Development and implementation of a parallel ankle rehabilitation robot: PRANK

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PROPOSAL SUMMARY SHEET

1. Date of submission of grade option: 25/04/2025
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 Evolution and Classification

Dong et al [1] conducted a comprehensive review of parallel ankle rehabilitation robots (PARRs), classifying them by mechanical architecture, actuation methods, and control strategies. Designs such as 2-UPS/RRR and 3-RRS mechanisms have been explored for their ability to replicate complex ankle movements including dorsiflexion, plantarflexion, inversion, and eversion.

Jamwal et al. [2], [3], [4] contributed significantly to the design optimization of PARRs using genetic algorithms and impedance control frameworks. Their work emphasizes workspace analysis, singularity avoidance, and compliant actuation—often achieved through pneumatic muscle actuators (PMAs).

2.2 Control Strategies and Patient Interaction

Advanced control strategies such as *adaptive impedance control* and *patient-cooperative control* have been developed to enhance safety and engagement during therapy. These approaches allow the robot to respond dynamically to patient effort, promoting active participation and neuroplastic recovery.

Li et al. [5] introduced passive compliance training to mitigate risks during early rehabilitation stages. Similarly, Zhang et al. [6] proposed a compliant ankle rehabilitation robot (CARR) with enhanced safety features.

2.3 Design Optimization and Actuation Redundancy

Multi-objective optimization techniques, including differential evolution and fuzzy inference, have been applied to improve kinematic performance and reduce mechanical complexity. Redundant actuation is often employed to avoid singularities and expand the feasible workspace, as demonstrated by Wang et al. [7] and Tsoi et al. [8].

Recent designs also incorporate series elastic actuators (SEAs) and cable-driven mechanisms to improve gait symmetry and reduce joint stress.

2.4 Integration of EMG and Machine Learning

Emerging systems integrate electromyographic (EMG) signals and deep learning models to estimate user intent and personalize therapy. These approaches enable real-time trajectory adaptation and enhance the responsiveness of the robot to voluntary muscle activity.

2.5 Clinical Validation and Home-Based Applications

Several studies have validated the efficacy of PARRs in clinical settings, showing improvements in range of motion, muscle strength, and gait symmetry. Shah Nazar and Pott [9] emphasized the need for domestic usability, proposing ARRS designs that incorporate virtual and augmented reality for increased patient motivation.

Meta-analyses comparing functional electrical stimulation (FES) and ankle-foot orthoses (AFOs) suggest that robotic systems can match or exceed traditional methods in therapeutic outcomes.

2.6 Research Gaps and Future Directions

Despite significant progress, several challenges remain:

- Compactness and portability for home use.
- Real-time adaptation to patient variability.
- Cost-effective manufacturing for broader accessibility.
- Standardized clinical protocols for robot-assisted therapy.

Future work should focus on modular, low-cost designs with integrated biosignal feedback and cloud-based data analytics. The fusion of biomechanics, control theory, and human-centered design will be key to advancing ankle rehabilitation robotics.

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, controlled via an admittance-based algorithm and integrated with a serious virtual reality game, will be capable of accurately estimating the ankle's range of motion (ROM). The ROM values derived from the system will show strong correlation and minimal deviation when compared to those obtained from a validated optoelectronic motion capture system, thereby demonstrating the feasibility of reliable kinematic assessment through the robot's onboard sensors and software.

Chapter 6

THEROTICAL FRAMEWORK

6.1 theoretical framework

6.2 Human gait

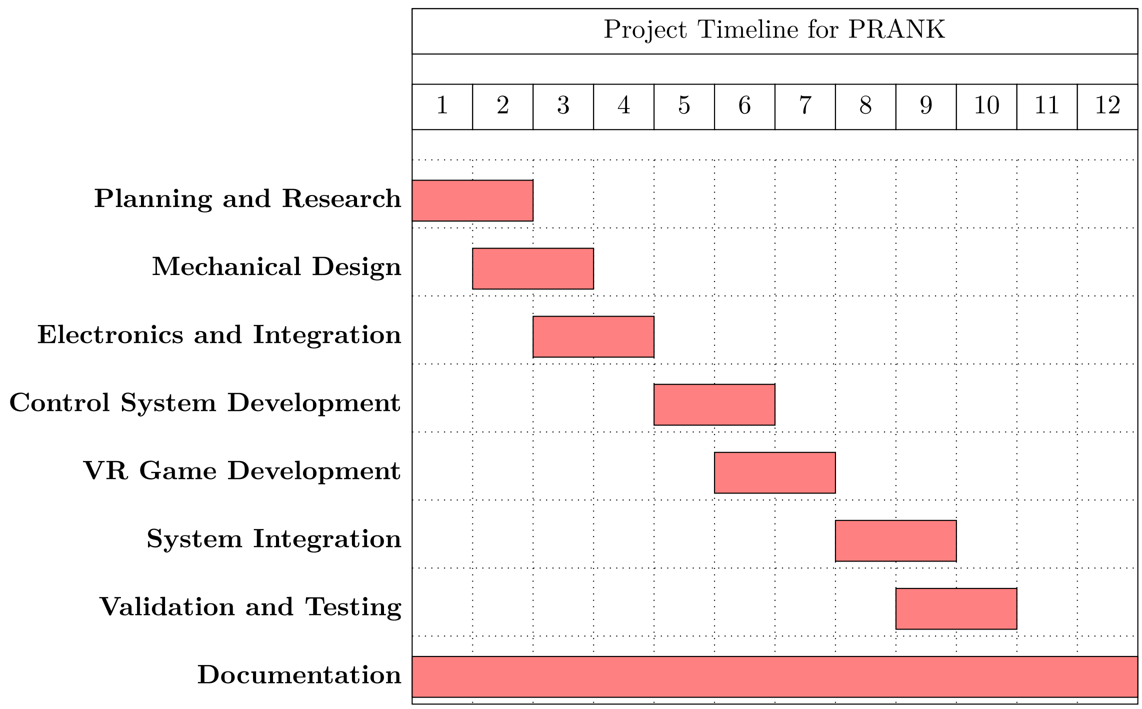
The gait analysis is carried out on the basis of the gait cycle, that can be taken as representation of person's walking patterns, and comparison of several cycles indicates the variability of the pattern **Baker2013**. The gait cycle is normalized from 0% to 100%, because each pattern have different timing, so is not objective realize a comparison between them **Medved2021**, it can be described with spatial and temporal parameters.

Chapter 7

MATERIALS AND METHODS

Chapter 8

SCHEDULE



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 $\times$ 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 $\times$ \$10/hr (development + testing)	1,200
Total Budget		**2,760**

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ANNEXES