Development of a Ligament-Mimetic Compliant Joint for Low-Cost 3D-Printed Ankle-Foot Orthoses (AFO)

Riset Internasional (RI-19)

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Background & Research Context

Ankle-Foot Orthoses (AFOs) are widely used to assist individuals with gait impairments, particularly those experiencing foot drop. Conventional AFOs provide ankle stability and dorsiflexion assistance; however, rigid structures and conventional mechanical hinges may restrict natural ankle movement, increase mechanical complexity, and reduce user comfort.

The development of 3D-printed AFOs offers opportunities for lightweight, customized, and cost-effective rehabilitation devices. However, achieving controlled ankle motion while maintaining sufficient structural stability remains a significant engineering challenge

This research focuses on developing a ligament-mimetic compliant joint using a rotational bistable mechanism to provide controlled ankle movement through elastic deformation without conventional mechanical hinges.

Keywords: Ankle-Foot Orthosis (AFO), Compliant Mechanism, Rotational Bistability, Snap-Through, Finite Element Analysis.

Objectives & Proposed Solutions

This research aims to develop a 3D-printed rotational bistable hinge for ankle-foot orthoses through a compliant mechanism approach.

The proposed solutions include:

Compliant Joint Development: Designing a rotational bistable mechanism capable of providing controlled angular movement through elastic deformation.

Computational Investigation: Employing Finite Element Analysis (FEA) to evaluate deformation, stress distribution, torque response, and snap-through behavior.

Geometrical Optimization: Investigating the influence of design parameters, particularly fin thickness and geometric configuration, on rotational stiffness and mechanical performance.

The proposed approach is expected to provide a lightweight and integrated joint structure with controlled rotational behavior, supporting the development of more adaptable 3D-printed AFOs.

Methods & Implementation

The research combines mechanism design, finite element analysis, and analytical modeling to evaluate the mechanical performance and optimize the proposed rotational bistable hinge.

Mechanism Configuration and Additive Manufacturing

The rotational bistable hinge is developed based on a compliant mechanism concept, utilizing elastic deformation to achieve controlled rotational motion and snap-through behavior. The structural configuration and geometrical parameters are defined to investigate their influence on the mechanical performance of the hinge. The design is prepared for fabrication using additive manufacturing.

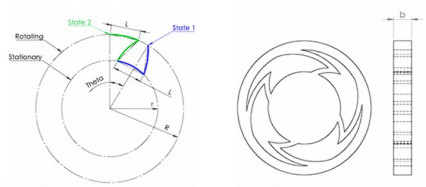


Figure 1. Proposed four-fin rotational compliant mechanism and geometric variables

Finite Element Analysis

Finite Element Analysis (FEA) is conducted to investigate the mechanical behavior of the proposed hinge. The model incorporates appropriate discretization, boundary conditions, material constitutive properties, and nonlinear solution procedures to capture large deformation and snap-through behavior.



Figure 2. Finite element configuration of the rotational compliant mechanism

Analytical Modeling

An analytical model is developed to describe the relationship between hinge geometry, strain energy, and rotational response. The model considers equilibrium stability, snap-through switching thresholds, and the influence of contact and irreversible deformation. Analytical predictions are subsequently compared with finite element moment–angle responses for model identification and validation.

Material Screening and Optimization

Different material properties and geometrical configurations are investigated through finite element simulations. The effects of material selection and key design parameters, particularly fin thickness, on stiffness, torque response, and structural integrity are evaluated. The simulation results are used to identify suitable design configurations and establish constraints for further optimization.

Results & Research Progress

The research has progressed through the development of the rotational bistable hinge concept and its preliminary computational investigation using Abaqus.

Initial finite element simulations have demonstrated snap-through behavior, indicating the potential of the proposed compliant structure to achieve bistable rotational motion.

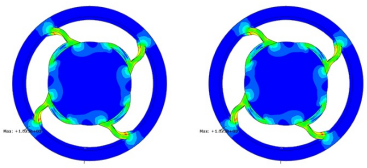


Figure 3. Representative von Mises stress distributions of the mechanism

The preliminary investigation has also identified several engineering challenges:

Structural Stiffness: The current design exhibits relatively high stiffness, requiring further geometrical refinement.

Material Behavior: The influence of PLA material properties, including elastic and plastic deformation, requires further investigation.

Torque Response: Further optimization is needed to achieve the desired torque magnitude and rotational behavior.

These findings provide a basis for subsequent design refinement and computational optimization.

Outputs & Research Sustainability

The research outputs include:

- A CAD model of the proposed rotational bistable compliant hinge.
- A finite element simulation model for evaluating mechanical behavior.
- Preliminary computational data on deformation, stress distribution, and snap-through response.
- An optimized design concept for integration into a 3D-printed ankle-foot orthosis.
- Scientific publications documenting the research findings.

Future Development

Further work will focus on geometrical optimization, material characterization, prototype fabrication, and experimental mechanical validation.

The long-term objective is to establish a foundation for lightweight, customizable, and affordable 3D-printed AFOs, contributing to the development of accessible rehabilitation technologies.