Introduction

Recent ankle rehabilitation research has introduced the use of robotic exoskeletons to enhance muscle strength and correct gait. Fixed-position robots assist in early-stage training but cannot be used while walking. Wearable exoskeletons support walking but struggle with foot rotation along the z-axis. Full lower-limb devices offer broader support but are bulky and not specialized for ankle injuries, making them less convenient. This research aims to address these limitations.

Structural Design

Motion Direction	ROM (Degree)
Dorsiflexion	20.3–29.8
Plantarflexion	37.6–45.8
Inversion	14.5–22.0
Eversion	10.0–17.0
Abduction	15.4–25.9
Adduction	22.0–36.0

Figure #1: Range of motion (RoM) of the ankle joint [1]

Figure #2: The axis of motion of the ankle joint, graph created by finalist using Adobe Photoshop, 2025

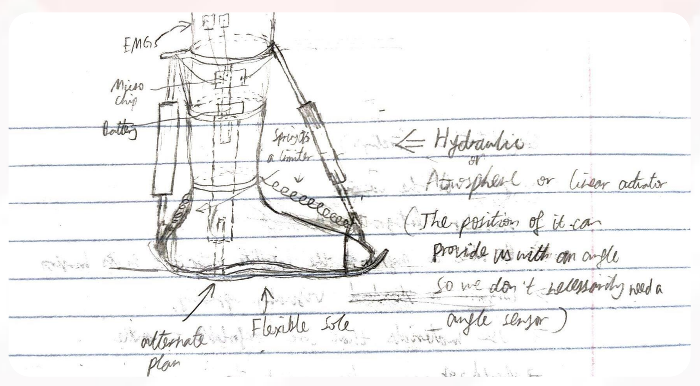

Figure #3: Preliminary drawing for the exoskeleton, drawing created by finalist on paper, 2024

Requirements

- **Support & Stability**: The exoskeleton must provide support while allowing movement for rehabilitation
- **Natural Motion**: Designed to support all six directions of motion (see Fig. 1 & 2)
- **Safety Mechanisms**: Include mechanical stops or limiters to prevent excessive joint movement
- **Sensors**: Supports electromyography (EMG) and inertial measurement units (IMU) to monitor muscle activity and gait

Design

- **Materials**: Made of thermoplastic polyurethane (TPU), carbon fiber reinforced polylactide (PLA-CF), and a commercially available ankle brace for a balance of rigidity and comfort
- **Actuation**: Uses linear actuators and stepper motors to generate sufficient force (see Fig. 4)
- **Component Housing**: A chamber under the foot platform accommodates the microcontroller, battery, and motor drivers for efficient space use and easy access
- **Degrees of Freedom**: Provides 3 Degrees of Freedom (3DoF) to enable natural movement while assisting rehabilitation (see Fig. 4)

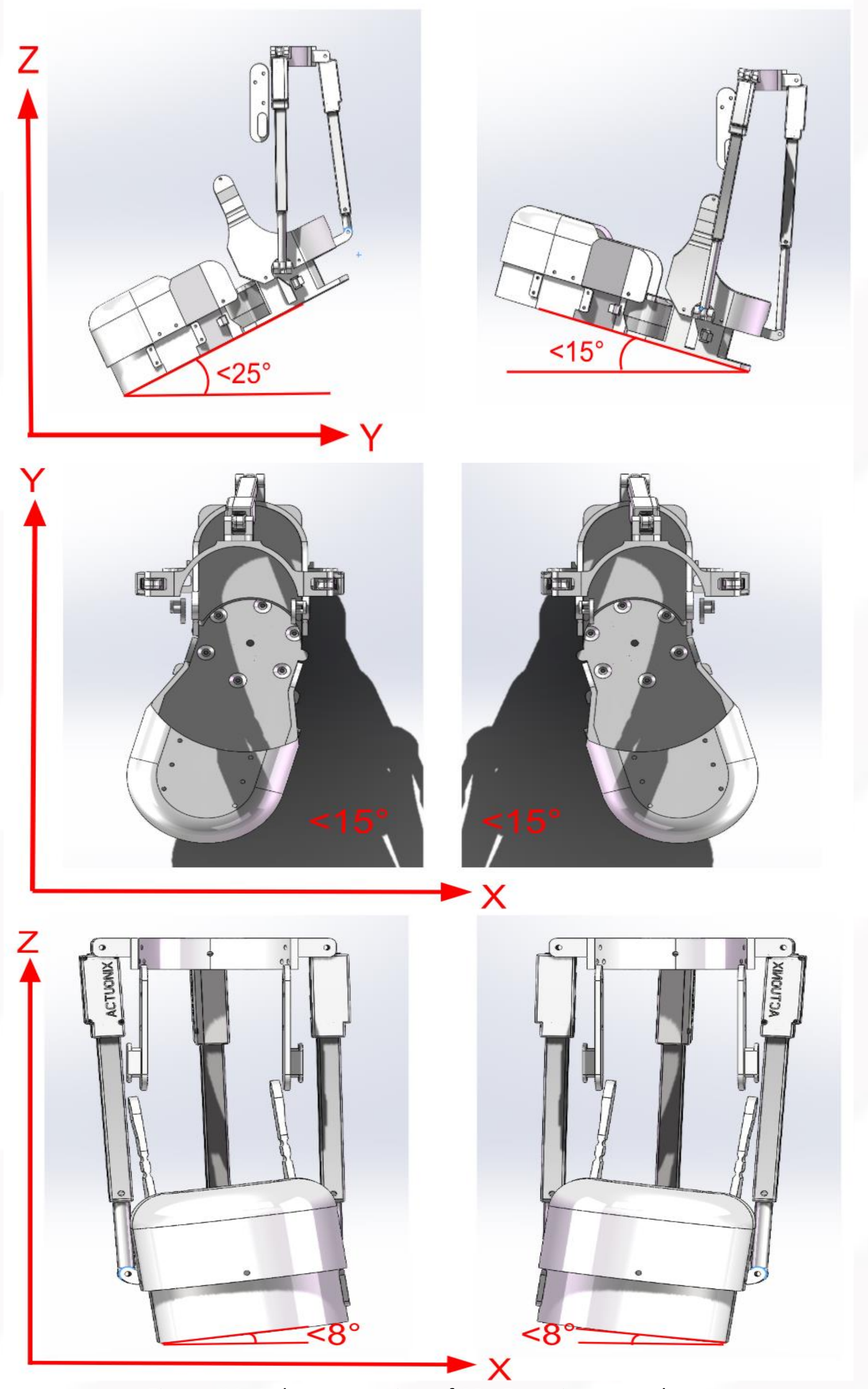

Figure #4: A demonstration of 3DoF motions, graph created by finalist using SOLIDWORKS, 2025

Prototype

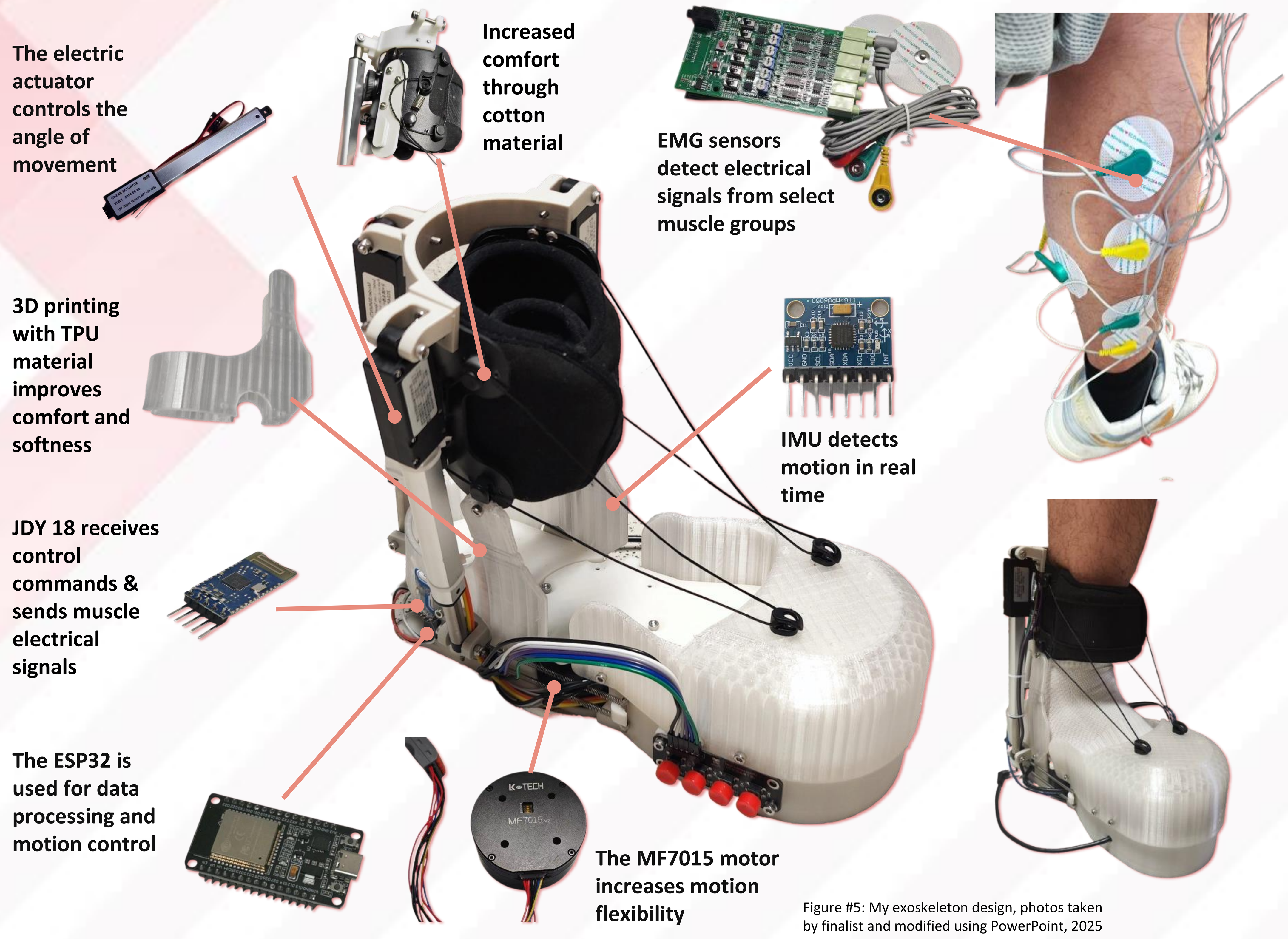

Figure #5: My exoskeleton design, photos taken by finalist and modified using PowerPoint, 2025

Algorithm for the AI Model

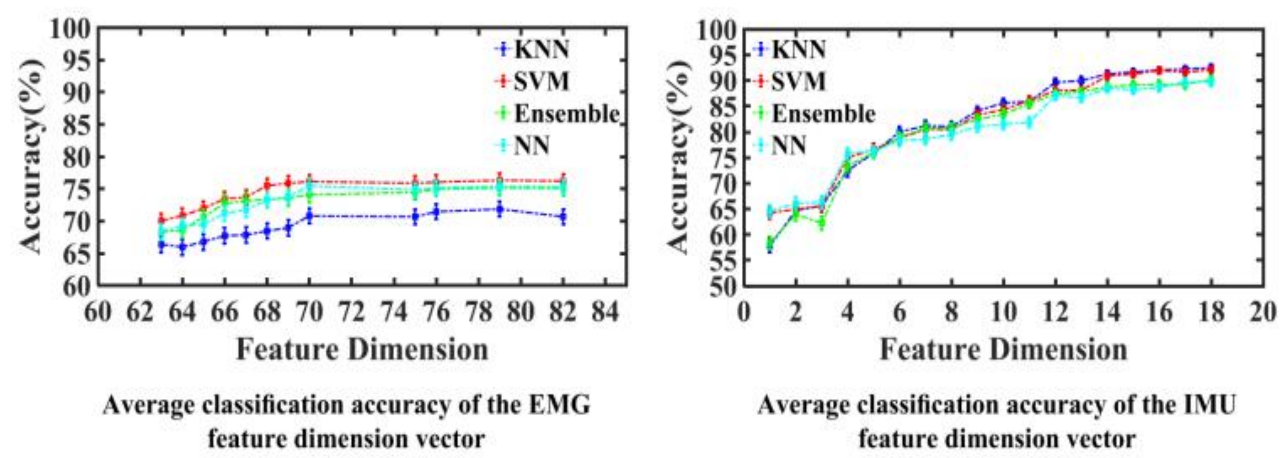

Figure #6: Average classification accuracy as a function of the feature dimension vector [2]

- **Support Vector Machine (SVM) for Classification**: Identifies gait phases using EMG and IMU signals, distinguishing stance and swing
- **Gaussian Process Regression (GPR)**: Predicts optimal actuator torque based on deviations from a healthy gait
- **Dynamic Support**: Ensures personalized movement correction by responding to muscle activity and motion patterns
- **High Accuracy**: The model reaches an accuracy of 91.66% for classification (see Fig. 6)

Figure #7: The process of motion state analysis, graph created by finalist using PowerPoint, 2025

Experiments and Analysis

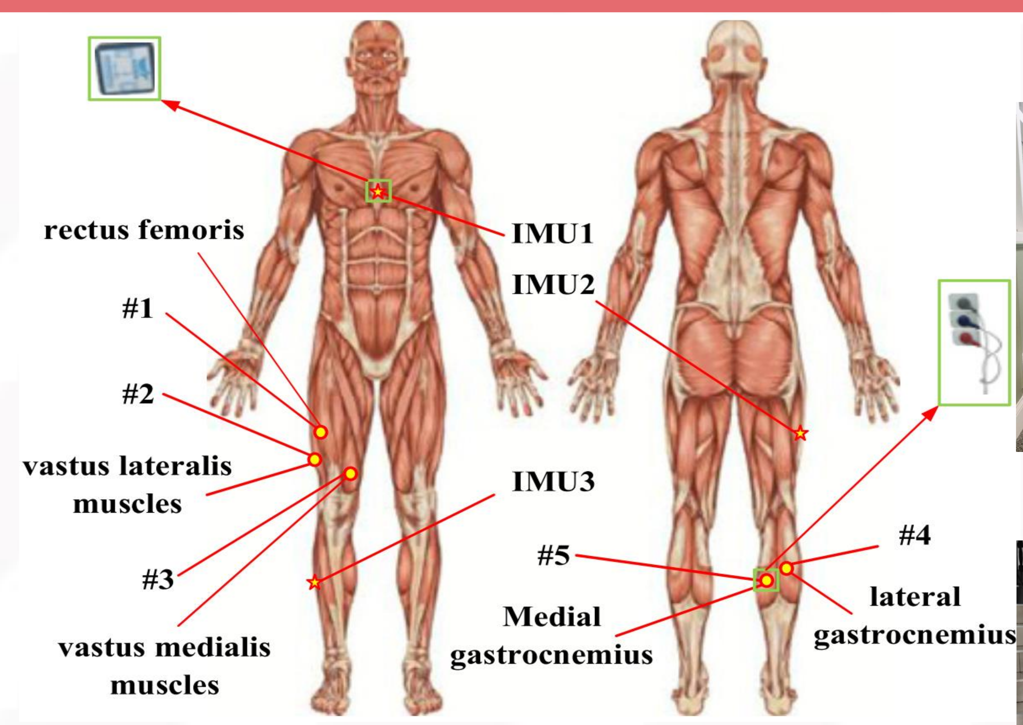

Figure #8: Positions of sensors [2]

- **Evaluation Focus**: Tested accuracy, responsiveness, and effectiveness in real-time gait correction
- **Data Collection**: EMG and IMU data were analyzed across multiple trials (see Fig. 8)
- **SVM Performance**: Achieved high precision in detecting stance and swing phases
- **GPR Effectiveness**: Accurately estimated actuator torque for smooth, adaptive assistance

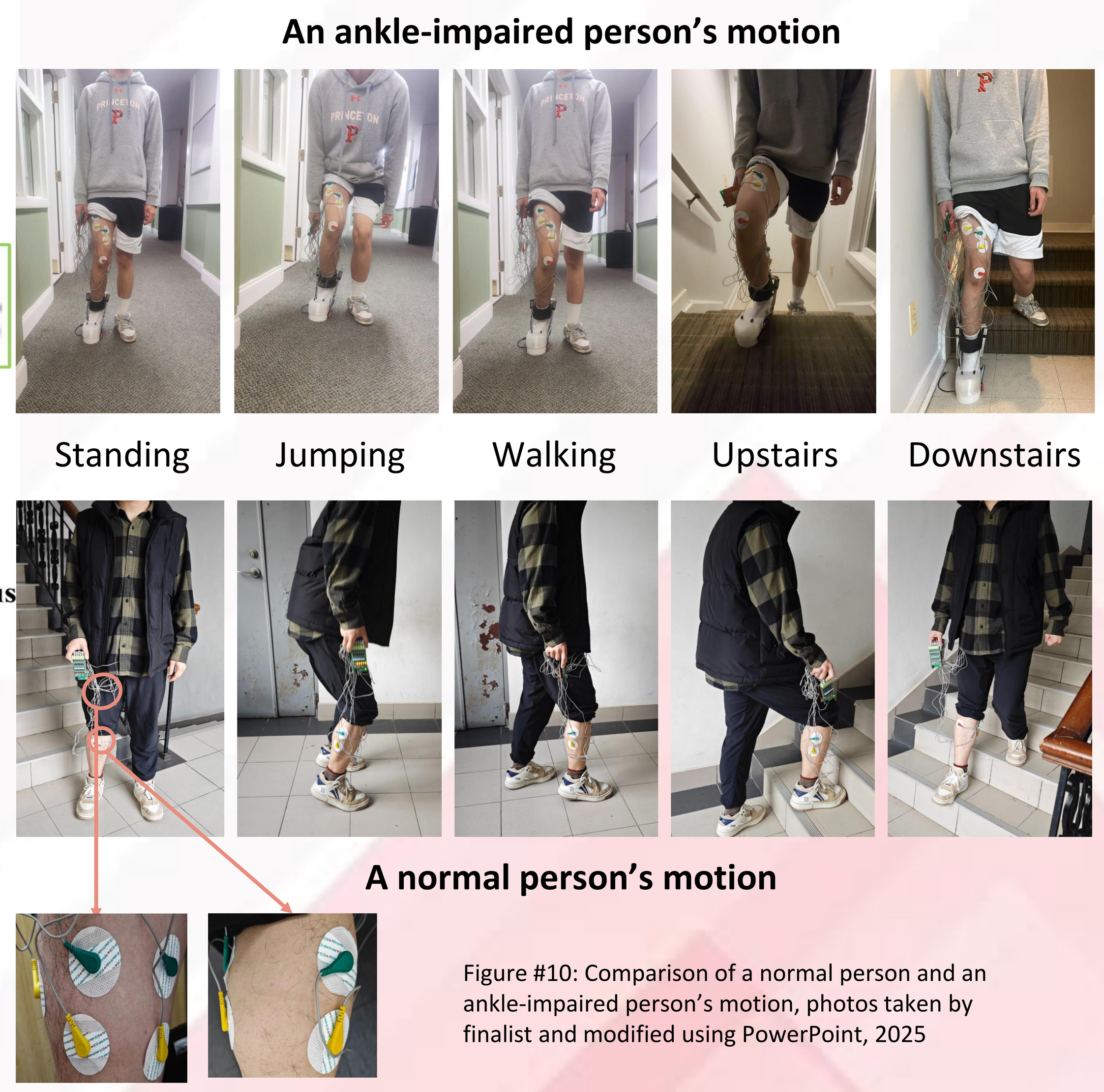

Figure #10: Comparison of a normal person and an ankle-impaired person's motion, photos taken by finalist and modified using PowerPoint, 2025

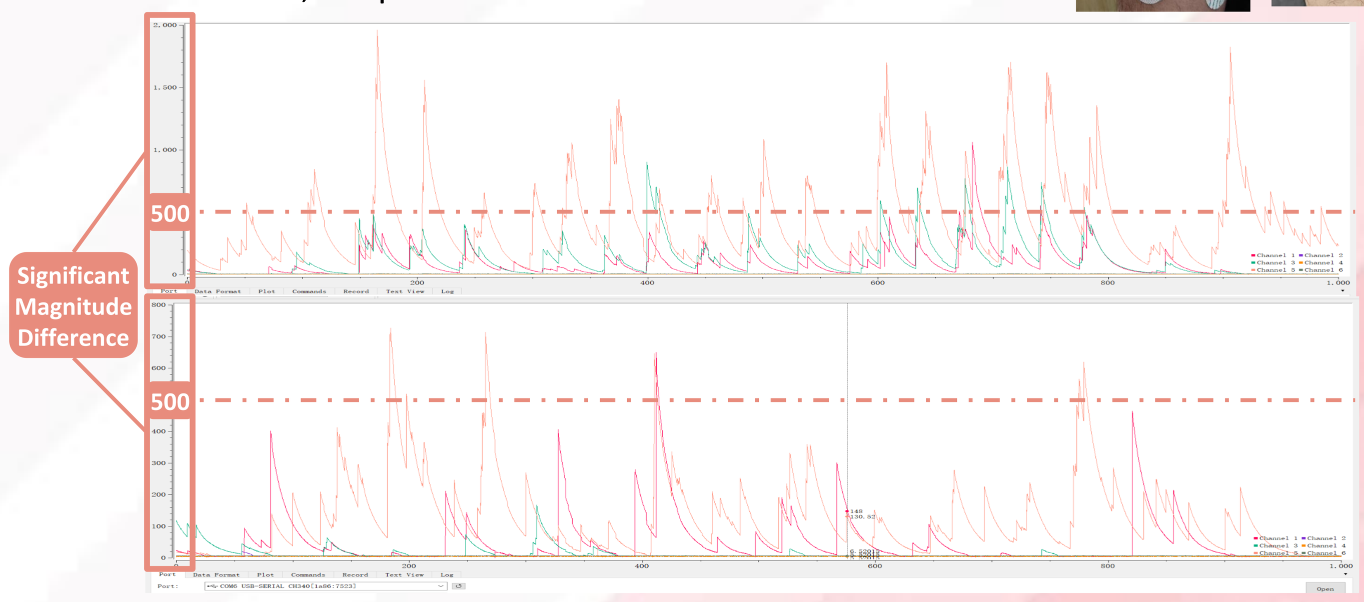

Figure #9: Changes in EMG data during walking, graph created by finalist using SerialPlot, 2025

The results show improved gait symmetry and a 70% reduction in muscle strain, confirming effective real-time support. Comparative trials demonstrated better step consistency and weight distribution with the exoskeleton. This was further supported by differences observed in EMG data between assisted and unassisted walking (see Fig. 9). Minor issues like response latency and weight balance were noted, suggesting future improvements in the actuator speed and ergonomics. These findings validate the system's potential for personalized ankle rehabilitation.

Embedded System

Real-Time Processing
Microcontroller Unit (MCU) processes signals for adaptive control and rehabilitation assistance

Sensor Integration
Six-channel EMG detects muscle activation; IMU tracks motion, acceleration, and velocity

Actuator Control
The embedded controller sends commands to motor drivers for precise movement assistance

Power Management
Regulates energy use, optimizes battery life and prevents overheating

Wireless Communication
Enables remote data transmission for adjustments

Efficiency & Adaptability
Ensures real-time responsiveness and user-friendly rehabilitation support

Control System

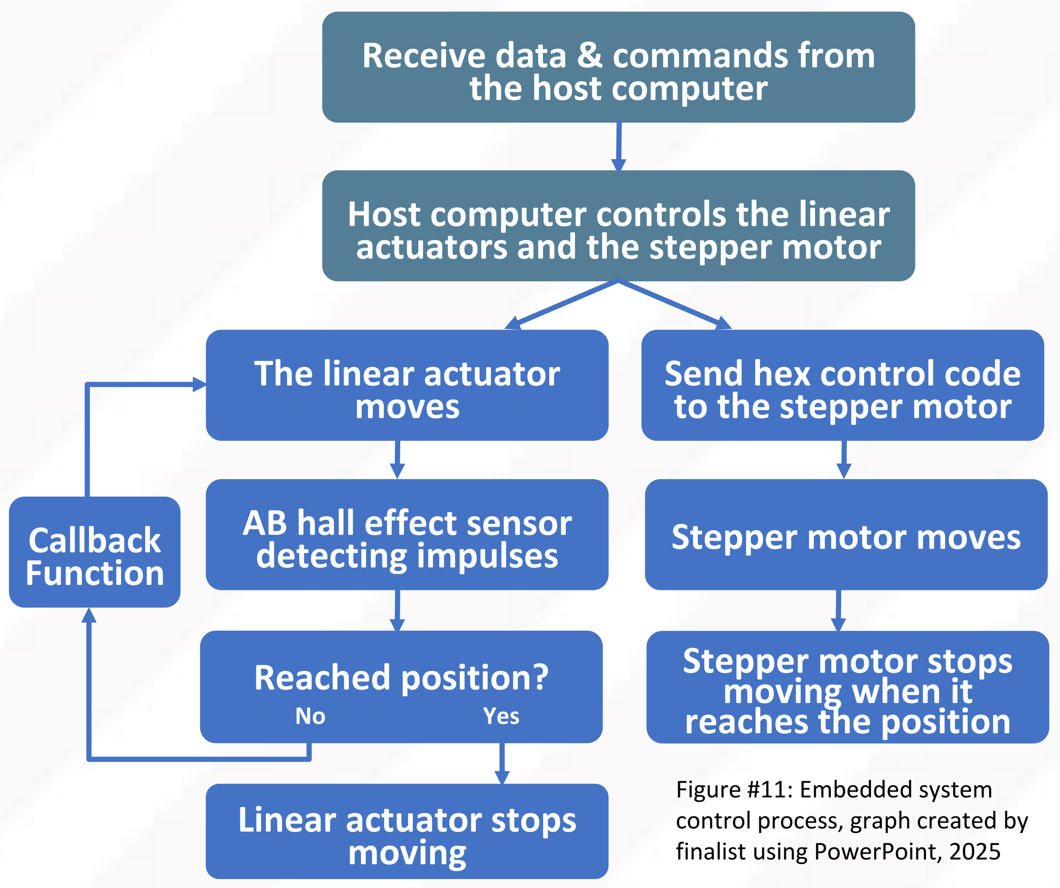

Figure #11: Embedded system control process, graph created by finalist using PowerPoint, 2025

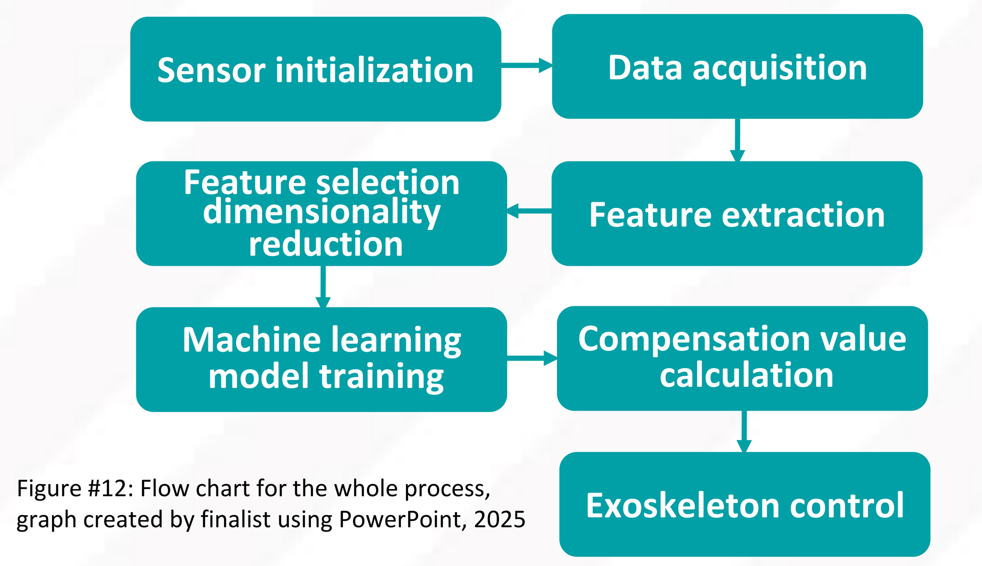

Figure #12: Flow chart for the whole process, graph created by finalist using PowerPoint, 2025

Conclusion

This study successfully developed and validated a real-time adaptive ankle exoskeleton using SVM and GPR to deliver personalized support. The system improved gait symmetry and reduced muscular strain, demonstrating its potential as an intelligent rehabilitation device. With a total cost of approximately $330, which is significantly lower than that of most existing solutions, the exoskeleton offers a more affordable option for clinical and personal use. In the future, improving response speed, comfort, and power consumption will make the exoskeleton easier to use in clinics and help more people with enabled recovery.

Future Ideas

- **Hardware Optimization**: Reduce weight with carbon fiber composites and improve battery efficiency
- **Software Enhancements**: Train SVM and GPR on larger datasets for better gait classification and control
- **Latency Reduction**: Optimize real-time processing and actuator response speed
- **User Testing**: Expand trials to diverse users to refine personalized assistance
- **Electroencephalogram (EEG) Integration**: Implement brain-machine interface (BMI) for control, aiding users with severe muscle weakness
- **Wireless & Cloud Features**: Enable remote monitoring, AI-driven adjustments, and rehabilitation progress tracking
- **Clinical Application**: Enhance usability for real-world medical rehabilitation

Figure References

1. Sergazin, G., Zhetenbayev, N., Tursunbayeva, G., Uzbekbayev, A., Sarina, A., Nurgizat, Y., & Nussibaliyeva, A. (2024). Design, Simulation and Functional Testing of a Novel Ankle Exoskeleton with 3DoFs. *Sensors*, *24*(19), 6160. https://doi.org/10.3390/s24196160
2. Zhou, B., Wang, H., Hu, F., Feng, N., Xi, H., Zhang, Z., & Tang, H. (2020). Accurate recognition of lower limb ambulation mode based on surface electromyography and motion data using machine learning. *Computer Methods and Programs in Biomedicine*, 193, 105486. https://doi.org/10.1016/j.cmpb.2020.105486