Design, Development and Testing of Intelligent Frameworks for Ankle-Foot Prosthetics and Gait Assessment

Abstract

Lower limb prosthetic prescription and control remain challenging due to the need to balance mechanical safety, adaptive gait assistance, clinical interpretability, and evidence-based decision-making across diverse patient profiles. Existing approaches often address these aspects in isolation, resulting in fragmented systems that lack end-to-end integration from biomechatronic design to clinically accountable deployment. To address these limitations, the present work develops a unified framework for intelligent ankle foot prosthetic systems that integrates mechanical design and validation, material optimization, multimodal sensing, data-driven gait analysis, and clinically interpretable decision support. A powered ankle foot prosthesis is designed and validated through analytical modeling and finite element analysis to ensure structural integrity, load-bearing safety, and modularity for sensor and control integration. The problem related to material selection for critical components is formulated using multi-criteria decision-making techniques to systematically balance biomechanical performance, durability, manufacturability, and cost. Adaptive locomotion capability is enabled through wearable sensing and algorithmic inference, including plantar pressure-based gait phase detection, inertial sensing, and proactive environment perception. Signal processing and machine learning pipelines are developed to extract gait dynamics and user intent in real time. In parallel, a vision-based gait analysis framework using explainable deep learning models is introduced to support automated detection of gait abnormalities with interpretable attention mechanisms. To bridge engineering outputs with clinical workflows, a safety-aware clinical decision support system is proposed for evidence-based recommendations on ankle-foot prosthetics. The system employs a deterministic, rule-based policy engine grounded in curated clinical guidelines, while large language models (LLMs) are restricted to auxiliary roles, such as free-text structuring and explanation generation. This design ensures transparency, citation traceability, and clinician oversight. Quantitative evaluation using clinician-labelled vignettes and usability studies demonstrates agreement within the range of expert variability, supporting the practical feasibility. Overall, the proposed framework establishes a clinically responsible pathway that connects prosthetic hardware design, intelligent sensing and control, explainable artificial intelligence, and evidence-based clinical decision-making, contributing to next-generation prosthetic systems that are adaptive, interpretable, and suitable for real-world deployment.

Keywords: Ankle foot prosthesis; biomechatronic system design; finite element analysis; multi-criteria decision making; wearable sensing; gait analysis; explainable artificial intelligence; clinical decision support systems.