Development and implementation of a parallel ankle rehabilitation robot: PRANK

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PROPOSAL SUMMARY SHEET

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2. Summary table

Title	Development and implementation of a parallel ankle rehabilitation robot: PRANK
Area	Robotics
Research Group	DAVINCI
Type of research	Experimental development

Table 1: Proposal Summary Table

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Abstract

Human gait is a fundamental component of mobility, autonomy, and overall quality of life. Among the joints involved in locomotion, the ankle plays a crucial role in absorbing shock during heel strike and facilitating propulsion during the push-off phase. Impairments in ankle function—whether due to neurological conditions, trauma, or post-surgical recovery—can significantly compromise gait, balance, and independence. Robotic rehabilitation has emerged as a promising alternative to traditional therapy, offering consistent, repeatable, and quantitatively measurable support.

This project proposes the development of a Parallel Ankle Rehabilitation Robot (PARR), actuated through an RRR electric motor configuration and controlled via an admittance algorithm based on real-time force feedback. The system is complemented by a serious game implemented in virtual reality, designed to enhance patient engagement and tailor therapy difficulty dynamically based on ankle range of motion (ROM) and user-applied force. The project focuses on the mechatronic development of the robot and the comparative validation of its ROM measurement accuracy against an optoelectronic motion capture system, aiming to demonstrate the system's feasibility for reliable biomechanical evaluation and future deployment in clinical environments.

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Chapter 1

PROJECT JUSTIFICATION

Gait is a fundamental aspect of human independence and well-being. Within the gait kinetics, the ankle joint plays a pivotal role in absorbing impact forces during heel strike and generating propulsion during toe-off. When the ankle's function is impaired—due to conditions such as stroke, orthopedic trauma, or neurodegenerative disease—patients face significant limitations in mobility, balance, and daily autonomy.

Rehabilitation is essential for restoring ankle functionality, yet conventional methods often lack the consistency, objectivity, and sustained engagement required for optimal recovery. Furthermore, existing robotic devices for gait rehabilitation typically do not include mechanisms specifically designed for targeted ankle strength recovery. In this context, robotic rehabilitation systems offer the advantages of repeatability, precise measurement, and the ability to adapt therapy to an individual's progress. Additionally, serious games and virtual reality environments have shown considerable promise in enhancing motivation and participation—key factors that directly influence rehabilitation outcomes.

This project addresses these needs through the development of PRANK (Parallel Robot for ANKle rehabilitation), a parallel robotic platform actuated by an RRR configuration and controlled through admittance strategies. It aims to offer a safe, adaptive, and engaging therapeutic environment. By integrating a serious game and a real-time feedback loop that adjusts difficulty based on force and range of motion (ROM), the system seeks to promote user-centered recovery while providing measurable, high-fidelity data. Additionally, validating PRANK's ROM measurement capabilities against an optoelectronic motion capture system will support its use as a reliable biomechanical assessment tool in future clinical settings.

Chapter 2

STATE OF ART

Ankle rehabilitation is essential for restoring mobility and balance in patients affected by neurological or musculoskeletal disorders, such as stroke, cerebral palsy, or foot drop. Robotic systems have emerged as powerful tools to deliver consistent, adaptive, and measurable therapy. Among these, **parallel robots** offer unique advantages in terms of stiffness, load capacity, and multi-degree-of-freedom control, making them particularly suitable for ankle rehabilitation.

2.1 Mechanical Architectures and Kinematic Design

Parallel mechanisms such as 2-UPS/RRR, 3-RRS, and cable-driven structures have been widely explored for ankle rehabilitation due to their compactness and ability to replicate complex joint movements [1], [2], [3], [4], [5], [6]. Optimization techniques including genetic algorithms and differential evolution have been applied to improve workspace, avoid singularities, and enhance isotropy [7], [8], [9].

2.2 Actuation and Compliance Strategies

Actuation methods vary from pneumatic muscle actuators (PMAs) [2] to series elastic actuators (SEAs) and cable-driven systems [5], [10]. Compliance is critical for safety and adaptability, especially in early rehabilitation stages. Passive and active compliance strategies have been proposed to reduce joint stress and accommodate patient variability [11], [12].

2.3 Control Algorithms and Patient Interaction

Advanced control strategies such as adaptive impedance control, fuzzy logic, and patient-cooperative control have been developed to enhance engagement and safety [3], [5], [13]. EMG-based intent recognition and deep learning models are increasingly integrated to personalize therapy and enable real-time trajectory adaptation [14], [15].

2.4 Clinical Validation and Functional Outcomes

Clinical studies have demonstrated improvements in range of motion, gait symmetry, and muscle activation using robotic systems [9], [10], [16]. Comparative analyses with traditional methods such as ankle-foot orthoses (AFOs) and functional electrical stimulation (FES) show that robotic therapy can match or exceed conventional outcomes [17], [18].

2.5 Design for Home-Based and Modular Use

Recent efforts focus on portability and modularity to enable home-based rehabilitation [9], [10]. Reconfigurable robots allow adaptation to different patient profiles and therapy stages **singh2025design** , [19]. Integration with virtual reality and remote monitoring platforms is also being explored to improve motivation and continuity of care [15], [20].

2.6 Biomechanical Foundations and Emerging Technologies

A comprehensive understanding of ankle biomechanics is essential for designing effective rehabilitation robots. Classical studies have established the role of the ankle-foot complex in propulsion, balance, and gait symmetry [21], [22], [23]. These insights inform the kinematic and dynamic requirements of robotic systems, particularly in replicating dorsiflexion and plantarflexion patterns.

Recent advances in wearable sensing and machine learning have enabled more precise estimation of motor intent. EMG-based signal processing combined with deep neural networks has shown promise in predicting dorsiflexion and guiding adaptive control [24]. Cable-driven exoskeletons powered by series elastic actuators offer compliant assistance while enhancing gait symmetry [25]. Similarly, soft robotic platforms such as T-FLEX integrate modular actuation and flexible interfaces for post-stroke rehabilitation [26].

Virtual reality and telerehabilitation are gaining traction as complementary tools for home-based therapy. Systematic reviews highlight their effectiveness in improving postural balance and engagement in patients with neurological disorders [27]. These technologies align with the broader trend toward decentralized, patient-centered rehabilitation.

Comparative studies between robotic therapy, ankle-foot orthoses (AFOs), and functional electrical stimulation (FES) suggest that robot-assisted interventions can achieve equal or superior outcomes in gait restoration and muscle activation [28], [29]. These findings support the integration of robotic systems into mainstream clinical protocols.

2.7 Challenges and Future Directions

Despite progress, challenges remain:

- Ensuring compact, low-cost designs for domestic use.
- Achieving real-time adaptation to patient effort and variability.
- Standardizing clinical protocols for robot-assisted therapy.
- Integrating biosignal feedback and cloud-based analytics.

Future work should focus on scalable architectures, hybrid actuation, and intelligent control systems that fuse biomechanics, machine learning, and human-centered design.

Chapter 3

OBJECTIVES

3.1 General

Develop a parallel ankle rehabilitation robot using admittance control strategies, serious virtual reality-based games and an RRR electric motor configuration, adapting the difficulty of therapy based on real-time ankle range of motion (ROM) and force feedback.

3.2 Specifics

- Design, fabricate and assemble a 3-axis parallel structure based on electric motors to fit the controlled movement of the ankle.
- Develop an admittance control system that adjusts therapy resistance based on patient interaction, based on force feedback, ensuring adaptive rehabilitation.
- Create a virtual reality serious game to engage patients in interactive rehabilitation, enhancing motivation and adherence to therapy.
- Implement a difficulty adjustment algorithm based on real-time ankle ROM measurements to provide progressive rehabilitation tailored to the patient's recovery status.
- Evaluate system performance through simulations and subject trials, measuring effectiveness in improving ankle mobility, patient experience, ROM calculus and control algorithm performance.

Chapter 4

DELIMITATION AND SCOPE

This project encompasses the design, development, and initial technical validation of a parallel ankle rehabilitation robot (PARR) featuring an RRR configuration and admittance control. The system integrates real-time force feedback and a virtual reality-based serious game to promote engagement and adaptive therapy based on ankle range of motion (ROM). The scope includes mechanical design, electronic design, control system implementation, development of the VR environment, and a ROM evaluation strategy using an optoelectronic motion capture system as a reference standard.

However, the study is delimited to engineering and software development stages. It does not involve clinical trials with patients or assessment of long-term rehabilitation outcomes. Likewise, while the VR component is designed to enhance engagement, this work does not evaluate its psychological or motivational impact. Validation efforts are limited to simulations and technical comparisons with healthy subjects or artificial inputs to quantify kinematic performance and ROM estimation accuracy.

Chapter 5

HYPOTHESIS

The developed parallel ankle rehabilitation robot, featuring an adaptive admittance-based control algorithm and integrated with a serious virtual reality game, will accurately estimate the ankle's range of motion (ROM). The system will support variable resistance modes tailored to the user's motor capacity and rehabilitation stage. ROM measurements obtained from the robot will show high correlation and minimal deviation compared to those captured by a validated optoelectronic motion capture system, demonstrating the feasibility of reliable kinematic assessment through onboard sensors and software.

Chapter 6

THEROTICAL FRAMEWORK

6.1 Human gait

Human gait is one of the most important tasks of daily life, as it allows people to maintain independence and live with autonomy, mobility, and dignity. Impairments in gait due to neurological or musculoskeletal conditions can significantly affect quality of life, making rehabilitation a critical component of recovery and functional reintegration.

The gait analysis is carried out on the basis of the gait cycle, that can be taken as representation of person's walking patterns, and comparison of several cycles indicates the variability of the pattern [30]. The gait cycle is normalized from 0% to 100%, because each pattern have different timing, so is not objective realize a comparison between them [31], it can be described with spatial and temporal parameters.

6.1.1 Spatial parameters

The main spatial parameters are shown in figure 6.1 and described bellow:

- Step: the movement of the one foot in front of the other.
- Stride: step of one foot followed by another step for the other.
- Foot contact: it is considered as the beginning of the gait cycle, in healthy people it is referred to as *heel strike*.
- Step length: distance traveled for one foot in front of the same part of the other foot.
- Stride length: distance between two consecutive gait cycles.
- Step width: mediolateral separation of the feet, also known as stride width.

6.1.2 Temporal parameters

Temporal parameters are listed bellow:

- Stride time: duration of gait cycle (time between two foot strikes).

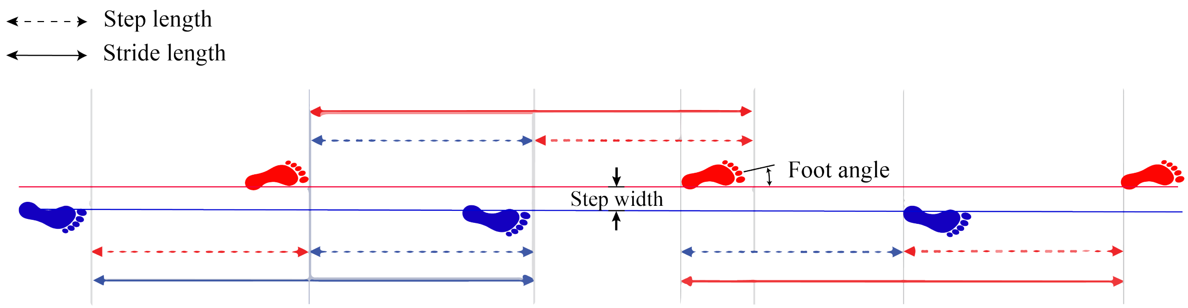

Figure 6.1: Gait spatial parameters. Source: edited by author from [30].

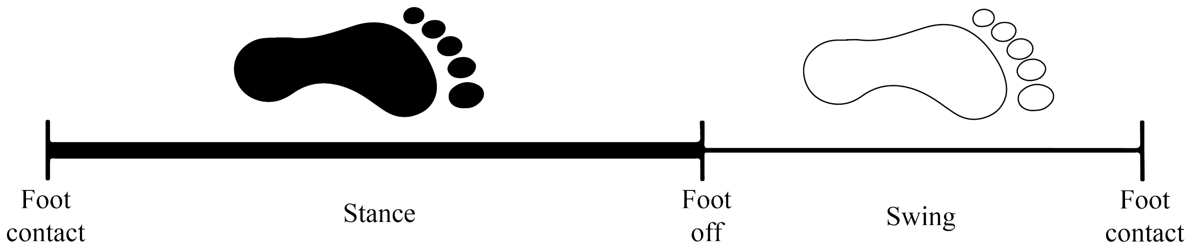

Figure 6.2: One side gait phases. Source: edited by author from [30].

- Cadence: it is a more commonly term used to specify the duration of the cycle in indirect way. And is described by:
$$\frac{\#cycles}{time\ interval} \tag{6.1}$$
- Walking speed: distance traveled in a given time in meters/second, if cadence is in steps per minute and stride length is in meters the calculation is given by:
$$\frac{cadence * stride\ length}{120} \tag{6.2}$$

Gait is globally divided into two phases, *stance* and *swing*. The first occur when foot is in contact with the ground, on the other hand, the swing occur when it is not. The stance phase ends when foot off (toe off); the same point at which the swing begins, as illustrated in the figure 6.2,

The scheme can include the events of both legs, and is divided into first double support (both feet in contact with ground), single support, second double support and swing, as is shown in figure 6.3. Single support and swing are long phases, so a subdivision is a good choice: *early*, *middle* and *late* as can be seen in the figure [30], [32].

Any impairment in the ankle joint manifests as alterations in gait parameters, disrupting the cyclical and repetitive nature of walking. This leads to increased energy expenditure and triggers compensatory mechanisms in other muscle groups to maintain locomotion, often resulting in instability and a heightened risk of falling.

The PRANK ankle rehabilitation robot is grounded in biomechanical, neurophysiological, and human-machine interaction principles that guide its design and control strategy. Below outlines the theoretical foundations that justify the system's architecture, control approach, and therapeutic goals.

6.2 Biomechanical Modeling of the Ankle

The human ankle plays a critical role in gait, contributing to propulsion, balance, and shock absorption. It operates in coordination with the knee and hip as part of the lower limb kinematic chain. Biomechanical models often simplify the ankle as a single-degree-of-freedom joint, focusing on dorsiflexion and plantarflexion, while more advanced models incorporate multi-axis dynamics and impedance variations across gait phases [33]. These models are essential for simulating joint behavior and designing control strategies that replicate natural movement.

6.3 Motor Rehabilitation and Neuroplasticity

Motor recovery after injury or neurological impairment relies on neuroplasticity—the brain's ability to reorganize through repetitive, goal-oriented movement. Rehabilitation robotics leverage this principle by enabling high-intensity, task-specific training. Key motor learning principles include feedback, variability, and active participation, all of which enhance cortical reorganization and functional recovery [34], [35]. The PRANK system integrates these principles through interactive tasks and adaptive control.

6.4 Human-Machine Interfaces in Rehabilitation

Effective rehabilitation requires intuitive and responsive interfaces between the user and the robotic system. These interfaces must accommodate physical comfort, cognitive engagement, and safety. Advances in flexible electronics and soft robotics have enabled more ergonomic designs that conform to the user's anatomy [36]. Additionally, virtual reality (VR) environments provide immersive feedback, increasing motivation and facilitating motor learning through gamified rehabilitation tasks [37].

6.5 Clinical Evaluation Metrics

Quantifying rehabilitation outcomes is essential for validating system effectiveness. Clinical metrics include range of motion, gait symmetry, balance, and patient-reported outcomes. Instruments such as the Rehabilitation Measures Database offer standardized tools for assessing

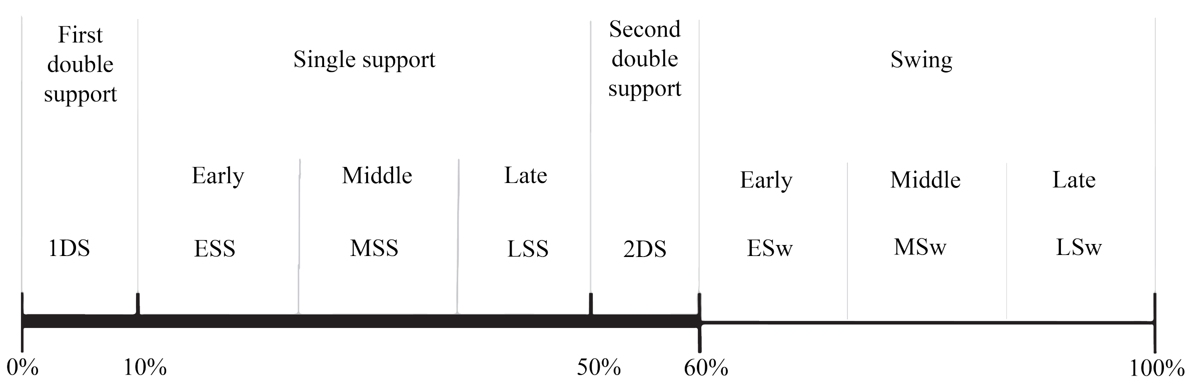

Figure 6.3: Both sides gait phases. Source: edited by author from [30].

ankle functionality and tracking progress over time [38]. These metrics inform both the design of therapeutic protocols and the evaluation of system performance.

Chapter 7

MATERIALS AND METHODS

This section describes the components and methodology used in the development of the PRANK ankle rehabilitation robot, with reference to international standards that guide safety, performance, and software quality in rehabilitation robotics.

7.1 Mechanical Structure

The PRANK robot is designed with three degrees of freedom (DoF), enabling controlled movement in dorsiflexion/plantarflexion, inversion/eversion, and internal/external rotation. The mechanical structure follows safety principles outlined in ISO 13482 and ISO/TS 15066, which define requirements for personal care and collaborative robots. The frame is built using lightweight aluminum and 3D-printed joints to ensure modularity, ergonomic alignment, and safe physical interaction. The foot interface includes adjustable straps and a contoured support to minimize risk during use.

7.2 Actuation and Sensing

Each DoF is actuated by a brushless DC motor with integrated encoders, selected to meet performance criteria similar to those in ISO 9283. Torque estimation is achieved through current sensing and mechanical modeling. The system includes encoders for motion tracking and a 3D load cell for force feedback. Electrical safety considerations are guided by ISO 60601-1, addressing insulation, leakage current, and electromagnetic compatibility.

7.3 Control Architecture

The control system supports multiple rehabilitation modes: passive, assistive, and resistive. In assistive mode, the robot applies torque to guide the user's movement along predefined trajectories. In resistive mode, it generates opposing torque to challenge the user's effort and promote muscle strengthening. These modes are implemented using nonlinear control strategies and admitance-based control. The controller runs on a real-time embedded platform, with communication handled via serial or CAN protocols. Safety features include torque limits, emergency stop mechanisms, and compliance with ISO 10218-1 and ISO/TS 15066.

7.4 Virtual Reality Interface

A custom VR serious game developed in Unity provides interactive tasks that promote ankle mobility and coordination. The game receives real-time data from the robot and delivers visual, sound and haptic feedback to the user. Human-machine interaction principles from ISO 13482 and ISO/IEC 25010 are considered to ensure usability, engagement, and therapeutic relevance.

7.5 Software Environment

Software development follows lifecycle guidelines from ISO/IEC 62304 and ISO/IEC 12207, ensuring modularity, traceability, and maintainability. Embedded control is implemented in C++, while high-level coordination and data logging use C# and Unity Game Engine. Control algorithms are validated in MATLAB/Simulink prior to deployment. Sensor data and user interaction metrics are logged for offline analysis and performance evaluation.

7.6 Experimental Protocol (Planned)

A pilot study will be conducted with healthy participants to evaluate system usability, comfort, and preliminary effectiveness. The protocol will include tasks in all three control modes and collect metrics such as range of motion, task completion time, and user feedback. The ROM calculation will be verified using an optoelectronic tracking system.

7.7 System Architecture

Figure 7.1 presents the overall system architecture, detailing the integration between the embedded control hardware and the software modules responsible for data processing, user interaction, and rehabilitation logic.

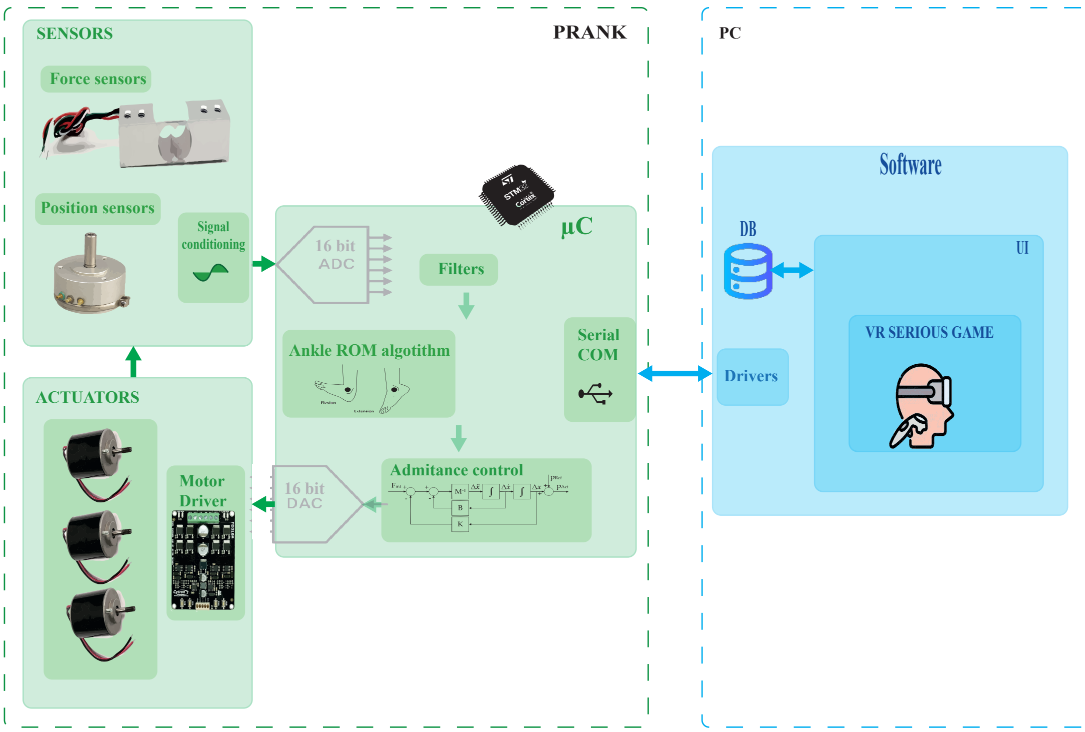

Figure 7.1: PRANK System schematic

Chapter 8

SCHEDULE

The development of the PRANK ankle rehabilitation robot is structured into a series of well-defined phases, each with specific objectives and deliverables. The project schedule was designed to ensure logical progression, allow for parallel development where feasible, and provide sufficient time for integration and testing.

The timeline spans 12 months and is illustrated in the Gantt chart below. The schedule includes the following key phases:

- **Planning and Research (Months 1–2):** Initial exploration of rehabilitation needs, literature review, and definition of system requirements.
- **Mechanical Design (Months 2–3):** CAD modeling, selection of actuators and sensors, and preparation for prototyping.
- **Electronics and Integration (Months 3–4):** Design and assembly of the embedded system, including motor drivers, signal conditioning, and sensor integration.
- **Control System Development (Months 5–6):** Implementation of nonlinear control strategies tailored to ankle biomechanics, with simulation and hardware-in-the-loop testing.
- **VR Game Development (Months 3–7):** In parallel with hardware development, a virtual reality game is designed to provide engaging rehabilitation tasks and real-time feedback.
- **System Integration (Months 8–9):** Merging of mechanical, electronic, and software components into a unified prototype.
- **Validation and Testing (Months 9–10):** Functional testing, user trials, and performance evaluation.
- **Documentation (Months 1–12):** Continuous documentation of design decisions, test results, and final thesis document.

Milestones such as *Prototype Ready* are strategically placed to mark critical transitions and ensure alignment between subsystems. The modular structure of the schedule allows

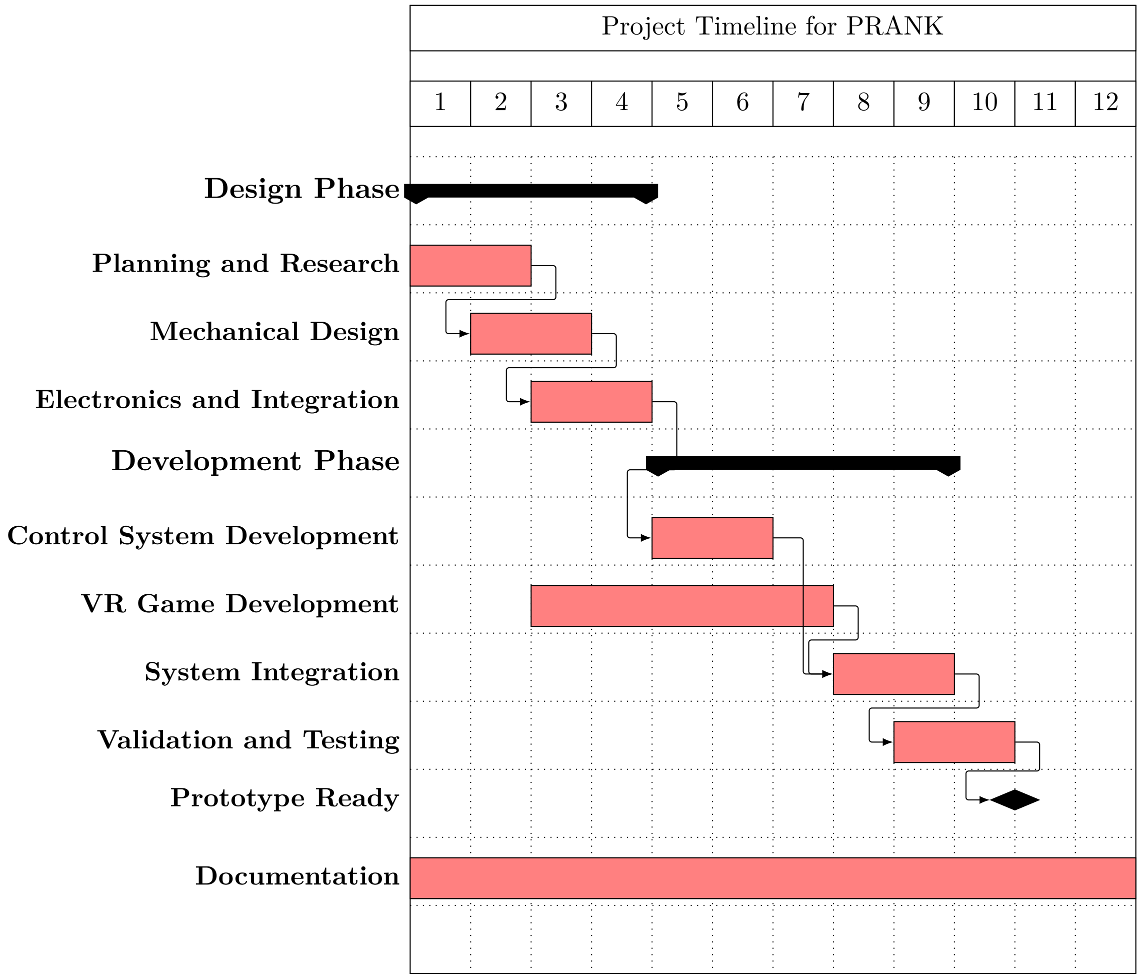

Figure 8.1: Gantt chart showing the 12-month schedule for the PRANK ankle rehabilitation robot project.

for iterative refinement and parallel task execution, particularly in the software and control domains.

This schedule serves as both a planning tool and a progress-tracking mechanism, ensuring that the project remains on track and aligned with its rehabilitation goals.

Chapter 9

PROJECT RESOURCES

This chapter outlines the technical requirements, material resources, and estimated costs associated with the development of the PRANK system (Parallel Robot for ANKle rehabilitation). It includes a detailed breakdown of mechanical components, electronic subsystems, software tools, and validation instruments necessary to construct and implement the rehabilitation platform. Additionally, the chapter provides an initial estimation of development time and budget, supporting the project's feasibility and helping guide logistical and financial planning. These projections will serve as a reference for resource allocation during the execution phase of the project.

Table 9.1: Preliminary Resource and Cost Estimation for PRANK

Category	**Description**	**Estimated Cost (USD)**
3D Printing	PLA filament, high-resolution printing (frame and joint parts)	180
Electronic Components	Microcontroller (STM32), force sensor, IMUs, wiring, connectors	500
Motors	3 × Brushless DC motors with encoders	240
Motor Drivers	Compatible drivers with current control	90
Mechanical parts	Bearings, couplings, screws, aluminum parts	100
VR Headset	Oculus/Meta Quest 2 (or equivalent)	300
Software Licenses	Unity Pro/Unreal (if needed), MATLAB/Simulink (edu license)	0–100
Validation Tools	Access to optoelectronic motion capture lab	50
Personal Labor	Estimation of 120 hours × $10/hr (development + testing)	1,200
Total Budget		**2,760**

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ANNEXES