Modular Prosthetic Ankle-Foot Design for K2 Ambulation

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Introduction

Individuals with lower-limb amputations rely on prosthetic devices to restore mobility and independence.

- Prosthesis prescription is commonly guided by the Medicare Functional Classification Levels, which range from non-ambulatory (K0) to high-impact athletes (K4).
- **K2-level ambulation** is characterized by low-activity walking such as level-ground gait and minor environmental barriers.

Figure 1. This figure displays the Medicare Functional Classification Levels from K0-K4.

Human walking is described by the gait cycle. This project focuses on analyzing structural performance during the key phases of stress during gait:

- **Stance**: Body weight is balanced over the stationary foot
- **Toe-off:** Foot pushes the body forward, with only the toes touching the ground

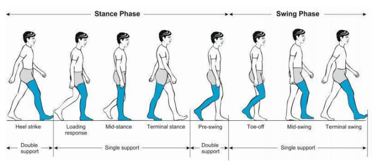


Figure 2. This figure displays the phases of the normal gait cycle.

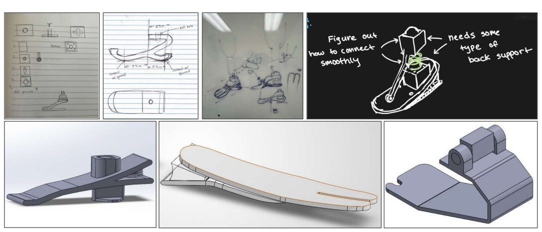
Objective

This project proposes a modular, axial foot-ankle prosthetic to improve adaptability and structural reliability for K2 users.

Methods

Computer-aided design (CAD) and static Finite Element Analysis (FEA) were performed on SOLIDWORKS to evaluate performance and identify potential failure points before building physical prototypes.

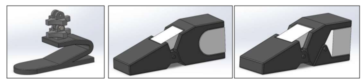
- Designs were tested under simulated conditions during the stance and toe-off phases of gait for a maximum body weight of 200 lb (91 kg).
- Material properties of PLA-CF and EVA foam were assigned to the prosthetic components



Multiple concept sketches were created to explore a range of geometric configurations.

These concepts were then modeled in SOLIDWORKS to visualize each design in 3D and evaluate their feasibility before simulation and further refinement. FEA results then prompted iterative modifications to the designs.

Results



Three design concepts were composed following research surrounding the gait cycle and its movements along with material research to ensure optimal comfort, durability, and functionality.

Design One

Design One offered *cost-effective materials* and mechanical components with *simple fabrication methods* to provide an affordable prosthetic solution.

However, this design had some errors found within further investigation using FEA:

- These findings identified the heel region as a critical area for reinforcement and informed subsequent design iterations.

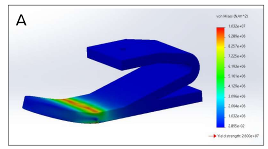


Figure 3A. Toe-off Phase Simulation
- Design is capable of withstanding forces involved in toe-off
  - However the design undergoes a lot of *deformation*

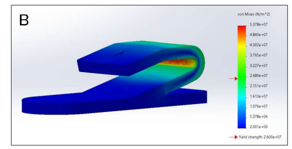


Figure 3B. Stance Phase Simulation
- Revealed stress values that exceeded the material's yield strength
  - *Peak stresses* occur at the *bend of the foot* in the heel region.

Design Two

Design Two separates the foot into two components connected by a hinge to allow controlled bending. An EVA foam insert between the primary structural members is also introduced, allowing it to reduce rigid stress between the components.

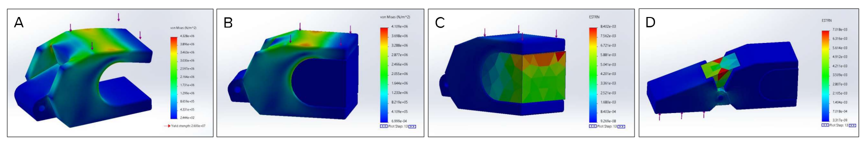


Figure 4A. No foam: Stance
- Elevated stresses are concentrated along the upper curved surface of the heel

Figure 4B. With foam: Stance
- Elevated stresses are still present with the foam insert
- Similar stress concentrations as in **Figure 4A**

Figure 4C. With foam: Stance
- *Strain* occurs within the foam heel insert
- Foam compresses and absorbs applied load

Figure 4D. With foam: Toe-off
- Foam compresses and absorbs applied load
- Low *strain concentration* at the hinge joint

FEA results revealed structural limitations that prompted the development of Design Three. During the stance phase, elevated von Mises stresses were observed along the curve of the heel. Even with foam, these concentrated stresses were still present.

Design Three

Design Three builds upon the second iteration by introducing an additional hinge at the heel to improve load transfer into the foam during stance. This modification focuses on optimizing how body weight is transmitted through the heel.

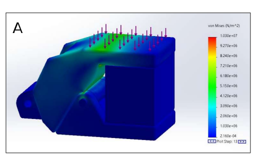


Figure 5A. Stance: Stress Analysis
Stress is primarily distributed along the upper member, remaining in low stress ranges.
- Smoother stress gradients compared to **Figure 4B**
- Indicates an improvement in load sharing and reduced stress concentration

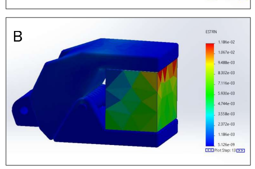
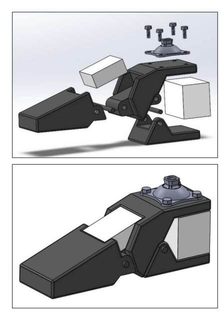


Figure 5B. Stance: Strain Analysis
Highest strain occurs within the foam block (green to red regions).
- Confirms that the foam is actively compressing under load
- PLA components exhibit relatively low strain, indicating a maintained stiffness



Overall, Design Three improves the heel's performance under stance by enhancing load transfer and energy absorption into the foam.

Future Work

Overall, this project tackles a real world problem with engineering.

We have accomplished an early-stage exploration of a modular ankle-foot prosthetic system for K2 ambulation, using *computational analysis* to compare design versions and materials.

The results aim to reduce development risk and guide future fabrication and mechanical bench testing.

Future Work

Expansion upon limitations of the current prototype:

PLA-CF and EVA foam were selected for initial modeling based on their ease of access and affordability.

This design can easily be 3D printed using this material!

Future iterations of this prototype will implement materials such as aluminum or fiber reinforced polymers, improving:

- Fatigue performance
- Bearing strength

Fabrication of the design with implementation of new materials will consist of:

- CNC machining for metallic parts
- Injection molding or composite layup processing for fiber-reinforced composites

Following fabrication, *mechanical bench* testing will be utilized to validate FEA analysis.

- *Compression testing* will evaluate the structural strength, stiffness and deformations at peak loading
- *Cyclic loading* will assess durability of the hinges and selected materials.

Ultimately, this foot is designed to be a part of a complete transtibial prosthetic, implementing an adjustable pylon and socket, and expanding the target population to individuals with amputations below the knee.

References

Figure 1. Figure from Zepeda. Demystifying K-Levels for Prosthetics: Understanding your Mobility. 2023

Figure 2. Figure from Pirker, Walter, and Regina Katzenschlager. Gait Disorders in Adults and the Elderly: A Clinical Guide. 2017

Figure 6. Figure from Lee Childers and Wurdeman. Transtibial Amputation: Prosthetic Management. 2025