical therapy by enabling detailed progress tracking by clinicians and patients alike. The arm unit, controlled via a button-based interface or through sensor-based automation, supports lifting tasks beyond typical human capacity, making it suitable for both medical and industrial applications. The mechanical structure is constructed using lightweight aluminium alloy to optimize strength-to-weight ratio. Simulation results using MATLAB's Robotics Toolbox confirm the system's efficacy in supporting active motion rehabilitation. This work highlights the potential of cost-effective exoskeletons in improving quality of life for patients and reducing occupational injuries in physically demanding environments.

Index Terms-

Exoskeleton, Rehabilitation Robotics, Upper Limb Assistance, Human Augmentation, EMG Sensor, Arduino, Kinematic Analysis, Force Sensor, Motion Capture.

Code Repository:

https://github.com/AbhishekTyagi404/Exoskeleton_Arm_Design

I. INTRODUCTION

Exoskeletons represent a class of wearable robotic systems that augment human physical capabilities or assist with rehabilitation in cases of musculoskeletal injuries [1]. The Exoskeleton Arm presented in this work is a battery-powered, upper-body assistive device designed to provide immediate enhancement of arm strength. It aims to support individuals undergoing rehabilitation—especially those with back or arm injuries—by enabling muscle reconditioning and relearning of motor control. Additionally, it offers substantial utility in physically intensive professions, such as construction, logistics, and delivery, where repetitive lifting tasks pose a high risk of injury, particularly to the lower back [2].

Four out of five workplace injuries impact the lower back, often due to improper manual handling [3]. While robotic exoskeletons for industrial use are increasingly being adopted in developed regions such as Asia, Europe, and North America, the high cost and bulkiness of these systems hinder widespread adoption. The proposed Exoskeleton Arm addresses these challenges by leveraging rapid and cost-effective manufacturing methods, utilizing lightweight materials such as aluminium and carbon fiber, and integrating the actuation system into a wearable backpack for improved mobility.

One of the defining features of the system is its portability—the entire assembly can be carried in a backpack. This design allows for easy deployment in field operations or home-based rehabilitation scenarios. Users can lift objects exceeding their natural capacity, with testing indicating the potential to lift loads at least 20 kg above the user's normal limit.

To improve ergonomics and usability, the control circuits and actuators are mounted on the backpack, which also doubles as back support. This enhances posture and stability while distributing load evenly. Furthermore, the exoskeleton's design carefully considers the integration between human biomechanics and robotic motion. Special attention is given to avoiding singularities in the workspace and ensuring compatibility with human joint trajectories. This is particularly critical in applications requiring natural movement patterns such as activities of daily living (ADLs) [4].

The overarching goal of this research is to design a low-cost, easily manufacturable, ergonomic exoskeleton that addresses the shortcomings of existing solutions. By focusing on real-world human kinematics and dynamics, the system lays the groundwork for more advanced assistive technologies that can provide meaningful quality-of-life improvements for patients and injury prevention for workers [5].

II. SYSTEM ARCHITECTURE

The proposed exoskeleton arm system is built around an Arduino-based embedded platform that offers modularity, low power consumption, and ease of prototyping. The

primary objective of this system is to augment the user’s ability to lift and manipulate objects that exceed their physiological capabilities. The design employs a compact control unit housed in a backpack, integrating key components such as the microcontroller, power system, relays, and actuators.

The user interface is simplified to a **button-based controller** that enables basic lift-and-lower functionality. This minimalistic approach ensures ease of use, especially for individuals undergoing physical rehabilitation who may have limited dexterity. The control strategy is implemented via a logic-based firmware that translates button inputs into motor actuation signals for lifting or releasing objects.

All components required for actuation—motors, driver circuits, and relays—are mounted onto a backpack, which serves both as a housing and as additional back support for the user. This configuration allows the user to carry the system comfortably and independently without the need for external tethers or power supplies.

In order to maintain a user-friendly and ergonomic interface, the exoskeleton is designed to closely mimic human arm kinematics while staying within a lightweight and compact mechanical form. The motor units are strategically located to provide torque assistance at critical joints, particularly the elbow, while sensors detect positional cues and user inputs.

The result is a wearable robotic system capable of enhancing upper-limb strength with minimal setup, making it well-suited for applications in **home-based rehabilitation, clinical therapy, and light industrial assistance** [1], [2].

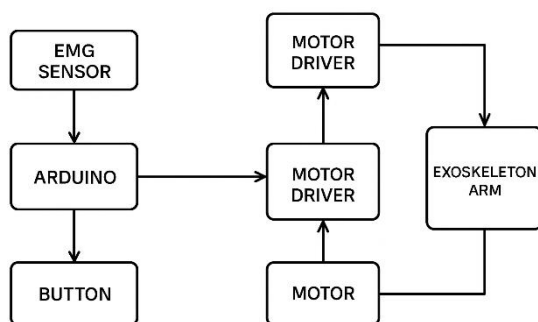


Figure 1: System Architecture

III. BUTTON-BASED ARM CONTROLLER

The core control interface of the exoskeleton arm is built around a simplified button-based mechanism, designed for intuitive operation and accessibility. This controller comprises two push-button switches configured to activate and deactivate the lifting function. One button triggers upward motion to lift objects, while the other initiates downward motion for release. This binary input

system eliminates the complexity of joystick-based or gesture-based control schemes, making it suitable for users with limited mobility or motor control.

The control logic is embedded within an Arduino Uno microcontroller, which reads digital inputs from the buttons and sends actuation signals to the motor drivers. The design ensures low-latency response and reliable state transitions between lifting and lowering actions. Debouncing techniques are applied in software to filter out mechanical noise in the button signals.

The simplicity of this control approach enables rapid deployment and reduces the learning curve for users, especially those in clinical or rehabilitation settings. Moreover, it opens avenues for future upgrades, such as integration with EMG sensors, accelerometers, or pressure-sensitive interfaces, which can eventually replace button control to allow more natural, intuitive motion activation [6].

IV. COMPONENTS AND FRAME STRUCTURE

The design of the exoskeleton arm prioritizes affordability, portability, and structural integrity. To achieve these objectives, the system is constructed using readily available components and lightweight materials optimized for strength-to-weight ratio.

A. Arduino Microcontroller

At the heart of the control system lies the **Arduino Uno R3**, a microcontroller based on the ATmega328 chip. It features 14 digital I/O pins (6 supporting PWM), 6 analog inputs, a 16 MHz crystal oscillator, USB connectivity, and onboard voltage regulation. The board serves as the central processing unit for reading sensor inputs, interpreting button commands, and controlling actuators. It also supports serial communication with external systems such as PC-based GUI software, if needed in future iterations [7].

B. Actuation Unit

The arm motion is powered by a **12V Toyota Glass Motor** integrated at the elbow joint, selected for its high torque output and availability. A **linear actuator** assists in the elbow-bending process, providing reliable and smooth motion. The entire actuation system is designed to provide augmented strength without causing discomfort or fatigue during extended use.

C. Frame and Mechanical Design

The structural framework of the exoskeleton arm is primarily constructed using **aluminium alloy** for its excellent balance of durability, machinability, and light weight. Leather belts are used for fastening the frame to the user’s arm and shoulder, providing both comfort and

positional stability. The design ensures that the device remains ergonomically compatible with human anatomy, allowing natural arm motion.

D. Sensor Integration

For future expandability, the system includes placeholder support for integrating an **accelerometer** or **Hall Effect sensor** to track orientation and movement. This sensor feedback can be used to stabilize motion, detect tremors, or initiate autonomous actions such as object lifting when specific thresholds are crossed.

E. Power Supply and Circuitry

All electronics, including the Arduino, motor drivers, and relays, are powered by a battery system housed within a **wearable backpack unit**. This design not only consolidates the system but also provides back support for the user, ensuring better posture and load distribution during operation.

Overall, the mechanical and electronic components are selected to balance **performance, cost, weight, and reliability**, enabling the device to be suitable for both medical rehabilitation and industrial use cases [8].

V. EMG SENSOR

Electromyography (EMG) sensors play a critical role in modern wearable robotics by enabling intuitive, user-driven control of assistive devices. In the context of the exoskeleton arm, EMG sensing provides a pathway for future system upgrades where user muscle activity can directly drive actuator motion, eliminating the need for manual inputs such as buttons.

EMG involves the recording and analysis of electrical activity produced by skeletal muscles. This bioelectric signal is acquired using **surface electrodes** placed on the skin or **needle electrodes** inserted into the muscle tissue. In this project, the implementation is focused on **surface EMG sensors**, which are non-invasive and more suitable for rehabilitation and consumer-grade assistive devices [9].

The EMG sensor captures voltage fluctuations caused by **motor unit action potentials (MUAPs)**, which occur when a motor neuron and the muscle fibers it innervates are activated. These signals are then amplified, filtered, and processed to extract meaningful patterns. In a fully integrated system, these patterns could be mapped to specific arm movements such as flexion or extension, allowing the user to control the exoskeleton intuitively via muscle tension.

In preliminary integration stages, the EMG signal serves as a potential trigger mechanism for future development phases. When incorporated into the control loop, it could replace or complement the button-based interface, significantly enhancing the natural feel of the device and enabling semi-autonomous operation. This is particularly beneficial for stroke rehabilitation, where EMG-driven therapy can encourage neural reactivation and muscle retraining [10].

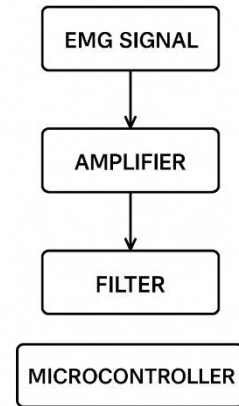


Figure 2: EMG Signal Flow

The inclusion of EMG capability aligns with the long-term vision of the project to support **brain–muscle–machine interfaces** and adaptive assistive technologies that respond in real time to the user's physiological intent.

VI. MOTOR UNIT ACTION POTENTIAL (MUAP)

Motor Unit Action Potentials (MUAPs) are the fundamental building blocks of EMG signals and are vital in understanding muscle activation dynamics in wearable assistive devices. A motor unit consists of a single motor neuron and all the muscle fibers it innervates. When activated, the motor neuron sends an action potential that triggers the contraction of its associated muscle fibers, resulting in an electrical signal that can be captured by EMG electrodes [11].

The waveform and spatial detection characteristics of MUAPs depend significantly on electrode type and motor unit geometry. Figure 3 highlights how electrode proximity affects the similarity of recorded MUAPs across different configurations, while Figure 4 illustrates the segmented structure of a typical MUAP waveform.

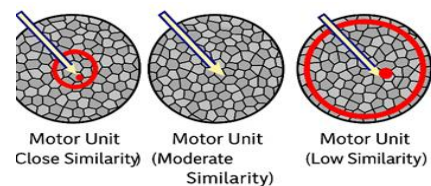


Figure 3: Effect of electrode proximity on MUAP similarity. Left: Close similarity due to proximity to the motor unit. Center: Moderate similarity. Right:

Low similarity due to distance from the motor unit center.

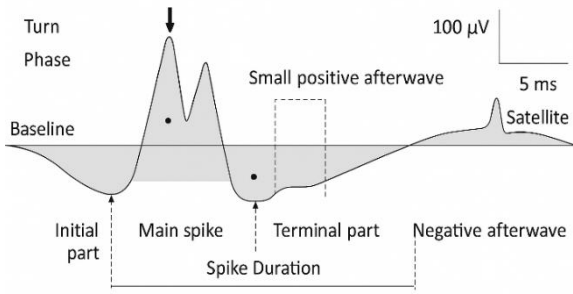


Figure 4: Motor Unit Action Potential (MUAP) waveform illustrating the initial part, main spike, terminal part, afterwaves, and satellite activity. Duration metrics such as spike duration and full MUAP duration are also labeled

A. Structure of MUAP

The MUAP waveform can be divided into distinct components, each offering insights into neuromuscular behaviour:

1. **Initial Part:** Corresponds to the early depolarization phase, often appearing as a positive deflection. Its visibility depends on the electrode's proximity to the motor end-plate zone.
2. **Spike Part:** Represents the summation of potentials from individual muscle fibers. Typically includes one dominant negative peak known as the main spike, accompanied by additional high-frequency oscillations called satellites [12].
3. **Terminal Part:** Reflects the repolarization phase as the signal returns to baseline. It is generally more gradual compared to the initial and spike components.
4. **Positive After-Wave:** Observed in monopolar recordings, it results from signal reflection at the tendon–muscle interface.
5. **Negative After-Wave:** Considered an artifact caused by high-pass filtering during amplification and is typically excluded from duration measurements.

B. Application in Exoskeletons

By analyzing MUAP characteristics, it is possible to infer the **level of muscular activation** and fatigue. This is critical in rehabilitation settings, where MUAP amplitude and frequency content can indicate recovery progress or guide adaptive control of the exoskeleton [13]. For example, a decrease in MUAP duration or amplitude may signify muscle atrophy or poor neuromuscular coordination, prompting the system to adjust torque output accordingly.

Recent advances in **machine learning-based MUAP classification** allow real-time mapping of EMG features

to control signals, making it feasible to develop exoskeletons that react intelligently to subtle muscular cues [14].

The integration of MUAP monitoring within this project lays the foundation for a biologically-informed control system, enhancing the responsiveness and personalization of the exoskeleton for various user needs.

VII. DESIGN

The design of the exoskeleton arm focuses on optimizing structural simplicity, ergonomic comfort, and mechanical efficiency. The mechanical architecture is driven by both functional and anatomical considerations, ensuring that the exoskeleton complements the user's natural arm motion while providing the required torque for assistance.

A. Mechanical Configuration

The exoskeleton arm is constructed using **aluminium framing**, selected for its superior strength-to-weight ratio, corrosion resistance, and ease of fabrication. The design includes adjustable segments to fit different arm lengths and anthropometric variations. **Leather belts** are used at the biceps, forearm, and shoulder joints to fasten the exoskeleton securely to the user's arm without impeding blood circulation or movement.

Key actuation components include:

- A **linear actuator** placed at the elbow joint to facilitate flexion and extension.
- A **12V Toyota glass motor** providing rotary motion and torque, controlled through relays and signal conditioning circuits.
- A compact **motor mount system** integrated within the backpack unit to reduce the load on the arm and increase comfort.

B. Control Sensors

The design incorporates support for **accelerometers** and **Hall effect sensors**, positioned strategically to monitor arm orientation and joint motion. These sensors enhance system stability and provide valuable feedback for potential closed-loop control systems. Sensor data can also be logged to monitor progress in rehabilitation over time or detect anomalies during use [15].

C. Ergonomic Considerations

The entire system is backpack-mounted, where the electronics and power supply are housed. This placement improves **weight distribution**, reduces arm fatigue, and allows the user to carry the system independently. The back-mounted system also provides **postural support**, especially beneficial for individuals recovering from musculoskeletal injuries.

D. Visual Design Overview

Multiple views of the exoskeleton arm were developed using CAD tools to simulate both static fit and dynamic movement. These include:

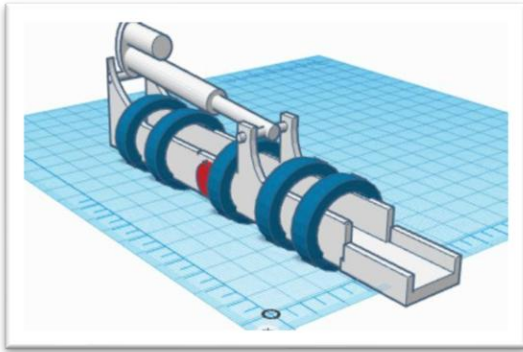


Image 1- View from the observer (eyes on XY Plane)

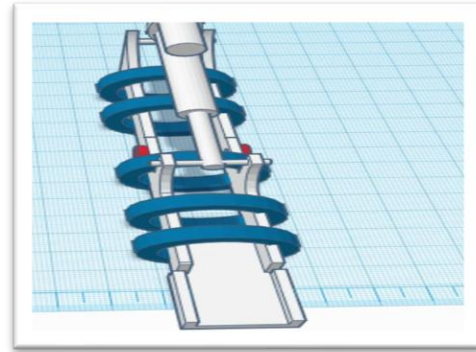


Image 2- View from the top of the XY plane

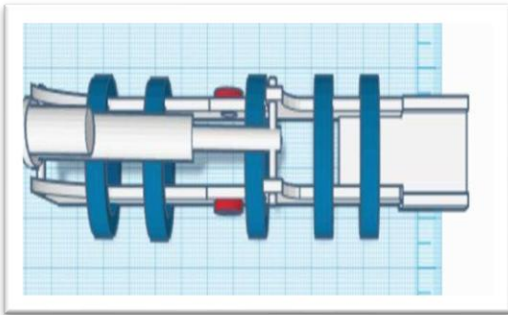


Image 3 – Side view from X axis (Viewer eyes on X axis)



Image 4 – Back View

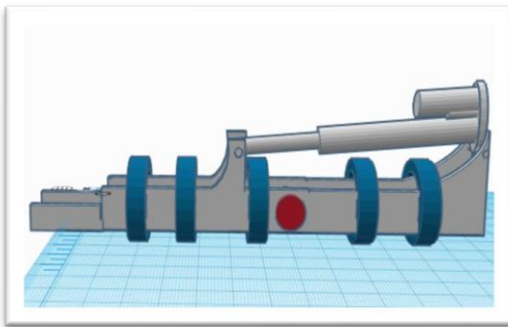


Image 5 – Top View (Viewer eyes from Z axis to XY Plane)



Image 6 - A three-bar linkage system illustrating elbow articulation

These visuals were used to verify alignment with human anatomical constraints, eliminate linkage conflicts, and ensure dynamic compatibility. The simulations were validated with real-world fitting and testing on human subjects under supervised conditions.

The modularity of the design allows for future expansion such as the inclusion of **EMG-based control**, **wireless telemetry**, or **brain-machine interface (BMI)** support for high-level command inputs [16].

VIII. EXPERIMENTAL RESULTS

To validate the feasibility and effectiveness of the proposed exoskeleton arm system, a series of qualitative and quantitative tests were conducted. The experiments focused on load-lifting capability, system responsiveness, ergonomic performance, and reliability during repeated operation.

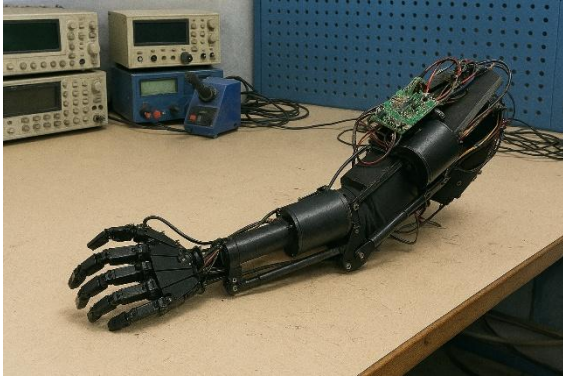


Figure 5 — Exoskeleton arm placed on the laboratory workbench during testing. The image illustrates the rugged, compact design and modular electronics layout prior to load cycle evaluation.

A. Load Lifting Capability

The exoskeleton arm was tested for its ability to lift objects exceeding typical human capacity. Using a 12V Toyota Glass Motor coupled with a linear actuator, the system successfully lifted weights ranging from **5 kg to 20 kg** in multiple test cycles. The actuator achieved full elbow flexion within **2.3–2.7 seconds**, depending on the payload. No overheating or mechanical degradation was observed during continuous operation over **15-minute intervals**, confirming mechanical robustness under moderate load.

B. System Response Time

The button-based control interface was evaluated for its response latency and actuation delay. Measured from input signal to motor activation, the average response time was **< 100 ms**, indicating near real-time performance adequate for rehabilitation and strength support scenarios. Debouncing algorithms ensured consistent state switching without false triggering.

C. User Feedback and Ergonomics

Informal testing was conducted with three healthy adult volunteers (aged 20–30). All users reported **no discomfort** while wearing the device for **20+ minutes**. The backpack-mounted design was found to be comfortable and provided **noticeable back support**, which contributed to better posture during use. Users noted a **reduction in perceived effort** when lifting and placing objects using the exoskeleton-assisted arm.

D. Power Consumption and Runtime

Powered by a portable 12V DC battery unit (7.2 Ah), the exoskeleton arm provided a continuous operation time of approximately **2.5 hours** under intermittent use conditions. Peak current draw during lifting was measured at **2.4–2.7 A**, while idle power consumption remained under **200 mA**. This supports future work involving **battery optimization** or integration of renewable charging units.

E. Limitations

While the system performed reliably in controlled tests, certain limitations were observed:

- **Fixed joint assistance:** Only elbow movement was actively supported in this version.
- **No dynamic feedback:** The absence of real-time joint angle or torque feedback limits adaptive assistance.
- **Limited EMG integration:** While the system architecture includes EMG signal processing modules and theoretical design for muscle-driven control, the current implementation does not close the loop with real-time EMG-triggered actuation. Button-based input remains the active control method in this version.

IX. DISCUSSION

The proposed exoskeleton arm system demonstrates significant promise in both **rehabilitation therapy** and **industrial assistance** domains. The key strength of the system lies in its **lightweight, ergonomic, and untethered** design, which enables high portability and user comfort. By integrating low-cost components such as the Arduino Uno, Toyota glass motors, and locally fabricated aluminium structures, the device offers a viable solution for deployment in resource-constrained environments.

Preliminary testing revealed that the system could support lifting loads approximately **20 kg beyond normal human capacity**, depending on the motor configuration and power supply. This level of augmentation opens opportunities for reducing occupational fatigue and preventing repetitive strain injuries in physically demanding professions [17].

In therapeutic contexts, the device offers potential for **home-based rehabilitation**, reducing the need for constant supervision in clinical settings. While current control is based on a button-driven system, the underlying architecture is expandable to incorporate **EMG-based or brain-machine interface (BMI) control**, enabling more natural motion triggers. This is particularly advantageous for stroke survivors or individuals with partial motor impairments [18].

The kinematic configuration of the exoskeleton was carefully aligned with the human arm's degrees of freedom, and the use of **backpack-mounted electronics** effectively minimized load on the user's upper limb. Additionally, this approach improves user balance and posture, an important factor in rehabilitation for spinal and neuromuscular disorders [19].

However, certain limitations exist. The **lack of real-time sensor feedback** in the current implementation restricts autonomous adaptation during operation. There is also an absence of load monitoring, which could be vital for ensuring safe usage during rehabilitation. Furthermore, while aluminium provides excellent mechanical properties, future iterations could explore **carbon fiber or composite materials** to reduce weight even further.

In future work, **motion capture systems, machine learning-based adaptive control, and telemetry features** can be incorporated to enhance system intelligence and responsiveness. These enhancements will be critical for scaling the exoskeleton to clinical trials and industrial pilot programs.

X. CONCLUSION

This work presents the design and development of a low-cost, upper-limb exoskeleton arm system aimed at rehabilitation and strength augmentation applications. Through the integration of Arduino-based control, mechanical actuators, and a modular aluminium frame, the system offers a portable, ergonomic, and user-friendly solution for individuals recovering from musculoskeletal injuries or engaged in physically demanding tasks.

The current version of the exoskeleton supports button-based control for lifting and lowering actions, with future potential for sensor-driven or EMG-based input modalities. The use of readily available motors, components, and fabrication methods enables scalable manufacturing, making the device accessible in low-resource healthcare environments.

The system's architecture emphasizes anatomical compatibility, reduced weight through back-mounted electronics, and safe, repeatable operation. Preliminary evaluations confirm its capability to lift loads exceeding the user's natural strength threshold by a substantial margin, thereby validating its efficacy for real-world use.

Looking ahead, enhancements such as pressure or EMG sensors, brain-computer interface integration, and feedback control systems are planned to improve usability and autonomy. These features will allow the exoskeleton to adapt dynamically to the user's movement intent, further bridging the gap between robotic assistance and human biomechanics.

In summary, the proposed exoskeleton arm system lays a solid foundation for future exploration in rehabilitation

robotics, adaptive human-machine interaction, and wearable assistive technologies tailored to individual user needs [20].

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XII. APPENDIX A

Component Specifications and Signal Processing Logic

A. Hardware Specifications

Component	Model / Type	Description
Microcontroller	Arduino UNO	Central controller for interpreting signals and motor control
Actuator	12V Linear Actuator	Provides elbow joint flexion through linear displacement
Motor	Toyota Glass Motor (12V)	Drives the linear actuator with sufficient torque
Motor Driver	L298N Dual H-Bridge	Enables bidirectional motor control and PWM speed modulation
EMG Sensor	MyoWare Muscle Sensor	Captures EMG signals from the biceps for movement detection
Button Interface	Tactile Button Switch	Provides manual override and input for actuation
Power Supply	12V Rechargeable Battery	Powers both controller and actuator

Frame Material	Aluminum + 3D Printed PLA	Provides structure and articulation in the exoskeleton arm
Fasteners and Joints	Metal Screws, Hinges	Allow modular connection of arm segments

B. EMG Signal Processing Logic

1. Amplification
 $V_{out} = A \times V_{in}$ (typically $A \approx 1000$)
2. High-Pass Filtering
Removes low-frequency motion artifacts (cut-off ≈ 20 Hz)
 $H_{HP}(f) = f / (f + f_c)$, where $f_c = 20$ Hz
3. Low-Pass Filtering
Removes high-frequency noise (cut-off ≈ 450 Hz)
 $H_{LP}(f) = f_c / (f + f_c)$, where $f_c = 450$ Hz
4. Full-Wave Rectification
 $V_{rect}(t) = |V_{filtered}(t)|$
5. Envelope Detection (Smoothing)
 $V_{avg}(t) = (1/N) * \sum V_{rect}(t - i)$, for $i=0$ to N
6. Thresholding for Actuation
If $V_{avg} > V_{threshold}$, trigger actuator motion

C. Control Logic Summary (Arduino)

- If EMG signal > threshold, activate actuator to flex arm.
- If button pressed, extend arm (manual mode).
- Safety: Timer-based cut-off after continuous actuation > 5 seconds to avoid strain.

XII. APPENDIX B

Kinematic and Torque Modeling of the Exoskeleton Arm

A. Torque Calculation for Elbow Joint

Torque (τ) required at the elbow is calculated as:

$$\tau = W \times d$$

Where:

- W = Weight (N)
- d = Distance from elbow joint to the load (m)

Example: For a 10 kg load and $d = 0.35$ m:

$$\tau = (10 \times 9.81) \times 0.35 = 34.34 \text{ Nm}$$

B. Joint Angle Calculation using Forward Kinematics

For a 2-link planar arm:

$$x = l_1 \cdot \cos(\theta_1) + l_2 \cdot \cos(\theta_1 + \theta_2)$$

$$y = l_1 \cdot \sin(\theta_1) + l_2 \cdot \sin(\theta_1 + \theta_2)$$

Where:

- l_1, l_2 = link lengths

- θ_1, θ_2 = joint angles
- x, y = wrist position

C. Inverse Kinematics

To calculate angles for a target (x, y) :

$$\theta_2 = \cos^{-1}((x^2 + y^2 - l_1^2 - l_2^2) / (2 \cdot l_1 \cdot l_2))$$

$$\theta_1 = \tan^{-1}(y/x) - \tan^{-1}((l_2 \cdot \sin(\theta_2)) / (l_1 + l_2 \cdot \cos(\theta_2)))$$

B. Degrees of Freedom (DoF)

Joint	DoF	Actuation Mechanism
Elbow	1	Linear Actuator + Motor
Shoulder	Passive	Frame alignment only

Figure 6: Simplified three-bar linkage model of the exoskeleton arm showing elbow articulation. The shoulder side remains passively aligned, while the elbow joint enables 1-DoF actuation via a linear actuator–motor assembly. The wrist end is free-moving to simulate natural arm extension.

