Book of Abstracts of MMT Symposium
Mechanism and Machine Theory Symposium
Flores et al. (Eds)

MMT Symposium
60th Anniversary of Mechanism and Machine Theory
June 21-23, 2026 Porto, Portugal

MORPHOLOGICAL INTELLIGENCE IN PASSIVE DYNAMICS: A DESIGN INVESTIGATION OF BIOMECHANICALLY-INSPIRED BIPEDAL ROBOTS

Aikaterini Smyrli[1,2,3], Evangelos Papadopoulos[1,2,3]

[1] HERON - Hellenic Robotics Center of Excellence, Athens, Greece
[2] Robotics Institute, ATHENA Research Center, Marousi, Greece {katerina.smyrli@athenarc.gr; egpapado@athenarc.gr}
[3] National Technical University of Athens, Greece

1 INTRODUCTION

This work investigates the dynamics of bipedal locomotion through the modeling and progressive refinement of passive bio-inspired mechanical walkers, with emphasis on applications in robotics and lower-limb prosthetic systems. The study follows a structured mechanism-design progression, beginning from a minimal passive configuration and incrementally incorporating anatomically inspired elements that shape hybrid gait dynamics. The central hypothesis is that stable and energetically efficient walking behavior emerges primarily from mechanical morphology. By systematically augmenting structural features, quantitative relationships between geometry, mechanism design, inertial distribution, and passive gait characteristics are established.

2 BASE PASSIVE MODEL

The investigation begins with a compliant bipedal base model equipped with semicircular feet and axial leg elasticity (Figure 1a). Despite its structural simplicity, this system exhibits stable passive walking cycles on a shallow negative slope, reproducing key characteristics of human gait [1].
A nondimensional formulation is introduced to eliminate scale dependence and to express gait behavior through a compact set of design parameters. This representation enables fixed-point identification of periodic gaits and systematic sensitivity analysis with respect to design parameters. The base model establishes the fundamental mapping between morphology and gait stability, step frequency, hip displacement, and energetic efficiency.
The analytical predictions are validated through multibody simulations of a digital twin and through experimental evaluation of a physical prototype, demonstrating strong agreement between theoretical and physical behavior [2].

3 FOOT MORPHOLOGY AND ROLLOVER DYNAMICS

Building upon the base configuration, the first stage of augmentation concerns foot geometry. The classical circular rocker (Figure 1b) is first replaced by a semielliptical profile (Figure 1c) that approximates the evolving curvature of the human foot during rollover [3]. This modification enables parametric investigation of curvature progression and its influence on ground reaction forces, ankle trajectory, gait stability, and walking velocity.
The formulation is subsequently generalized to accommodate any convex foot geometry (Figure 1d). This extension allows the direct integration of biomimetic rollover shapes extracted from human walking experiments [4]. The resulting passive walkers reproduce ankle trajectories of increasing biomechanical fidelity and enable prediction of ground contact behavior across arbitrary foot profiles.

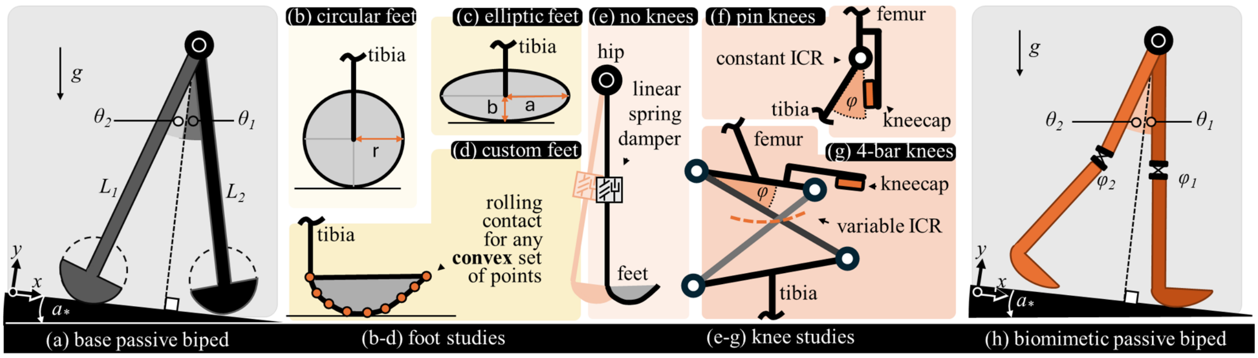

Figure 1: Design evolution of the investigated biped systems. (a) Base passive biped descending a slope a_*. (b) Circular feet. (c) Elliptic feet. (d) Detail of the custom convex foot geometries defined as arbitrary point sets. (e) No-knees biped with compliant legs. (f) Pin-joint knees. (g) Detail of the biomimetic four-bar knee mechanism. (h) Biomimetic passive biped.

4 KNEE MECHANISM DESIGN

The straight-leg model (Figure 1e) is further enriched through the introduction of knee joints. An initial passive kneed configuration employing pin joints (Figure 1f) enables swing-phase ground clearance while preserving gait stability [5]. Stable periodic gaits are identified and evaluated under parameter variations.

Subsequently, a biomimetic four-bar knee mechanism inspired by the human cruciate ligament system is introduced (Figure 1g). The four-bar architecture generates a variable instantaneous center of rotation (ICR) and configuration-dependent mechanical advantage [6]. Comparative analysis demonstrates improved compliance, reduced peak impact loads, and enhanced energetic performance relative to simple pin-joint knees. These findings highlight the decisive role of joint-level mechanism design in shaping global locomotion dynamics.

5 PASSIVITY-INSPIRED LEVEL-GROUND WALKING

Once a biped exhibits stable passive gait behavior, the same dynamically efficient motion can be sustained on level ground while preserving the low energy costs associated with the passive trajectory [7]. The analysis demonstrates that the establishment of passive stability constitutes the essential prerequisite for efficient level-ground locomotion. Thus, passive dynamic design serves as the foundation for energetically favorable walking beyond sloped environments.

6 HUMAN WALKING INTEGRATION

In parallel, a markerless stereo-camera-based gait analysis framework was developed to extract sagittal-plane kinematic and kinetic data from human walking trials [8, 9]. Using neural-network pose estimation and inverse dynamics, joint torques and ground reaction forces are estimated without markers or force plates. These human data inform and calibrate the mechanical models, ensuring convergence of the studied behaviors toward real biomechanical patterns.

7 CONCLUSION

This work presents a mechanism-driven framework for passive biped design, progressing from a minimal compliant walker without knees to configurations with biomimetic feet and knee architectures, each evaluated in terms of stability, impact mitigation, and energetic efficiency.

The results demonstrate that locomotion behavior is governed by morphological intelligence: rollover geometry, joint architecture, and inertial distribution determine the emergence and characteristics of stable hybrid gait cycles. Grounding design in biomechanically-inspired passive dynamics enables energy-efficient walking consistent with human biomechanics, providing theoretical guidance for biomimetic robots and lower-limb prosthetic systems.

ACKNOWLEDGMENTS

This project is funded by the European Union under Horizon Europe (grant No. 101136568 - HERON).

Funded by
the European Union

REFERENCES

[1] Smyrli, A., Bertos, G., and Papadopoulos, E., “A generalized model for compliant passive bipedal walking: sensitivity analysis and implications on bionic leg design,” *ASME J. of Biomech. Eng.*, Oct 2021, 143(10): 101008.

[2] Vasileiou, C., Smyrli, A., Drogosis, A., and Papadopoulos, E., “Development of a passive biped robot digital twin using analysis, experiments, and a multibody simulation environment,” *Mechanisms and Machine Theory*, v. 163, Sep 2021.

[3] Smyrli, A., Ghiassi, M., Kecskemethy, A., and Papadopoulos, E., “On the effect of semielliptical foot shape on the energetic efficiency of passive bipedal gait,” *IEEE/RSJ Int. Conf. on Int. Rob. and Sys.*, Macau, China, 2019.

[4] Smyrli, A. and Papadopoulos, E., “A methodology for the incorporation of arbitrarily-shaped feet in passive bipedal walking dynamics,” *IEEE Int. Conf. on Robotics and Automation*, Paris, France, May 31-June 4, 2020.

[5] A. Smyrli and E. Papadopoulos, ”Modeling, Validation, and Design Investigation of a Passive Biped Walker with Knees and Biomimetic Feet,” *Int. Conf. on Robotics and Automation*, Philadelphia, PA, USA, 2022.

[6] Smyrli, K., and Papadopoulos, E., “Improved biped walking performance around the kinematic singularities of biomimetic four-bar knees,” *IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, Kyoto, Japan, 2022.

[7] D. Maligianni, F. Valouxis, A. Kantounias, A. Smyrli and E. Papadopoulos, ”A Virtual Gravity Controller for Efficient Underactuated Biped Robots,” *IEEE Int. Conf. on Robotics and Automation*, Atlanta, GA, USA, 2025.

[8] K. Tsintzira, A. Smyrli, A. Mastrogeorgiou and E. Papadopoulos, ”Low-Cost Markerless Gait Analysis Using a Minimal Human Model,” *IEEE Int. Conf. on Bioinformatics and Bioengineering*, Athens, Greece, 2025.

[9] O. I. Stavrakakis, *et al.*, ”Guidelines For Optimal Human Mesh Generation Using Deep Learning-Driven Avatar Reconstruction For Gait Analysis,” *IEEE-RAS Int. Conference on Humanoid Robots*, Nancy, France, 2024.