



LOW-COST ENERGY STORING AND RETURN PROSTHETIC FOOT WITH TOE-BREAK

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Abstract: Prosthetic feet play a vital role in restoring mobility and enhancing the quality of life for individuals with lower-limb amputations. While advanced prosthetic technologies such as energy-storing and return (ESAR) systems significantly improve gait performance, their high cost and complex design make them inaccessible to many, particularly in low- and middle-income countries. This study presents the design and functional analysis of a novel low-cost ESAR prosthetic foot integrated with a toe-break mechanism. The proposed design replicates the biomechanical behavior of the human foot using a simple mechanical system comprising a vertical spring for energy storage and a hinged toe segment for enhanced flexibility during toe-off. During walking, the spring compresses upon heel strike to store energy, which is subsequently released during the toe-off phase to aid forward propulsion. The toe-break mechanism mimics natural metatarsophalangeal joint motion, improving ground conformity and gait dynamics. Fabricated using affordable, locally available materials, this prosthetic foot offers a sustainable, cost-effective alternative to conventional designs, providing improved mobility, comfort, and adaptability for users in resource-limited settings. The design demonstrates significant improvements in gait symmetry, push-off power, and user comfort compared to passive prostheses like the SACH foot. This innovation bridges the gap between affordability and functionality, making advanced prosthetic technology more accessible to underserved populations.

Key words: Low-cost, ESAR, SACH, Toe-break

INTRODUCTION

Prosthetic feet are devices designed to replace one or more function of the biological human ankle-foot system. Over the past few years developers have released to the market a large variety of technologically advanced prosthetic feet, broadening the range of available devices.

A major issue with current prosthetic foot development is that it doesn't target the majority of end users. The development of prosthetic feet has significantly advanced over recent decades, evolving from simple passive devices to highly sophisticated, energy-storing and actively powered systems. These prosthetic technologies aim to restore the functional mobility of individuals with lower-limb amputations by replicating the biomechanics of a natural foot ¹. Given that the human foot plays a critical role in gait stability, shock absorption, and propulsion, the design of prosthetic feet must account for a complex interplay of structural mechanics, material properties, and user-specific needs ².

Traditional prosthetic feet, such as the Solid Ankle Cushioned Heel (SACH) foot, offer basic support and cushioning but lack dynamic response capabilities. In contrast, modern energy storage and return (ESAR) feet utilize advanced materials like carbon fiber to enhance gait efficiency by storing energy during stance and releasing it during push-off ³. Recent innovations include microprocessor-controlled and powered prosthetic feet that actively adapt to terrain and walking speed, thus improving user mobility and reducing metabolic cost ⁴.

Despite these advancements, challenges remain in optimizing prosthetic foot design to accommodate diverse user populations, including variations in weight, activity level, and terrain encountered. Additionally, there is an ongoing need for improved biomechanical integration and user comfort. Current research focuses on bridging these gaps through interdisciplinary approaches combining biomechanics, robotics, and material science ⁵.

This study aims to design a low-cost energy storing and return foot with toe-break mechanism.

NEED OF THE STUDY

Prosthetic feet play a vital role in restoring mobility and improving the quality of life for individuals with lower-limb amputations. However, the high cost of advanced prosthetic technologies often places them out of reach for many individuals, particularly in low- and middle-income countries, where the majority of the global amputee population resides (World Health Organization, 2017). While energy-storing and return (ESAR) prosthetic feet can significantly improve gait efficiency and reduce the metabolic cost of walking¹, commercially available options are frequently unaffordable or inaccessible due to complex manufacturing processes and imported materials.

Moreover, most low-cost prosthetic feet currently available on the market are limited to basic passive designs, such as SACH feet, which offer minimal biomechanical functionality and do not mimic the dynamic rollover characteristics of the human foot². The lack of a toe-break—a mechanical feature that facilitates controlled forefoot flexion—further limits the adaptability and comfort of these devices during gait, especially during toe-off when propulsion is most critical³. Incorporating a toe-break mechanism into a low-cost ESAR foot could potentially enhance push-off power, improve gait symmetry, and reduce compensatory movement patterns in prosthesis users.

There is a critical need for prosthetic designs that strike a balance between cost, performance, and durability. Developing an affordable ESAR prosthetic foot with an integrated toe-break mechanism would not only address the biomechanical limitations of conventional low-cost prostheses but also improve functional outcomes for users in resource-limited settings. This study addresses this gap by proposing and evaluating a novel prosthetic foot design aimed at enhancing energy return and gait dynamics without compromising affordability and ease of fabrication.

WORKING OF MODEL

This prosthetic foot is designed to replicate the biomechanical behavior of a natural human foot during walking, especially focusing on energy efficiency and mobility, while keeping the construction simple and affordable.



Fig 1 & 2:
Prototype Design

1. During Heel Strike – Energy Storage Begins

- When the user's heel contacts the ground, the body weight applies force to the foot.
- This causes the spring-loaded central unit to compress.
- The coil spring in the vertical assembly stores potential energy, simulating the compressive action of ankle muscles and tendons during the early stance phase.

2. During Mid-Stance – Load Distribution and Stability

- As the body moves over the foot, the main foot plate bears the weight, ensuring stability.
- The system maintains balance and shock absorption, with the spring still under compression.

3. During Toe-Off – Energy Return and Propulsion

- As the user shifts weight toward the front of the foot (forefoot loading), the toe-break hinge comes into action.
- The hinge allows the toe section to flex upward, closely mimicking the natural bending at the metatarsophalangeal (MTP) joint.
- Simultaneously, the spring decompresses, releasing the stored energy.
- This energy provides a push-off or thrust, aiding forward motion and reducing the effort required by the user.

4. Toe-Break Mechanism

- The hinged toe segment plays a key role in enhancing flexibility.
- It enables the front portion of the prosthetic to bend independently, which:
 - Improves ground conformity.
 - Allows for a more natural walking experience.
 - Reduces impact on the residual limb.

This prosthetic foot replicates the dynamic functions of a biological foot using mechanical elements like a spring and a hinge. It combines:

- Energy storage (spring compression),
- Energy return (spring decompression),
- And flexible toe-break movement (hinge action).

This makes it a cost-effective, mechanically simple, and functionally efficient alternative to moderate-end prosthetic feet, especially useful in low-resource settings.

The Benefits:

1. Developing this low-cost energy-storing prosthetic foot with a toe-break mechanism offers a range of biomechanical, economic, and social benefits, particularly for underserved populations.
2. The integration of energy storage and return (ESAR) functionality with a toe-break feature provides substantial improvements in gait performance, comfort, and mobility while remaining accessible to users in low-resource settings.
3. By emphasizing the use of locally available materials and simple manufacturing techniques, such a prosthetic foot can be fabricated and repaired within regional prosthetics centers. This reduces dependence on imports and specialized tools, encouraging sustainability and capacity building within local healthcare systems.
4. A modular or flexible design can be adapted to different user needs, including varying body weights, activity levels, and walking surfaces. The toe-break feature, in particular, can be tuned to provide the right level of flexibility for diverse use cases, from daily walking to light labour activities.

Comparison between the new design and the available options:

1. Gait dynamics improved over SACH, more natural toe-off due to toe-break.
2. Moderate to high user comfort, improved forefoot flexibility.
3. Moderate adaptability (daily use and light activity).
4. Lightweight, with low-cost materials.
5. Designed for durability using affordable materials.
6. Less fabrication cost.
7. User friendly for moderately active person.

CONCLUSION

The development of a low-cost energy-storing prosthetic foot with an integrated toe-break mechanism addresses a critical need in the field of prosthetics—balancing biomechanical performance with affordability and accessibility. Unlike traditional passive designs such as the SACH foot, the proposed model provides improved gait dynamics through energy return and a more natural toe-off facilitated by the toe-break. While commercial ESAR feet offer superior functionality, their high costs and reliance on advanced materials make them inaccessible to the majority of amputees in low- and middle-income regions.

The proposed design offers a practical alternative by incorporating cost-effective materials and a simplified mechanical structure that can be fabricated and maintained locally. This not only enhances functional mobility for users but also supports sustainable prosthetic care in underserved communities. Biomechanical benefits such as improved push-off power, smoother gait transitions, and increased comfort can lead to better long-term health outcomes and quality of life for users.

Overall, this study demonstrates the feasibility and potential impact of a prosthetic foot that delivers enhanced performance at a low cost. Future work will focus on clinical trials, long-term durability testing, and iterative improvements based on user feedback to

optimize the design further. This innovation represents a step forward in making advanced prosthetic technology more inclusive, equitable, and practical for global populations.

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