

Capstone Project Report

Upper-limb Exoskeleton for Power Augmentation

Ardana Utepbergen, Anel Saudanbekova, Miras Muratkanov

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Supervisor: Aibek Niyetkaliyev

Instructor: Togzhan Syrymova



Department of Robotics and Mechatronics
School of Engineering and Digital Sciences
Nazarbayev University

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Abstract

This project addresses the design and development of a shoulder–elbow exoskeleton aimed at enhancing worker endurance and reducing musculoskeletal strain during repetitive industrial tasks. The work focuses on balancing effective torque assistance with lightweight design, safety constraints, and wearer comfort. We began by establishing biomechanical torque targets, then synthesized CAD models and actuation schemes. Early validation via simulation indicates that assistive torques in the range of 30–45 Nm (shoulder) and 15–20 Nm (elbow) can be delivered without compromising joint kinematics. We have produced mechanical design, iterated on shoulder and elbow mechanisms, selected a high-torque motor (Cubemars AK80-64 KV80), initiated a benchtop actuator test rig, and drafted safety and ethics protocols. Subsequent stages will include hardware fabrication, sensor integration, closed-loop control implementation, pilot trials, task performance, and user feedback. The outcome is expected to demonstrate that human-in-the-loop torque assistance can improve ergonomics and productivity in real industrial environments.

Chapter 1: **Acknowledgements**

We would like to express our deepest gratitude to our Capstone supervisor, Professor Aibek Niyetkaliyev, for his continuous guidance, insightful feedback, and unwavering support, which were instrumental in shaping the direction of our work.

Our sincere appreciation goes to Sharafatdin Yessirkepov for his invaluable assistance in searching for and providing the necessary hardware components and critical parts for our project.

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Finally, we would like to thank all the students who participated in our testing sessions and volunteered to try on the exoskeleton. Their contribution and feedback were essential for the evaluation and refinement of our system.

Chapter 2: Introduction

2.1 Research Problem

Industrial workers routinely perform lifting, holding, or overhead tasks that impose repeated strain on the shoulder and elbow joints. Over time, this can lead to fatigue, reduced performance, and even long-term musculoskeletal disorders. Conventional ergonomic aids (like mechanical arms or assist devices) are often bulky or task-specific, lacking flexibility for dynamic, unstructured work.

While rehabilitation exoskeletons are well studied, power-augmentation exoskeletons for industrial use must operate in unconstrained motion, with safety, comfort, and transparency. The central problem this work tackles is:

Can we design an upper-limb exoskeleton that delivers meaningful assistive torque while preserving natural motion, minimizing weight, and ensuring safe human-robot interaction?

2.2 Research Motivation

Three motivating drivers guide this project:

1. **Ergonomic Health**

Reducing muscle load and fatigue can lower the incidence of work-related injuries and improve worker well-being.

2. **Productivity Enhancement**

A wearable assistive device that reduces the physical burden allows sustained performance in repetitive or physically demanding tasks.

3. **Scalable Industrial Integration**

Unlike stationary or task-specific devices, a portable exoskeleton with adaptive control and modular design could be more broadly adopted across industries.

2.3 Applications of the Research

The envisioned upper-limb exoskeleton has the potential to impact several domains where repetitive or overhead work is both physically demanding and injury-prone:

Logistics and Warehousing. Workers in warehouses routinely lift, carry, and place boxes ranging from 5–20 kg, often between waist and shoulder height. These tasks, when repeated over full shifts, contribute to shoulder fatigue and lower-back strain. An exoskeleton capable of providing shoulder and elbow torque assistance could reduce cumulative loading, allowing workers to sustain higher throughput without compromising safety.

Assembly Lines in Manufacturing. Automotive and electronics assembly lines frequently require workers to hold components overhead or at chest height for extended durations while securing or fastening them. Such static exertions cause localized muscle fatigue and reduce precision. Torque support at the shoulder can help maintain arm elevation with lower muscular demand, improving both endurance and assembly quality.

Maintenance and Inspection. Inspection and servicing tasks in power plants, aviation, and building facilities often involve working above head level—tightening bolts, connecting wiring, or manipulating tools in confined spaces. These contexts require not only assistance but also freedom of movement, since workers operate around pipes, conduits, or uneven surfaces. A wearable exoskeleton with compliant transmissions can provide sustained torque while preserving maneuverability.

Construction Environments. Construction workers regularly perform wall and ceiling installations, drilling, and repetitive fastening. These tasks involve high loads in awkward postures, increasing the risk of musculoskeletal disorders. A deployable exoskeleton could shift part of the mechanical burden away from the upper limbs, supporting endurance in environments where no fixed assist devices are available.

Cross-Domain Benefits. Across all domains, the device must demonstrate robustness under varied orientations, quick donning and doffing to adapt to short tasks, and adjustability to different body sizes. Successful deployment would not only reduce fatigue and injury risk but also improve consistency, precision, and overall productivity in industries where human labor remains central.

Chapter 3: Literature Review

Over the past decade, research on upper-limb exoskeletons has expanded considerably, driven by the demand for solutions that reduce fatigue and prevent musculoskeletal disorders in industrial environments. Hochreiter et al. [1] conducted a systematic review of intention prediction strategies, identifying electromyography (EMG), inertial measurement units (IMUs), and hybrid fusion approaches as promising methods for achieving user-adaptive control. Their findings emphasize that transparent human-machine interaction requires robust algorithms capable of responding to variable user states. Building on this, Falkowski et al. [2] examined actuation and drive mechanisms, ranging from Bowden cables to series-elastic transmissions, and highlighted the trade-offs between torque density, controllability, and user comfort.

Other works have explored the design and evaluation of passive, active, and hybrid systems. Pascucci et al. [3] demonstrated that semi-active devices can reduce muscular strain in material handling tasks without requiring large power sources. Shi et al. [4] proposed a lightweight cable-driven exosuit, prioritizing portability and comfort, while Shi et al. [5] introduced a four-degree-of-freedom exoskeleton with gravity compensation, showing improved ergonomic support. Comparative analyses such as those by Nasr et al. [6] assessed passive, active, and hybrid designs under lifting tasks, concluding that hybrid systems offer an attractive compromise between usability and energy efficiency. Industrial evaluations by Blanco-Ivorra et al. [7] further confirmed that active exoskeletons can reduce both metabolic cost and muscle activity during repetitive operations, validating their potential for logistics and assembly settings.

In terms of control strategies, the field has shifted from rigid position-based approaches toward adaptive human-in-the-loop methods. Admittance and impedance control frameworks have been applied to improve system stability under variable task demands [8, 9]. Studies on hybrid control have integrated IMU and EMG data streams to capture user intent more reliably, reducing latency and misclassification [1, 10]. These approaches enhance transparency, a key requirement for workers to trust and adopt wearable assistive devices in everyday practice. While many studies emphasize the integration of IMU and EMG signals for intent detection, this project takes an alternative approach by monitoring actuator current through multimeters. This choice is motivated by the need for stable, repeatable signals that are less affected by sensor drift or electrode variability, while still supporting robust intent-aware control.

Despite this progress, significant gaps remain in the literature. Evaluation protocols vary widely, preventing direct comparison across studies. Most exoskeletons have been tested on small populations, limiting generalizability. Technical trade-offs between torque assistance and overall device weight continue to constrain real-world deployment. Furthermore, intention detection remains susceptible to signal drift, electrode placement, and task variability. Addressing these limitations, the present project focuses on integrating proximal actuation with compliant transmissions, lightweight materials, and robust intent-aware control to deliver torque assistance that is both effective and practical for industrial users.

Chapter 4: System Design and Integration

4.1 Learning Portfolio

1. Key Learning Experiences

Technical Challenges: The primary technical hurdle involved designing a wearable system that balances structural stiffness with ergonomic mobility. This required transitioning from a restrictive gimbal shoulder support in the first prototype (Figure 6.1) to a more sophisticated curved scissor mechanism with rails in the second version (Figure 6.2) to preserve three degrees of freedom. Another significant challenge was actuation selection; a custom-designed 90:1 two-stage cycloidal gearbox for the GARTT ML3510 motor failed due to excessive friction from 3D-printed surface roughness. Additionally, implementing real-time control required mastering CAN bus communication between an Arduino Mega, an MCP2515 module, and high-torque actuators.

Initial Knowledge Gaps: At the project's start, we lacked experience integrating high-power brushless DC motors with a distributed control architecture via CAN bus. We also lacked an understanding of mechanical transparency and backdrivability, which we later discovered is a critical safety requirement to prevent users from feeling trapped by rigid transmissions. Furthermore, we initially struggled to account for FDM printing tolerances when designing precision transmission components like cycloidal pins.

Learning Methodology: We bridged these gaps by studying ROS 2 documentation and CubeMars SDKs to understand message structures and control modes. We employed systematic trial-and-error through benchtop testing with payloads of 1 to 10 kg to characterize the relationship between motor current and torque. Collaboration was essential, dividing responsibilities between biomechanical modeling in MATLAB and CAD design in Fusion 360.

Learning Progress: Initially, our process was characterized by mechanical confusion, specifically regarding why our 3D-printed gearboxes were stalling. After gaining a deeper understanding of mechanical efficiency and material properties, we shifted to selecting the CubeMars AK80-64, which provided the necessary torque density and backdrivability for a "human-in-the-loop" system.

2. Skills Gained

Technical Skills (Robotics-Specific): We gained a confident level in CAD design and prototyping by modeling moving linkages and telescopic assemblies using aluminum 6061 and carbon-fiber-reinforced polyamide. We reached a working level in hardware-software interfacing using CAN bus protocols and developed proficiency in motor control for both the ODrive-driven ML3510 and the final CubeMars AK80-64 actuators.

System Integration: Integration was achieved by connecting biomechanical simulation data with physical hardware. We used inverse dynamics to establish torque targets (30–45 Nm for the shoulder and 15–20 Nm for the elbow) and integrated these into a modular frame using telescopic aluminum tubes and nylon straps to fit different users.

Soft Skills: Our team coordination improved as we learned to handle technical failures. We adapted by splitting responsibilities and introducing better documentation, which allowed us to pivot quickly to high-torque integrated actuators without derailing the project timeline.

3. Future Learning Goals

Moving forward, our specific goals include integrating active EMG sensors for closed-loop intent detection to make the exoskeleton more responsive to user effort. We also aim to implement and tune an admittance controller to better manage dynamic transitions during lifting tasks. Finally, we plan to explore subtractive manufacturing processes for critical components to eliminate the friction and tolerance issues encountered with FDM 3D printing.

4.2 Ethics Portfolio

1. Ethical and Legal Issues

Our project centers on designing a wearable robotic exoskeleton that helps industrial workers reduce fatigue and prevent injuries during repetitive tasks. Because this device interacts directly with the human body, safety became our main ethical concern. We wanted to make sure that no movement or torque applied by the system could harm the user. To manage that, we introduced several safety layers—torque limits, current monitoring, and an emergency stop switch. These precautions give the wearer control and confidence while keeping the system within safe physical limits.

Intellectual property and fair use of research materials were also discussed. Since our work builds upon existing academic studies, we ensured every source was properly cited. We also intend to make our final findings openly available for educational and non-commercial use, promoting transparency and collaboration.

2. Informed Judgments and Trade-offs

Throughout development, we faced a series of trade-offs particularly between safety, performance, and practicality. Higher torque could improve performance but also increase risk, so we deliberately favored safer limits. Our control approach was designed to prioritize smooth, comfortable motion over aggressive force. This reflects a core engineering ethic: safety comes first.

We also debated the use of EMG versus torque-based sensing. EMG offers more detailed user information but can raise privacy and calibration issues. On the other hand, torque sensing is simpler and more reliable. We eventually used simpler method, excluding EMG.

Beyond the technical choices, we talked about the broader social effects of exoskeletons. Could they replace workers? Our conclusion was clear - they should support, not substitute, human labor. We framed our device as a tool for health and safety improvement, not automation-driven efficiency. This view guided every major design decision we made.

3. Sustainability and Social Responsibility

Sustainability shaped both our material choices and long-term design goals. We used lightweight and recyclable materials such as aluminum and composite parts, ensuring durability while minimizing environmental impact. We also emphasized modularity - components can be replaced or reused, reducing waste over time.

From a social perspective, we recognized that advanced wearable technologies could create inequality if only large companies can afford them. We tried to counter that by focusing on affordability and scalability, developing a design that small enterprises could eventually access. True responsibility, for us, means creating technology that makes work safer for everyone, not just for a few privileged sectors.

4. Examples of Ethical Practice

1. During pilot testing, participants will sign informed consent forms and may withdraw at any time. Tests will immediately stop if any discomfort or unexpected motion occurs.
2. We maintained transparency in research by properly citing all design inspirations and frameworks used in control algorithms.
3. We actively discussed possible negative scenarios such as over-assistance leading to muscle dependency or job displacement, ensuring our control design keeps users engaged and in control.
4. Every test and data-handling process follows Nazarbayev University's ethical guidelines and national regulations on occupational safety and data protection.

5. Conclusion

The experience of developing this project underscored that engineering ethics transcends a mere procedural checklist; it constitutes a fundamental professional mindset. Ethical considerations were integrated into every stage of the process, including design specifications, experimental protocols, and software development. By rigorously evaluating the human implications of our technical decisions, we ensured the final system was not only functional but also inherently responsible. Ultimately, our primary conclusion is that technological advancement must remain dedicated to the service and safety of the human user.

4.3 Mechanical Constraints

1. Weight and Dimensions: The structure must be lightweight to minimize fatigue and prevent excessive limb inertia.
2. Performance: The mechanism must provide sufficient assistive torque without becoming bulky.
3. Modularity: Links and mounts must be reconfigurable and replaceable to accommodate various users and tasks.

4.4 Ergonomic Requirements

1. Shoulder and elbow movement must remain non-restrictive.
2. The shoulder uses a complex multi-DOF mechanism, while the elbow employs a simple revolute joint aligned with the anatomical axis.
3. Belts, straps, and padding distribute loads across the torso to prevent force concentration on the spine.
4. Elastic Belt: Maximum untensioned length is 95 cm, with further extension possible when stretched.
5. Extrusions: Shoulder and forearm extrusion lengths range from 25 cm to 41.9 cm.
6. 4-Bar Linkage: Rod end bearings in the mechanism have a length range of 9.4 cm to 11.3 cm.

4.5 Torque and Motor Requirements

1. Target assistive torque: 30-45 Nm at the shoulder and 15-20 Nm at the elbow.
2. To allow for safety margins and peak demands, the motor at the shoulder should be capable of supporting loads up to approximately 50 Nm.

Chapter 5: Methodology

5.1 Overall Research Approach

The research followed an iterative, model-driven process. First, representative industrial tasks were identified and decomposed into their dominant joint motions. Next, a planar shoulder–elbow model of the human arm was constructed using anthropometric data for male and female workers. This model was used to simulate lifting tasks with different loads and speeds, and to compute the resulting joint torque, angular velocity, and power profiles via inverse dynamics. These simulation results informed the selection of actuators and transmissions, and guided the mechanical design of the exoskeleton structure in CAD. Finally, control and intent-sensing concepts were outlined, together with initial safety and ethical considerations, to prepare for future prototyping and experimental validation.

5.2 Biomechanical and Dynamic Modeling

Anthropometric Representation of the Upper Limb

To keep the analysis tractable while still biomechanically meaningful, the human upper limb was modelled as a two-link planar mechanism with two revolute joints: shoulder flexion/extension (joint 1) and elbow flexion/extension (joint 2). This captures the dominant motions involved in lifting boxes, holding tools, and performing overhead assembly.

Two representative body types were considered: a male subject (height 185 cm, mass 80 kg) and a female subject (height 165 cm, mass 50 kg). Segment lengths were defined as fractions of body height based on standard anthropometric ratios:

$$L_1 = 0.186H, \quad L_2 = 0.146H,$$

where L_1 is the upper-arm length, L_2 is the forearm–hand length, and H is body height. This yields upper-arm lengths of 0.344 m (male) and 0.307 m (female), and forearm–hand lengths of 0.270 m (male) and 0.241 m (female).

Segment masses were assigned as fixed percentages of body mass (2.8% for the upper arm, 2.2% for the forearm–hand), giving 2.24 kg and 1.76 kg for the male segments, and 1.40 kg and 1.10 kg for the female segments. Moments of inertia about the segment centres of mass were

approximated by uniform slender rods,

$$I = \frac{1}{12}mL^2,$$

resulting in almost 50% lower inertial parameters for the female limb segments. These anthropometric parameters were used directly in the dynamic model.

Planar Two-Link Arm Dynamics

The arm dynamics were modelled in the sagittal plane with generalized coordinates $q = [\theta_1, \theta_2]^T$, representing shoulder and elbow flexion angles. For each subject, an inverse-dynamics formulation was implemented in MATLAB to compute the joint torques required to track a prescribed motion:

$$\tau(q, \dot{q}, \ddot{q}) = H(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q),$$

where $\tau = [\tau_1, \tau_2]^T$ are shoulder and elbow torques, $H(q)$ is the inertia matrix, $C(q, \dot{q})\dot{q}$ accounts for Coriolis and centrifugal effects, and $G(q)$ represents gravitational loading due to segment masses and an external payload at the hand. The external load was included as a point mass at the distal end of the forearm–hand link and its contribution was propagated back to the joints.

This model allows direct computation of torque, angular velocity, and mechanical power at the shoulder and elbow for different movement speeds, payloads, and anthropometric profiles. It serves as the quantitative basis for actuator sizing and for defining realistic assistive torque targets.

5.3 Lifting Task Definition and Simulation Setup

To approximate common industrial tasks, a compound lifting motion was defined in which the worker flexes both shoulder and elbow from a relaxed position (0°) to an elevated position (90°). This represents moving a load from waist level to approximately shoulder level in front of the body.

Joint trajectories $\theta_1(t)$ and $\theta_2(t)$ were generated using a trapezoidal velocity profile. Each movement consisted of three phases: an acceleration phase, a constant-velocity phase, and a deceleration phase. This profile provides smooth transitions in velocity and acceleration and is a reasonable approximation of natural human lifting kinematics.

Three total movement durations were considered:

$$T_f = 4.0 \text{ s} \quad (\text{slow}), \quad T_f = 2.0 \text{ s} \quad (\text{medium}), \quad T_f = 1.0 \text{ s} \quad (\text{fast}).$$

For each duration, three payloads were simulated: 2 kg, 5 kg, and 10 kg located at the hand.

Together with the two anthropometric profiles (male and female), this resulted in 18 distinct conditions. For each condition, the MATLAB code computed joint angle, angular velocity, angular acceleration, torque, and power profiles at a sampling rate of 1 kHz.

5.4 Torque, Velocity, and Power Analysis

Male Subject

Figure 5.1 illustrates the torque, velocity, and power profiles for the male subject. Shoulder torques consistently exceed elbow torques (up to 80 Nm vs. 30 Nm) due to larger moment arms and segment weights. In fast lifts (1 s), inertial effects create multiple torque peaks, especially with 10 kg loads. Peak shoulder power exceeds 300 W, suggesting the exoskeleton should provide partial rather than full assistance.

Female Subject and Comparison

Figure 5.2 shows similar curve shapes but systematically lower magnitudes due to shorter limbs and smaller segment masses. Female shoulder torques are typically 30–40% lower than male values across all conditions, as gravitational and inertial loads scale with mass and length. These results confirm the model's anthropometric scaling and the need for adjustable assistance levels.

Conclusion

Simulations demonstrate that joint torque increases non-linearly with payload and dramatically with speed. The significant load differences between male and female subjects for the same task reinforce the importance of anthropometrically adaptive exoskeleton designs.

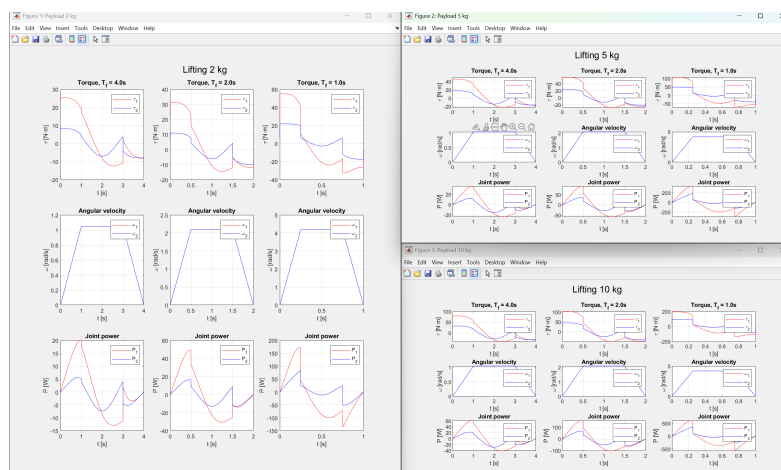


Figure 5.1: Simulated shoulder and elbow torque, angular velocity, and joint power profiles for the male subject (185 cm, 80 kg) lifting 2, 5, and 10 kg at slow (4 s), medium (2 s), and fast (1 s) speeds. Shoulder torques and power dominate due to larger moment arms and combined segment plus payload loading.

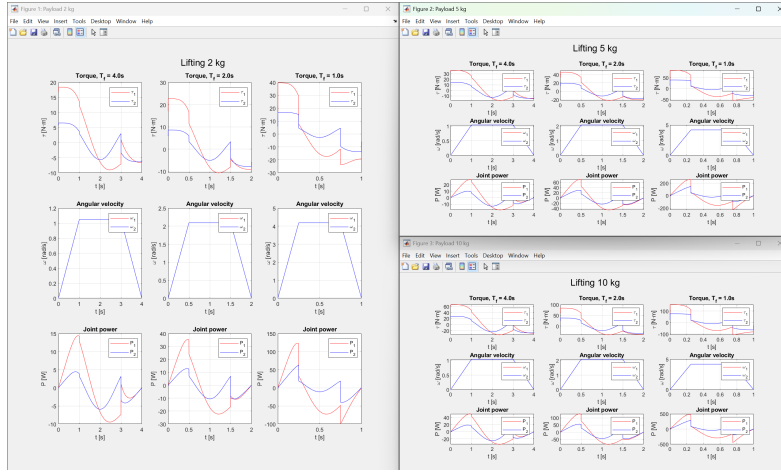


Figure 5.2: Simulated shoulder and elbow torque, angular velocity, and joint power profiles for the female subject (165 cm, 50 kg) under the same lifting conditions. Torques and power are systematically lower due to shorter limb lengths and smaller segment masses.

5.5 Implications for Mechanical Design and Control

The torque and power profiles obtained from the dynamic simulations directly inform the design of the exoskeleton. First, they justify the choice of assistive torque targets: supplying approximately 30–45 Nm of torque at the shoulder and 15–20 Nm at the elbow corresponds to offsetting a significant fraction of the human torque demand in typical 5–10 kg lifting tasks, without fully offloading the limb. This helps reduce fatigue while preserving the user’s sense of effort and control. Second, the magnitude and timing of torque peaks, particularly in fast lifts, motivate the selection of a high-torque, low-speed actuator such as the AK80-64 KV80. The actuator must be able to supply assistive torque within the target range while tolerating occasional higher loads and allowing safe interaction when unpowered or backdriven by the user. Third, the strong dependence of torque on movement speed and anthropometry suggests that the control system should be adaptive. An admittance controller with EMG and motor-current intent sensing adjusts assistance to the user’s real-time effort and motion, instead of following a fixed torque profile.

These methodological steps create a coherent link from biomechanical analysis, through dynamic simulation, to concrete design and control decisions for the upper-limb exoskeleton.

Chapter 6: Mechanical Design and CAD Progress

6.1 Prototype Version 1 (V1)

The first prototype 6.1 focused on establishing a basic shoulder joint support and overall geometry.

1. **Shoulder Joint Support:** A gimbal mechanism was chosen as the main support for the shoulder joint.
2. **Status:** Initial sketches and the first full CAD configuration were completed.
3. **Main Limitation:** The design restricted forward and backward shoulder movement and lacked sufficient body supports, which would have reduced comfort and natural mobility.

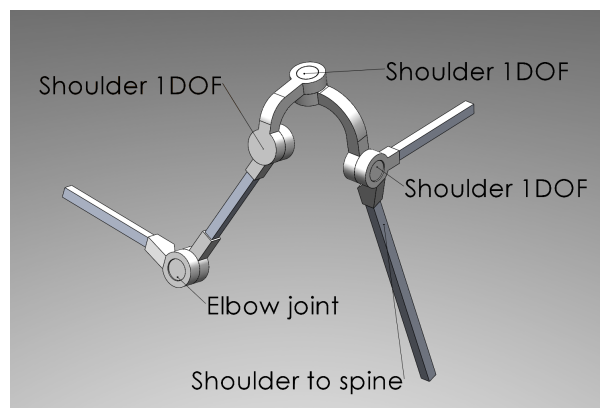


Figure 6.1: Version 1 of exoskeleton assembly

This version was useful to understand spatial constraints, but it revealed critical ergonomic limitations that motivated a redesign.

6.2 Prototype Version 2 (V2)

In the second iteration 6.2 and 6.3, the focus was on improving shoulder mobility and load support:

- **Shoulder Mechanism:** Inspired by prior work on upper-limb mechanisms, a curved scissor mechanism was implemented in the shoulder joint in a modified way. This mechanism serves as the main support for the arm's weight.
- **Degrees of Freedom:** Rails around the shoulder were added to maintain three degrees of freedom (3 DoF) and to enable forward and backward movement of the shoulder.
- **Ergonomics:** The revised design significantly improves range of motion while still providing structural stiffness for torque transmission.

V2 represents a more mature shoulder concept that can be further refined for manufacturability and integration with motors and transmissions.

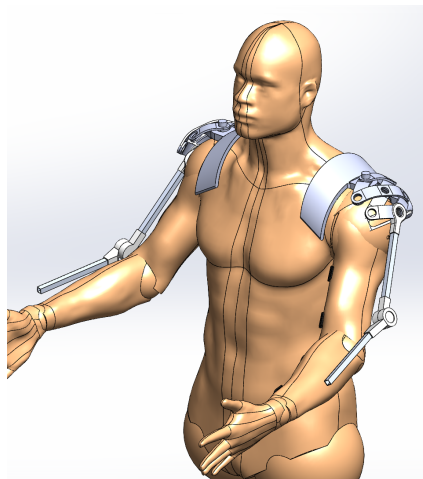


Figure 6.2: Front view

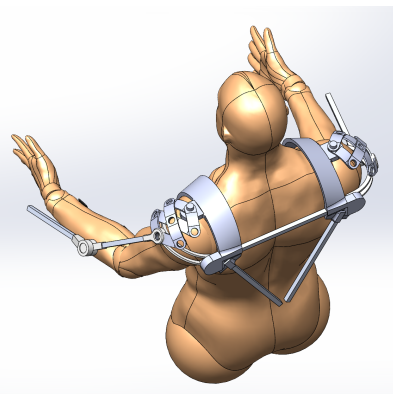


Figure 6.3: Top view

Version 2 of exoskeleton assembly

6.3 Prototype Version 3 (V3)

The V3 prototype is a bilateral upper-limb exoskeleton designed for industrial power augmentation (see Figure 6.4 and Figure 6.5). To minimize spinal loading, the architecture utilizes a waist belt connected via inclined aluminum 6061 tubes to a shoulder "vest," effectively transferring arm loads to the pelvis. The frame consists of carbon-fiber-reinforced polyamide shells and brackets, chosen for high specific stiffness and low mass.

Each shoulder module features a steel four-bar linkage with ball-joint terminations and brass bearing surfaces, as detailed in Figure 6.6. This configuration approximates physiological scapulo-humeral motion, allowing for unrestricted shoulder flexion, extension, abduction, and adduction within the functional workspace.

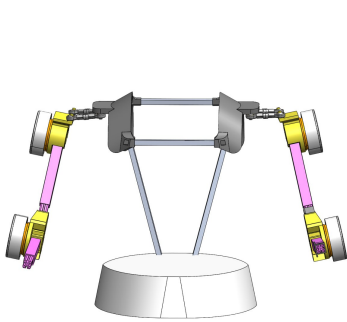


Figure 6.4: Front view

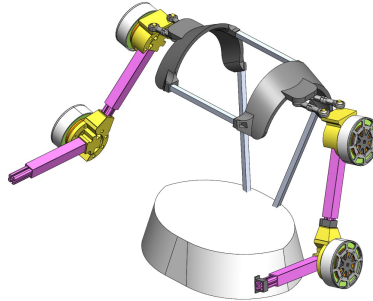


Figure 6.5: Side view

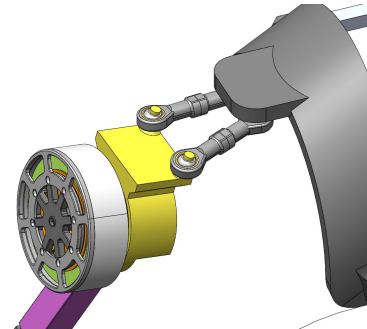


Figure 6.6: 4-bar linkage

Version 3 of exoskeleton assembly

Actuation is provided by AKE90-8 electric motors. The stators are secured via aluminum brackets, while the rotors couple directly to the moving links to provide torque to the upper arm and forearm. To accommodate user variability, the arm segments utilize telescopic aluminum assemblies with a 300 mm adjustment range, secured by bolt-and-nut pairs.

Human-machine coupling is achieved through adjustable nylon straps anchored to mounting blocks on the telescopic tubes. A redesigned shoulder pad, shown in Figure 6.7, serves as the primary load-redistribution interface, connecting the structural extrusions to the 4-bar linkage. This modular design ensures structural robustness and high kinematic compatibility with natural human motion.

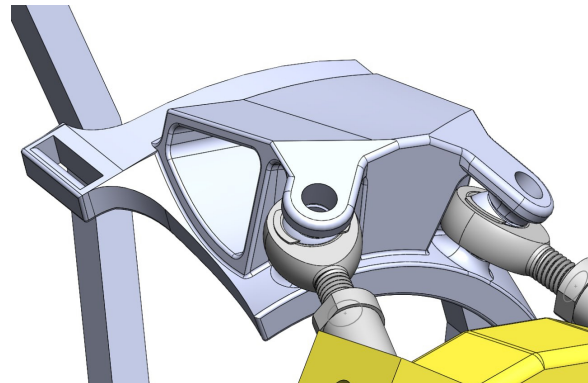
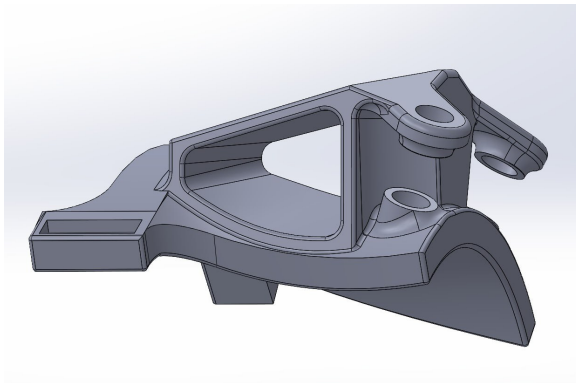


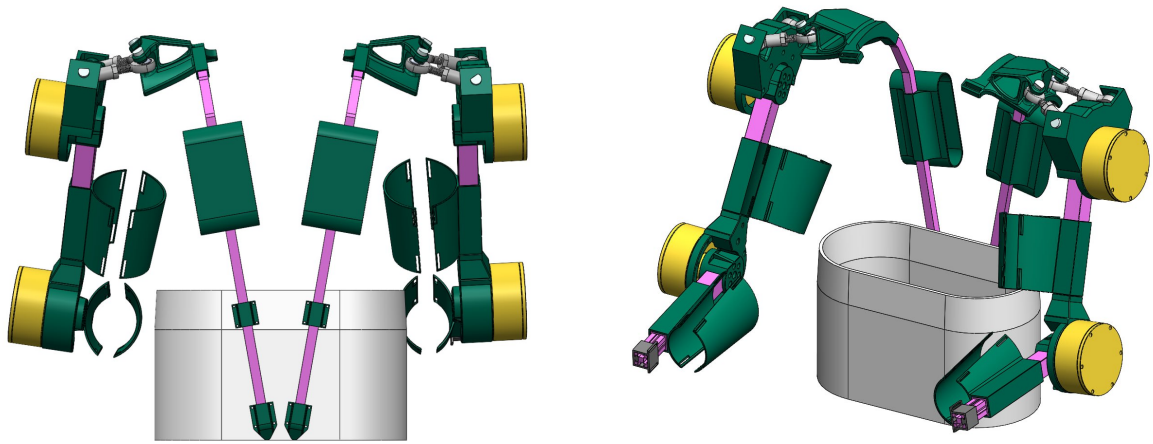
Figure 6.7: Shoulder pad design and its integration with the 4-bar linkage mechanism.

6.4 Final Prototype

The final prototype represents the culmination of the iterative design process, incorporating lessons learned from initial modular testing and mechanical refinements. By addressing previous challenges - such as structural alignment and hardware delays - the system has been successfully

integrated into a fully functional bilateral assembly.

This version features the intended CubeMars AK80-64 KV80 actuators, replacing the temporary 3D-printed dummy units used during the structural verification phase. The integration of these high-torque actuators, combined with the finalized power supply and control firmware, allows the exoskeleton to provide active assistance across the full range of motion. The final assembly demonstrates the required structural rigidity and coaxiality necessary for safe and effective human-robot interaction in industrial lifting tasks.



(a) Front view of the integrated bilateral exoskeleton.

(b) Side view showing the AK80-64 actuator placement.

Figure 6.8: Final prototype of the upper-limb exoskeleton featuring AK80-64 KV80 actuators.

Chapter 7: Real life implementation of exoskeleton

7.1 Actuation Iterations

7.1.1 Motor Selection and Evolution

The actuator selection process evolved through three iterations, focusing on the trade-off between torque density, mechanical efficiency, and backdrivability.

1. GARTT ML3510 with Custom Cycloidal Gearbox (Failed): Initially, a GARTT ML3510 motor (0.54 Nm peak) was paired with a 3D-printed two-stage cycloidal gearbox (90:1 ratio) to meet torque requirements. However, experimental testing revealed that FDM manufacturing tolerances and surface roughness introduced excessive internal friction. The motor could not overcome the gearbox's static resistance, leading to frequent stalling and low transmission efficiency.

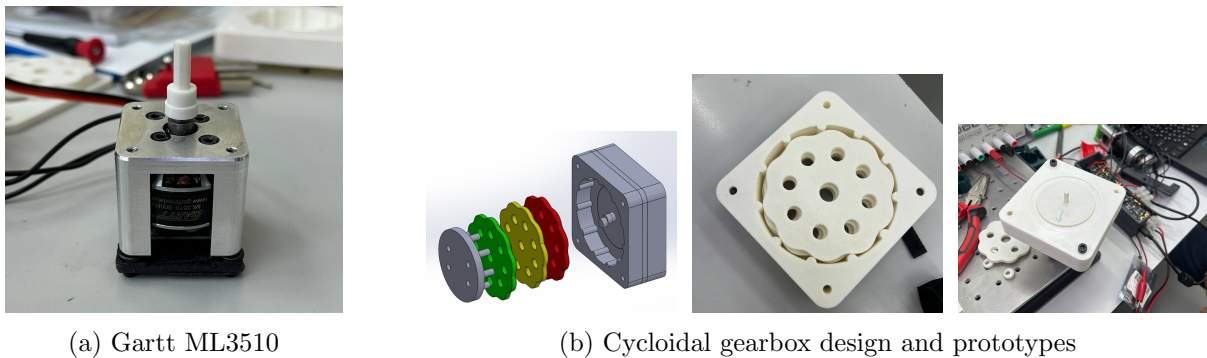


Figure 7.1: First iteration: Custom cycloidal actuation system.

2. Maxon EC90 flat with GP52C Gearhead (Failed): The second iteration used a Maxon EC90 motor with an 81:1 planetary gearhead, providing a sufficient 30 Nm output. While torque-compliant, the system lacked mechanical transparency. High reflected inertia and internal friction resulted in poor backdrivability, which increased perceived joint stiffness and compromised user safety during unpowered states.



Figure 7.2: Maxon EC90 unit



Figure 7.3: Final CubeMars AK80-64

3. Final Choice: CubeMars AK80-64 KV80 (Validated): The CubeMars AK80-64 was selected for its integrated planetary design, offering high torque density and superior back-drivability. Benchtop tests with payloads up to 10 kg confirmed its ability to deliver target assistive torques while maintaining low passive resistance. The exoskeleton's structural brackets and mounts were subsequently redesigned to accommodate the AK80-64's specific geometry, ensuring optimal force transmission and structural stiffness.

7.2 Mechanical Prototyping and Final Assembly

In the final phase, individual modules were integrated into a complete bilateral upper-limb exoskeleton, synchronizing the 4-bar shoulder linkages, telescopic segments, and joint modules. The assembly focused on ensuring structural coaxiality and optimizing the load path from the arm attachments to the waist belt.

To facilitate full system integration despite having only one functional CubeMars AK80-64 motor, three high-precision 3D-printed dummy actuators were fabricated. These replicas matched the original units' dimensions and mass distribution. To simulate rotational fluidity, the mock-ups integrated ball bearings (80 mm OD, 40 mm ID, 18 mm width). This approach enabled the verification of all mechanical interfaces and joint ranges of motion without hardware delays.

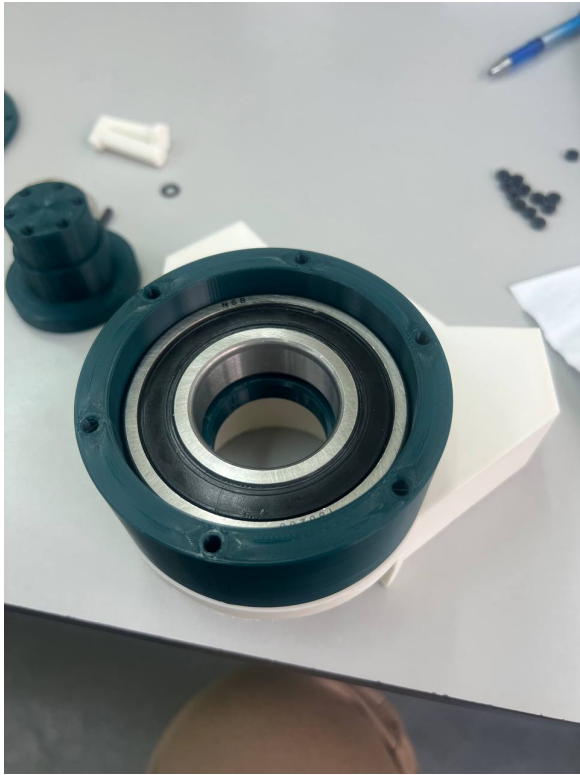


Figure 7.4: Ball Bearing



Figure 7.5: Assembled dummy motor

Figure 7.6: High-precision 3D-printed dummy motors designed to replicate the AK80-64 actuator dimensions and mounting points.

To validate the anthropometric adaptability of the design, the full assembly underwent a series of fitting trials with three different subjects of varying heights and body types. These trials were essential to verify the effectiveness of the telescopic aluminum extrusions and adjustable nylon straps. Despite the use of placeholder motors in three of the joints, the system demonstrated sufficient modularity to accommodate diverse limb lengths while maintaining the alignment of the mechanical joints with the anatomical axes. Feedback from these sessions led to final refinements in the padding of the shoulder shells and the tensioning mechanism of the waist interface, ensuring both ergonomic comfort and rigid load transmission.



(a) Subject A fitting



(b) Subject B fitting

Figure 7.7: Anthropometric validation trials: Full exoskeleton assembly fitted on three different subjects to test adjustability and ergonomic alignment.

7.3 Power Supply System and Battery Design

The power supply system was designed to meet the high current demands of the AK-series actuators while prioritizing safety and operational stability. The architecture is centered around a custom-built LiFePO₄ battery pack, selected for its inherent thermal stability and safety compared to standard Li-ion chemistries.

7.3.1 Battery Architecture and Specifications

The energy storage system consists of an 8S1P configuration utilizing high-capacity 32700 cells. The detailed specifications are summarized in the table below:

Table 7.1: Battery System Specifications

Component/Parameter	Specification
Cell Type	LiFePO4 (32700 units)
Configuration	8S1P custom assembly
Cell Capacity	7000 mAh
Nominal Voltage Range	24V – 48V
Nominal Current	7A

7.3.2 Power Management and Safety

To ensure reliable operation and protect the hardware, a dedicated Battery Management System (BMS) and multiple safety layers were integrated into the design.

Battery Management System (BMS): The pack is integrated with a Daly 8S 24V 20A BMS, which maintains precise voltage balancing and provides overcurrent protection. Supporting a continuous output of 20 A, the BMS offers a 2.5x safety margin over the motor’s nominal requirements, ensuring stability during peak load conditions.

Safety Protocols: Safety is managed through a multi-layered approach. A physical emergency switch is installed on the output line for immediate manual power disconnection. Furthermore, the control firmware implements automated power limits to trigger hardware-defined shutoffs if anomalies occur. Finally, the LiFePO4 chemistry inherently prevents thermal runaway, securing the system for industrial human-robot interaction.



Figure 7.8: Custom 8S1P LiFePO4 battery assembly with integrated Daly BMS.

7.4 Experimental Result: Load-to-Power Characterization

The AK80-64 KV80 actuator was tested under discrete payloads, specifically at 1 kg, 2 kg (Figure 7.10), 5 kg (Figure 7.9), 6 kg and 10 kg as part of a wider characterization from 1 to 10 kg at a 30 cm moment arm. These trials were conducted to quantify the relationship between mechanical load and electrical power consumption. This characterization, shown in Figure 7.12, validates the actuator's efficiency and thermal safety within the target assistive torque range of 2.94 Nm to 29.43 Nm.

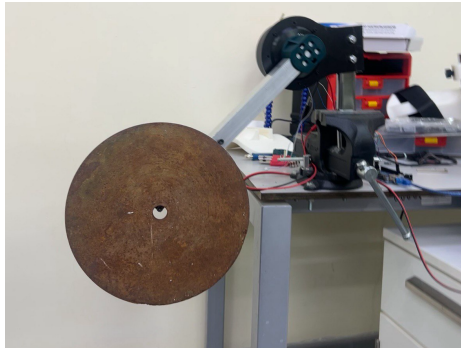


Figure 7.9: 5 kg load testing.

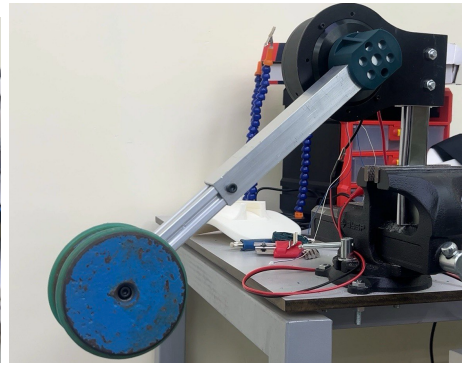


Figure 7.10: 2 kg load testing.

Figure 7.11: Experimental benchtop testing setup.

The data indicates a linear increase in power consumption at lower loads, rising from 3 W (1 kg) to 6 W (5 kg). A transition occurs beyond 5 kg, where the slope steepens as electrical demand reaches 10 W (6 kg) and eventually 21 W (10 kg). This aggressive scaling at higher payloads results from the increased motor current required to sustain nearly 30 Nm of torque. These results confirm that while the actuator is highly efficient at moderate loads, high-load operations approach the peak mechanical boundaries, necessitating the current-limiting strategies implemented in the firmware.

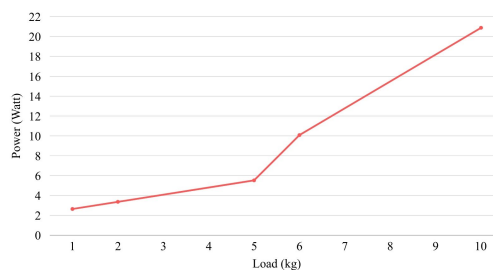


Figure 7.12: Load-to-power characterization for AK80-64 KV80.

Chapter 8: Control Strategy

8.1 Overview of Updated Control Architecture

The control strategy for the upper-limb exoskeleton was redesigned to shift from a multi-sensor fusion approach to a robust, encoder-only state-machine architecture. This transition improves system reliability by utilizing high-resolution position and velocity feedback directly from the CubeMars AK80-64 actuators via a CAN bus protocol. The system operates at a loop frequency of approximately 200 Hz, with a 5 ms delay between cycles to ensure stable communication. The core logic is governed by an intention-detection state machine that transitions between four functional modes: **IDLE**, **ASSISTING**, **HOLDING**, and **RELEASED**.

8.2 Controller Parameter Calculation (PID Tuning)

To ensure stability and transparency, the Proportional (K_p), Integral (K_i), and Derivative (K_d) gains were calculated based on the estimated mechanical properties of the exoskeleton arm and the desired response characteristics for industrial assistance.

8.2.1 Gain Determination Logic

The following values were derived to balance stiffness for position tracking with user safety:

- **Proportional Gain ($K_p = 20.0$):** This value was calculated to provide sufficient "stiffness" to lift target payloads. It translates the angular error in radians into a corrective torque significant enough to overcome gravity without causing oscillations.
- **Integral Gain ($K_i = 0.5$):** Set at a low value to eliminate steady-state error caused by the constant gravitational moment of the arm. An anti-windup constraint of ± 2.0 was calculated and implemented to prevent the integral term from accumulating excessively during physical obstructions.
- **Derivative Gain ($K_d = 4.0$):** This was determined by the damping ratio required to suppress oscillations and ensure smooth motion during high-speed transitions.

8.3 State Machine and Intention Detection

The system identifies user intention by monitoring the current joint position (*current_pos_rad*) and torque relative to predefined kinematic and force thresholds.

1. **IDLE State:** The controller holds the arm at the *LOWER_LIMIT_RAD* (0°). The system monitors for a voluntary lift past the *LIFT_THRESHOLD* of approximately 0.7 radians.
2. **ASSISTING State:** Triggered once the user lifts the arm past the threshold. The controller shifts the target to *UPPER_LIMIT_RAD* (90°), providing active torque support to complete the lift.
3. **HOLDING State:** Once the arm reaches the upper limit within a 1° tolerance, the system enters a steady-state hold to reduce user fatigue during overhead tasks.
4. **RELEASED State:** A safety and transparency mode. If the user pushes the arm past the *OVER_EXTEND_RAD* (92°), the system sets the torque command to zero. This allows the user to manually reset the arm to the IDLE position without motor intervention.

8.4 Firmware Implementation

The calculated PID logic is executed in the `process_intention_logic()` function. The controller calculates the required torque (*torque_cmd*), which is strictly capped at a *TORQUE_LIMIT* of 5.0 Nm for hardware safety. This command is transmitted via a MIT-protocol CAN message to the actuator.

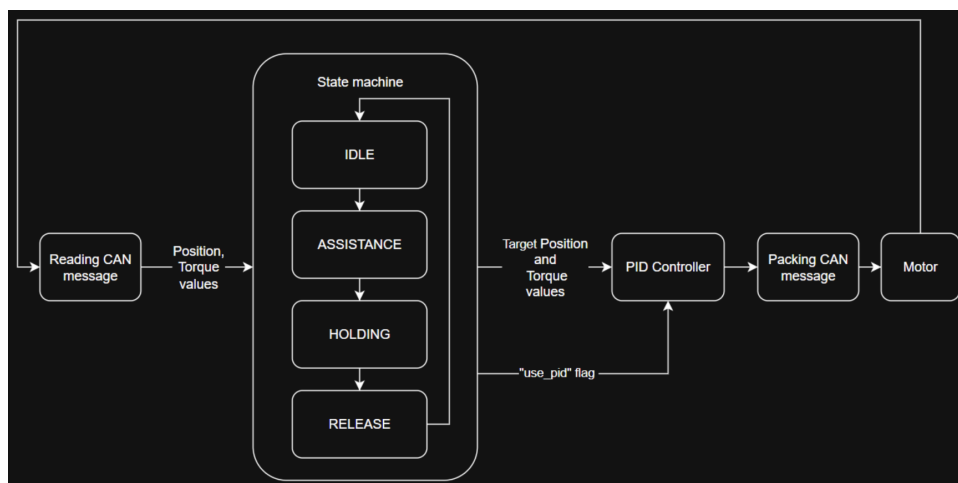


Figure 8.1: Encoder-Torque-Based Control Scheme.

This approach ensures the exoskeleton behaves as a responsive tool that anticipates and follows the user's trajectory through direct mechanical interaction and high-speed feedback loops.

8.5 Control Implementation

The control system uses an Arduino Mega 2560 with an MCP2515 CAN BUS Shield (1 Mbps). Motor operates in Mit mode, the actuator receives 8-byte commands defining target position, velocity and torque constraints controlled with gains. This gives us full-state feedback control while preventing abrupt accelerations or excessive power draw, prioritizing user safety. The current setup uses Position and torque-limited trajectories for stability, providing a scalable foundation for future EMG-based control and impedance modulation.

Chapter 9: Challenges and Future Work

9.1 Challenges

Torque vs. Wearability. One of the main challenges in exoskeleton design is balancing torque capacity with overall wearability. Higher torque typically requires larger actuators and higher gear reductions, which increase reflected inertia and add mass, particularly at distal locations. This reduces comfort and restricts natural movement. To mitigate this, the design prioritizes proximal actuation combined with compliant transmissions, reducing perceived load at the extremities while still delivering sufficient assistive torque [4, 11].

Procurement and Prototyping Constraints. A significant practical challenge encountered during the development phase was a critical delay in the hardware supply chain. Although four AK80-64 actuators were procured for the bilateral assembly, delivery was not fulfilled within the project's operational timeline. To maintain the development schedule, it became necessary to design and fabricate high-precision mechanical mockups. Replicating the exact dimensions, mounting interfaces, and rotational fluidity of the actuators using additive manufacturing and industrial bearings was essential to ensure that the structural validation and ergonomic fitting remained accurate to the final intended design.

Control Stability and Transparency. Another key challenge lies in maintaining system stability and transparency during human-robot interaction. Aggressive controller gains can lead to oscillations, while overly conservative tuning limits assistance effectiveness. Planned mitigation strategies include benchtop tuning of admittance profiles, application of rate limiting, and enforcement of passivity-inspired stability bounds. These steps ensure both safe interaction and effective assistance [3, 6, 7].

9.2 Future Work

Based on the current development and testing of the upper-limb exoskeleton, several key areas have been identified for future enhancement to improve performance, reliability, and user comfort.

9.2.1 Intention Detection and Control

To enhance the system's responsiveness, future iterations will focus on the integration of surface Electromyography (EMG) sensors to improve intention detection. Incorporating muscle activation data will allow for more intuitive control, enabling the exoskeleton to better anticipate voluntary movements before significant joint displacement occurs.

9.2.2 Power System Enhancements

Future improvements to the power supply architecture will focus on increasing energy density and maintaining cell health through the following measures:

- **Battery Configuration:** The current battery assembly will be expanded to an 8S2P parallel pack configuration to sum the output current and extend operational runtime.
- **Active Balancing:** An active balancing board will be integrated into the battery management system to ensure superior cell health and long-term voltage stability.

9.2.3 Mechanical and Structural Optimization

To refine the mechanical design and usability, the following structural goals have been established:

- **Passive Joint Integration:** The implementation of passive joints for the shoulder lift mechanism is being considered to optimize production costs and reduce overall system complexity.
- **Comfort and Dexterity:** Future designs will focus on improving ergonomic comfortability and extending the dexterity of the joints to allow for a more natural range of motion during complex industrial tasks.

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Appendix: Exoskeleton Control Firmware

The following source code represents the primary control loop and intention detection logic implemented on the Arduino Mega 2560. It utilizes the MCP_CAN library to interface with the CubeMars AK80-64 KV80 actuator via the MIT CAN protocol.

Listing 1: Complete Control Firmware for Intention-Based Assistance

```
1 #include <SPI.h>
2 #include <mcp_can.h>
3
4 // --- CAN Configuration ---
5 const int SPI_CS_PIN = 53;
6 MCP_CAN CAN(SPI_CS_PIN); [cite: 1]
7
8 // --- Motor Protocol Constants ---
9 const int MOTOR_ID = 0x01; [cite: 2]
10 const float P_MIN = -12.5f, P_MAX = 12.5f; [cite: 2]
11 const float V_MIN = -45.0f, V_MAX = 45.0f; [cite: 3]
12 const float T_MIN = -18.0f, T_MAX = 18.0f; [cite: 3]
13
14 // --- Intention Detection & Limits ---
15 enum SystemState { IDLE, ASSISTING, HOLDING, RELEASED }; [cite: 6]
16 SystemState currentState = IDLE;
17
18 const float TORQUE_LIMIT = 5.0f; [cite: 4]
19 const float DEG_TO_RAD = PI / 180.0f; [cite: 5]
20 const float LIFT_THRESHOLD = 0.7f * DEG_TO_RAD; [cite: 7]
21 const float UPPER_LIMIT_RAD = 90.0f * DEG_TO_RAD; [cite: 5]
22 const float OVER_EXTEND_RAD = 92.0f * DEG_TO_RAD; [cite: 8]
23
24 // --- PID Controller Variables ---
25 float Kp = 20.0f; [cite: 9]
26 float Ki = 0.5f; [cite: 9]
27 float Kd = 4.0f; [cite: 10]
28 float current_pos_rad = 0.0f, current_torque = 0.0f;
29 float integral = 0.0f, prev_error = 0.0f; [cite: 10, 11]
30 unsigned long last_time = 0;
31
32 void setup() {
33     Serial.begin(115200);
34     if (CAN.begin(MCP_ANY, CAN_1000KBPS, MCP_8MHZ) == CAN_OK) { [cite: 12]
35         Serial.println("CAN Initialized.");
36     } else {
37         while (1);
38     }
39     CAN.setMode(MCP_NORMAL); [cite: 13]
40     enable_motor(); [cite: 14]
41     last_time = millis();
42 }
43
44 void loop() {
45     read_motor_feedback(); [cite: 15]
46     process_intention_logic(); [cite: 15]
```

```

47     log_status(); [cite: 15]
48     delay(5); // ~200Hz loop
49 }
50
51 void process_intention_logic() {
52     float target_rad = 0.0f;
53     float torque_cmd = 0.0f;
54     bool use_pid = false; [cite: 16]
55
56     switch (currentState) {
57         case IDLE:
58             target_rad = 0.0f; use_pid = true;
59             if (current_pos_rad > LIFT_THRESHOLD) currentState = ASSISTING; [cite: 17]
60             break;
61
62         case ASSISTING:
63             target_rad = UPPER_LIMIT_RAD; use_pid = true;
64             if (abs(UPPER_LIMIT_RAD - current_pos_rad) < (1.0f * DEG_TO_RAD)) currentState =
                HOLDING; [cite: 19]
65             break;
66
67         case HOLDING:
68             target_rad = UPPER_LIMIT_RAD; use_pid = true;
69             if (current_pos_rad > OVER_EXTEND_RAD) { currentState = RELEASED; integral = 0; }
                [cite: 21, 22]
70             break;
71
72         case RELEASED:
73             torque_cmd = 0.0f; use_pid = false;
74             if (current_pos_rad < LIFT_THRESHOLD) currentState = IDLE; [cite: 23, 24]
75             break;
76     }
77
78     if (use_pid) {
79         unsigned long now = millis();
80         float dt = (now - last_time) / 1000.0f; [cite: 26]
81         if (dt <= 0) dt = 0.005f;
82         last_time = now;
83
84         float error = target_rad - current_pos_rad; [cite: 27]
85         integral += error * dt;
86         integral = constrain(integral, -2.0f, 2.0f); [cite: 27]
87         float derivative = (error - prev_error) / dt; [cite: 28]
88         prev_error = error;
89
90         torque_cmd = (Kp * error) + (Ki * integral) + (Kd * derivative); [cite: 29]
91         torque_cmd = constrain(torque_cmd, -TORQUE_LIMIT, TORQUE_LIMIT); [cite: 29]
92     }
93
94     send_mit_command(0.0f, 0.0f, 0.0f, 0.0f, torque_cmd); [cite: 30]
95 }
96
97 // Data Conversion Helpers (float_to_uint / uint_to_float) omitted for space [cite: 45,
    46]

```