

# Dynamic Biomechanical and Load Analysis of a Modular Prosthetic Foot for Active Transfemoral Prosthetic Systems

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**Abstract** - This study presents the dynamic analysis and experimental validation of a modular prosthetic foot designed for integration within an active transfemoral robotic prosthesis (SmartLeg). The work focuses on quantifying the time-dependent biomechanical response of the foot during gait and stair approach, with emphasis on load transfer, energy absorption, and propulsion. The proposed design features a segmented structure with an articulated forefoot, enabling controlled dorsiflexion and improved replication of physiological foot behavior. Dynamic performance was evaluated using finite element analysis (FEA) under representative loading conditions and experimental plantar pressure measurements obtained via a Zebris system. Ground reaction force profiles were normalized to body weight and analyzed across the stance phase. Statistical analysis using repeated-measures ANOVA indicated no significant difference in early stance loading between walking and stair approach ( $p > 0.05$ ). However, late stance propulsion forces were significantly higher during stair initiation ( $p < 0.001$ ), with a mean increase of 0.61 F/G (95% CI [0.52, 0.70]). The results demonstrate that the prosthetic foot exhibits stable dynamic behavior and sufficient structural reliability. Moreover, forefoot pressure patterns provide a robust indicator of locomotion intent, supporting the development of predictive, sensor-driven control strategies for adaptive prosthetic systems.

**Keywords:** Active prosthesis; prosthetic foot; dynamic analysis; gait biomechanics; plantar pressure; finite element analysis; adaptive control.

## I. INTRODUCTION

Restoring natural locomotion in transfemoral amputees requires prosthetic systems capable of reproducing not only kinematic motion but also the dynamic interaction between the limb and the ground [1,2]. Conventional passive prosthetic feet provide limited adaptability, particularly during high-demand tasks such as stair ascent, where force generation and timing are critical.

Recent advances in active prosthetic systems have enabled powered joint actuation and adaptive control; however, the **dynamic behavior of the prosthetic foot remains a limiting factor**. The foot governs ground reaction force (GRF) transmission, shock absorption, and propulsion, making it central to gait stability and efficiency.

This study focuses on the **dynamic analysis of a novel prosthetic foot**, integrating structural design, finite element modeling, and experimental validation. The objective is to characterize force-time distributions and identify biomechanical markers relevant for control and optimization.

The SmartLeg system is an active lower-limb prosthesis incorporating powered knee and ankle joints driven by linear actuators. These actuators provide controlled torque generation, enabling assistance during walking and stair climbing.

The control architecture combines sensor feedback with machine learning algorithms to adapt gait patterns in real time. Inputs include joint position, load measurements, and terrain estimation. Within this system, the prosthetic foot acts as the **primary interface for dynamic load exchange**, directly influencing control performance [4,5].



Figure 1: Modified above-knee prosthetic device

Within this framework, the prosthetic foot plays a critical role as the primary interface between the user and the ground, directly influencing gait dynamics, shock absorption, and propulsion [5,6].

## II. PROSTHETIC FOOT DESIGN FOR DYNAMIC PERFORMANCE

### 2.1 Biomechanical Motivation

Conventional prosthetic designs often assume a simplified collinear alignment between the foot, pylon, and knee joint. However, the human lower limb exhibits complex anatomical offsets and segment orientations, which are essential for efficient and natural gait.

Failure to replicate these biomechanical characteristics leads to asymmetric loading, reduced comfort, and increased metabolic cost. Therefore, the present design aims to introduce anatomical realism through structural segmentation, compliant elements, and adjustable alignment via modular interfaces [2,3].

### 2.2 Structural Configuration

The proposed prosthetic foot (Figure 2) consists of three functional layers:

**Elastic Support Layer:** Functions as a shock absorber during heel strike and load acceptance. The geometry incorporates a thicker heel region to emulate physiological impact attenuation and energy dissipation.

**Structural Skeleton:** Composed of a lightweight metallic framework (Al 2024 alloy) ensures load-bearing capacity.

**Articulated forefoot:** The structure is divided into rear foot and forefoot segments. Elastic forefoot enables dorsiflexion up to 30°.



Figure 2: Look of the prosthetic foot

### 2.3 Ankle Joint and Load Transmission

The ankle joint connects the foot to the prosthetic leg via a powered hydraulic actuator. Unlike rigid designs, this joint enables dynamic adaptation to ground reaction forces, reducing destabilizing moments.

The joint position is offset medially (30–35% of foot width) to better approximate anatomical alignment and improve load distribution.

### 2.4 Modular Adapter Integration

A standardized prosthetic adapter was incorporated to enable multi-planar alignment and modularity. This allows:

- Adjustment of foot orientation relative to the user in both sagittal and frontal planes
- Interchangeability of prosthetic feet, significantly increasing system versatility
- Improved alignment with the contralateral limb

Standard commercially available adapters (e.g., pyramid adapters) were incorporated to reduce manufacturing complexity and cost (Figure 3).

To accommodate the adapter, the foot design was reconfigured by separating the connection interface into an independent linking element. This modification preserved all functional characteristics while ensuring compatibility with standardized components.

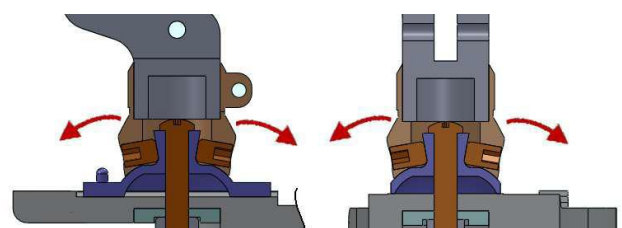


Figure 3: Angle adjustment in sagittal and frontal plane using adapter

## III. DYNAMIC FINITE ELEMENT ANALYSIS

Dynamic structural behavior was evaluated using finite element analysis (FEA) in SolidWorks Simulation.

### 3.1 Modeling Strategy and Assumptions

To evaluate the structural performance of the prosthetic foot under realistic operating conditions, a finite element analysis (FEA) was conducted with emphasis on **dynamic load transfer during gait** (Figure 4). Although implemented within a quasi-static simulation framework, the loading scenarios were defined to represent critical phases of the stance cycle, thereby approximating transient biomechanical behavior [7-11].

Dynamic Modeling of Prosthetic Foot

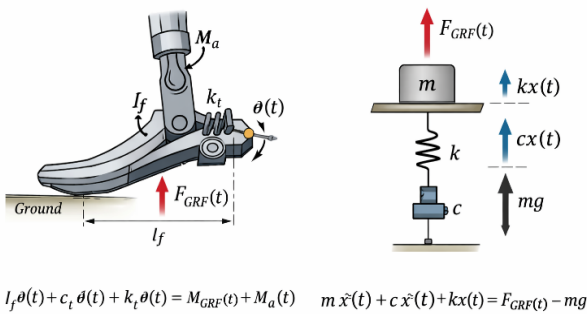


Figure 4: Dynamic model of the prosthetic foot

The prosthetic foot geometry was developed from the CAD model and discretized using a high-resolution tetrahedral mesh (Figure 5). Mesh refinement was applied in regions of expected stress concentration, particularly:

- The forefoot articulation joint
- The ankle connection interface
- Transition zones between structural segments

Material properties were assigned assuming isotropic linear elasticity. The primary load-bearing structure was modeled using **Al 2024 aluminum alloy**, characterized by a high strength-to-weight ratio suitable for dynamic applications. Contact interactions between components were simplified using bonded interfaces, while joint motion was constrained according to design limits.

Prosthetic Foot Geometry and Tetrahedral Mesh Discretization

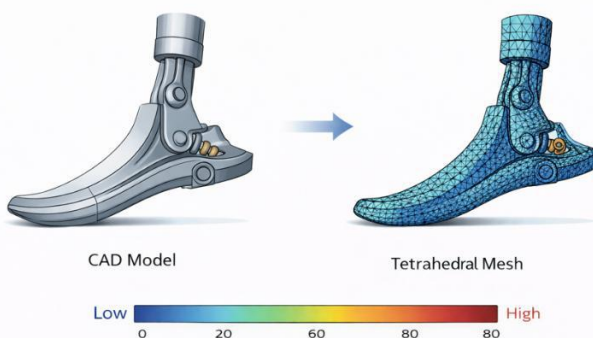


Figure 5: CAD model and discretized using a high-resolution tetrahedral mesh

### 3.2 Dynamic Loading Conditions

To capture the dynamic nature of human gait, multiple loading scenarios were defined based on biomechanical data for ground reaction forces (GRFs). These scenarios correspond to key phases of the stance period (Figure 6):

1. **Initial Contact (Heel Strike):**
  - Vertical impact force applied at the heel region
  - Represents rapid load transfer upon ground contact
2. **Mid-Stance:**
  - Distributed load across the plantar surface
  - Simulates full body weight support
3. **Terminal Stance (Push-Off):**
  - Concentrated force applied at the forefoot
  - Represents peak propulsion forces
4. **Stair Ascent Condition:**
  - Increased forefoot loading with forward-directed force components
  - Represents elevated mechanical demand during vertical displacement

All loads were scaled to a **reference body mass of 100 kg**, providing a conservative safety margin relative to the average user. Boundary conditions were defined such that the ankle joint interface was constrained in accordance with actuator attachment, while allowing rotational freedom consistent with dorsiflexion and plantarflexion limits.

Stress Distribution in Prosthetic Foot During Stance Period

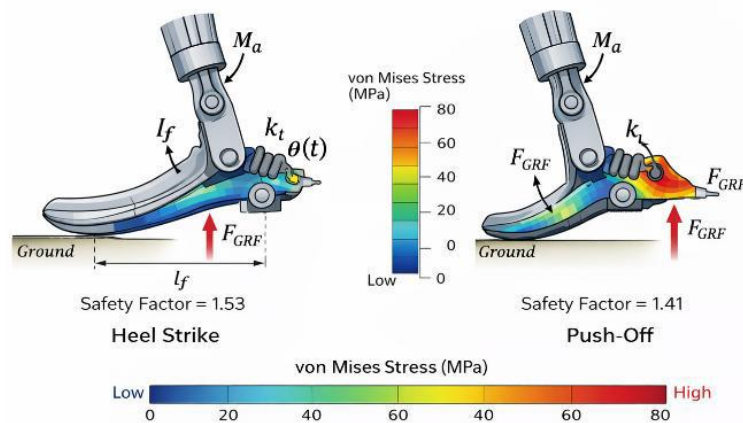


Figure 6: Stress distribution in prosthetic foot during stance period

### 3.3 Stress Distribution and Structural Response

The simulation results reveal that stress distribution within the prosthetic foot is strongly dependent on the phase of loading (Figure 7):

- **Heel Strike:** Stress is localized in the posterior region of the foot, with moderate magnitudes due to the energy-absorbing properties of the elastic base.
- **Mid-Stance:** Load is distributed more uniformly across the structure, resulting in relatively low stress gradients and minimal deformation.
- **Push-Off (Terminal Stance):** The highest stress concentrations occur in the **forefoot region**, particularly near the articulation joint and structural transition zones.

This distribution confirms that the forefoot is the primary load-bearing component during propulsion, consistent with experimental plantar pressure findings. Importantly, stress levels remained below critical thresholds in all simulated conditions.

Dynamic Finite Element Analysis (FEA) of Prosthetic Foot

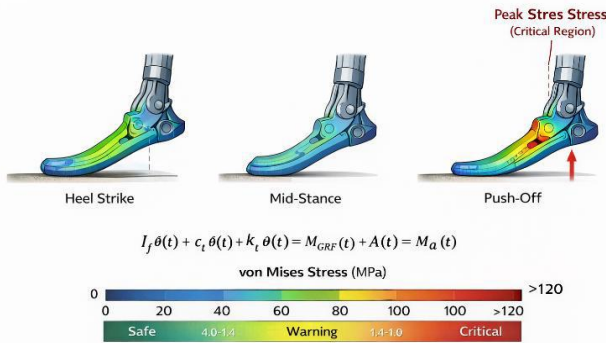


Figure 7: Dynamic finite element analysis of prosthetic foot

### 3.4 Deformation and Dynamic Compliance

Deformation analysis indicates that the prosthetic foot exhibits **controlled flexibility**, primarily in the forefoot segment. Maximum displacement occurs during push-off, where the articulated design allows angular deflection within the predefined limit ( $\sim 30^\circ$ ).

This behavior is essential for:

- **Energy absorption during early stance**
- **Energy release during late stance**
- **Smoothing of force transmission to the user**

The torsional spring integrated into the forefoot joint contributes to this compliance by providing resistance and restoring force, effectively acting as a **passive energy storage mechanism**.

The deformation patterns observed in FEA align with the experimentally measured increase in forefoot loading, reinforcing the role of this region in dynamic gait adaptation.

### 3.5 Safety Factor and Structural Integrity

The minimum factor of safety (FoS) for the prosthetic foot ranged from **1.41 to 1.65** under peak loading conditions. These values indicate that the structure operates within acceptable limits while maintaining a balance between strength and weight.

For the prosthetic pylon, higher stress concentrations were observed due to its geometric constraints and load-bearing role. Reinforcement of the pylon structure resulted in:

- **FoS  $\approx 2.25$  under nominal conditions**
- **FoS  $\approx 1.15$  under extreme loading scenarios**

Although the lower bound approaches critical limits, these extreme conditions exceed typical physiological loads, confirming that the design remains safe for practical use.

### 3.6 Correlation with Experimental Dynamics

A key outcome of the analysis is the strong correlation between simulated stress patterns and experimentally observed force distributions:

- Peak stresses in the forefoot correspond to **maximum plantar pressures ( $F_2$ )**
- Temporal alignment of loading phases matches the **force-time profile from gait measurements**

This agreement validates the modeling approach and confirms that the FEA captures the essential aspects of dynamic behavior.

### 3.7 Design Implications and Optimization Potential

The results highlight several important design considerations:

- The **forefoot region is the critical zone** for both stress and dynamic performance
- Controlled compliance improves energy transfer without compromising safety
- Structural reinforcement should focus on joint interfaces and transition regions

Future optimization may include:

- Use of **composite materials (e.g., carbon fiber)** for improved fatigue resistance
- Refinement of joint stiffness to better tune energy return
- Integration of **sensor elements within high-load regions** for real-time monitoring

## IV. RESULTS AND DYNAMIC ANALYSIS

### 4.1 Force–Time Profile Characterization

The normalized ground reaction force (GRF) profiles obtained from plantar pressure measurements exhibit the characteristic double-peak structure associated with human gait. These peaks correspond to distinct biomechanical phases within the stance period:

- **First peak ( $F_1$ ):** Initial loading response (weight acceptance phase)
- **Second peak ( $F_2$ ):** Terminal stance (propulsion phase)

Across all subjects and conditions, the temporal evolution of GRF remained consistent in shape, indicating that the prosthetic system preserves the fundamental structure of gait dynamics. However, notable differences emerge in the **magnitude and distribution of forces**, particularly in late stance.

The first peak occurred at approximately **23–26% of the stance phase**, reflecting rapid load transfer immediately following heel strike. The second peak occurred at approximately **79–82% of stance**, corresponding to push-off dynamics.

#### 4.2 Comparative Analysis of Locomotion Conditions

A direct comparison between level walking and pre-stair ascent reveals that:

- The **first peak force ( $F_1$ )** shows minimal variation between conditions
- The **second peak force ( $F_2$ )** exhibits a substantial increase during stair approach

Quantitatively, the increase in  $F_2$  ( $\Delta F_2 \approx 0.61$  F/G) represents a **~50% increase in propulsion demand**, indicating a significant shift in mechanical requirements prior to stair ascent.

This behavior reflects anticipatory biomechanical adaptation, where the user increases forefoot loading to prepare for vertical displacement.

#### 4.3 Statistical Robustness and Variability

To assess statistical significance, a repeated-measures ANOVA was conducted with locomotion condition as the independent variable.

- **$F_1$** : No statistically significant difference ( $p > 0.05$ ), confirming consistency in early stance mechanics
- **$F_2$** : Highly significant difference ( $p < 0.001$ ), indicating strong dependence on locomotion mode

The associated **95% confidence interval for  $\Delta F_2$  [0.52, 0.70]** demonstrates low variability and high reliability of this effect across subjects.

Furthermore, the coefficient of variation (CV) for  $F_2$  remained below 7%, suggesting that the observed increase is not only statistically significant but also biomechanically stable.

#### 4.4 Spatial Pressure Distribution Analysis

Beyond temporal dynamics, spatial analysis of plantar pressure revealed a consistent migration of peak loading toward the **forefoot region** during late stance.

During level walking:

- Pressure distribution is relatively balanced between midfoot and forefoot

During stair approach:

- Peak pressure is strongly concentrated at the **metatarsal region**

This shift indicates a transition from passive load support to **active propulsion generation**, with the forefoot acting as the primary force transmission interface.

Importantly, this spatial redistribution occurs **prior to foot-off**, suggesting its suitability as an early indicator of locomotion intent.

#### 4.5 Dynamic Energy Transfer Mechanisms

The observed force patterns can be interpreted in terms of energy storage and release:

- During early stance, energy is absorbed through elastic deformation of the heel and midfoot structures
- During late stance, this stored energy is partially released through forefoot dorsiflexion and push-off

The articulated forefoot design contributes to this mechanism by allowing controlled angular displacement, effectively acting as a **passive energy return system**.

FEA results support this interpretation, showing localized deformation in the forefoot region under peak loading conditions. This confirms that the structural design facilitates dynamic compliance without compromising integrity.

#### 4.6 Implications for Prosthetic Control and Intent Recognition

The strong and consistent increase in  $F_2$ , combined with its spatial localization, provides a reliable feature for real-time control systems.

Specifically:

- The **magnitude of  $F_2$**  can be used as a threshold-based trigger
- The **timing (~80% stance)** provides a predictable activation window

- The **forefoot location** informs optimal sensor placement

These characteristics enable the development of **predictive control strategies**, where the prosthetic system anticipates user intent (e.g., stair ascent) before execution.

Such predictive capability is essential for active prostheses, as it reduces response latency and improves coordination between user and device.

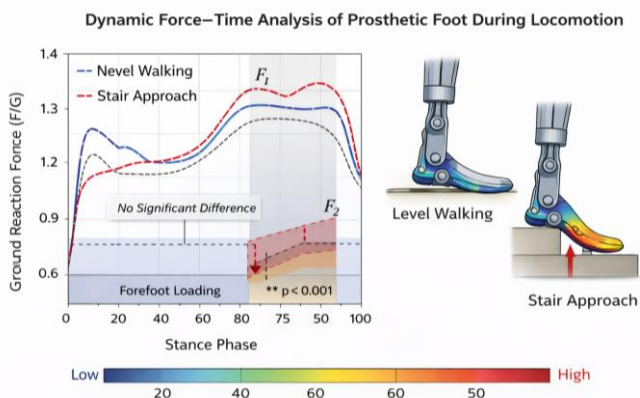


Figure 8: Dynamic force-time analysis of prosthetic foot during locomotion

#### 4.7 Integration with SmartLeg System Dynamics

Within the SmartLeg architecture, the prosthetic foot serves as a **sensor-rich interface** for dynamic interaction. The identified force-time features can be directly integrated into control loops governing:

- Ankle actuation timing
- Knee flexion assistance during ascent
- Transition between locomotion modes

By leveraging these dynamic signals, the system can shift from reactive to **adaptive and anticipatory control**, significantly improving functional performance.

### V. DISCUSSION AND CONCLUSION

The integration of structural design and dynamic analysis demonstrates that prosthetic foot performance must be evaluated beyond static criteria. The observed increase in late stance force highlights the importance of **energy transfer mechanisms and controlled deformation**.

Compared to rigid prosthetic feet, the proposed design allows:

- More natural load progression
- Reduced impact forces
- Enhanced propulsion efficiency

These characteristics are essential for active prosthetic systems relying on real-time control.

This study presented a comprehensive dynamic analysis of a modular prosthetic foot within an active transfemoral prosthetic system.

Key findings include:

- Stable structural performance under dynamic loading
- Significant increase in propulsion forces during stair approach
- Forefoot pressure as a reliable indicator of locomotion intent

The results support the integration of dynamic biomechanical metrics into prosthetic design and control. Future work will focus on real-time implementation of intent recognition algorithms and large-scale clinical validation.

### REFERENCES

- [1] Jelačić, Z, Dedić, R, Dindo, H (2020) Active above-knee prosthesis. *Elsevier Academic Press*, ISBN 978-0-12-818683-1
- [2] D. A. Winter, *Biomechanics and Motor Control of Human Movement*, 4th ed. Hoboken, NJ, USA: Wiley, 2009.
- [3] J. Perry and J. M. Burnfield, *Gait Analysis: Normal and Pathological Function*, 2nd ed. Thorofare, NJ, USA: SLACK Incorporated, 2010.
- [4] B. J. Hafner, D. J. Sanders, J. Czerniecki, and J. Fergason, "Energy storage and return prostheses: Does patient perception correlate with biomechanical analysis?," *Clinical Biomechanics*, vol. 17, no. 5, pp. 325–344, 2002.
- [5] H. Herr and A. M. Grabowski, "Bionic ankle-foot prosthesis normalizes walking gait for persons with leg amputation," *Proceedings of the Royal Society B: Biological Sciences*, vol. 279, no. 1728, pp. 457–464, 2012.
- [6] S. K. Au, M. Berniker, and H. Herr, "Powered ankle-foot prosthesis to assist level-ground and stair-descent gaits," *Neural Networks*, vol. 21, no. 4, pp. 654–666, 2008.
- [7] F. Sup, A. Bohara, and M. Goldfarb, "Design and control of a powered transfemoral prosthesis," *The International Journal of Robotics Research*, vol. 27, no. 2, pp. 263–273, 2008.
- [8] P. M. Quesada, L. A. Skinner, and S. J. Hanson, "Finite element analysis of a prosthetic foot during normal walking," *Journal of Rehabilitation Research and Development*, vol. 47, no. 8, pp. 771–780, 2010.

- [9] S. Portnoy, A. Gefen, et al., "Finite element modeling of the human foot for plantar pressure estimation," *Journal of Biomechanics*, vol. 42, no. 10, pp. 1486–1492, 2009.
- [10] A. Gefen, "Plantar soft tissue loading under the medial metatarsals in the standing diabetic foot," *Medical Engineering & Physics*, vol. 25, no. 6, pp. 491–499, 2003.
- [11] M. Hanlon and R. Anderson, "Real-time gait event detection using wearable sensors," *IEEE Transactions on Biomedical Engineering*, vol. 56, no. 1, pp. 105–113, 2009.

#### AUTHOR'S BIOGRAPHY



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