

Simulation-Driven Design and Optimization of a Parametric Flat-Foot with Elastic Pads for a Planar Biped Robot

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Abstract: This paper presents the simulation-driven design and optimization of a compliant foot for a planar biped robot. To enhance walking stability and reduce joint torques, 3D-printed elastic pads were fabricated and experimentally characterized through compression testing. These prototypes provided baseline stiffness and damping ranges that served as inputs to the simulation model. Using these data as a starting point, a genetic algorithm optimized pad parameters to minimize joint torque overloads while maintaining gait stability. Walking simulations were performed in MATLAB Simulink on flat terrain, comparing a rigid flat-foot with the optimized compliant foot with pads. Results demonstrated up to 46% reduction in peak hip torques and 35% reduction in knee torques, along with smoother contact forces and stable zero moment point (ZMP) trajectories. The study confirms that introducing passive compliance at the foot level improves bipedal locomotion efficiency without additional actuation.

1 INTRODUCTION

Foot-ground interaction significantly influences the stability, energy efficiency, and adaptability of bipedal walking robots. Unlike rigid mechanical feet, the human foot incorporates soft tissue structures and arches that naturally absorb impact, assist in balance, and conform to uneven terrain. Emulating these biomechanical features in robotic platforms remains a major research focus.

Various robotic foot designs have been explored in the literature to address impact mitigation and adaptability. Rigid flat feet are widely used due to their simplicity, but they transmit high contact forces to the structure. To reduce these forces, researchers have incorporated elastic elements, such as rubber pads (Li et al., 2008), pneumatic stiffness adjustment mechanisms (Zang et al., 2017), and multi-segment toe joints (ElDirdiry et al., 2017). Sandwich structures with compliant layers (El Asswad et al., 2017) and biomimetic feet with embedded passive joints (ElDirdiry et al., 2017; Venkadesan et al., 2020) have also been proposed to approximate human foot dynamics. However, most of

these solutions require complex control or mechanical modifications.

Recent work has also focused on optimization-based design. For example, El Asswad et al. (2017) used genetic algorithms to tune sandwich-type foot parameters for impact resistance, while Venkadesan et al. (2020) characterized stiffness properties of the human arch to guide robotic foot design. Despite these advances, few studies apply simulation-based optimization specifically aimed at minimizing joint torque within motor constraints during walking.

In this study, we propose a parametric flat-foot design with elastic pads that balances mechanical simplicity with improved impact buffering. Prototype pads were fabricated via 3D printing and experimentally characterized to determine their stiffness and damping properties. These data provided baseline ranges that served as inputs to the optimization framework, rather than being treated as fixed constants. The pads were then virtually optimized in simulation to minimize peak joint torques while maintaining gait stability.

The research builds on an existing planar biped robot platform YU-Bibot (see Figure 1), with six actuated joints (Şafak & Baturalp, 2023). A detailed

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simulation model is constructed using MATLAB Simulink, incorporating contact dynamics and joint actuation profiles derived from human-inspired gaits.

Elastic pads are modelled based on experimentally determined stiffness and damping values. A genetic algorithm is used to optimize the pad parameters, targeting the minimization of peak joint torques while respecting actuator limits. Simulation results demonstrate that the optimized foot configuration leads to reduced impact forces and joint loading compared to the baseline rigid flat-foot design.

Two configurations were investigated: a baseline rigid flat foot and a flat foot with optimized elastic pads. Comparative analysis highlighted the improvements in joint torque reduction, contact force smoothing, and zero moment point (ZMP) stability.

The rest of this paper is structured as follows: Section 2 describes the foot design and elastic pad fabrication; Section 3 outlines the simulation framework; Section 4 details the optimization methodology; Section 5 presents results and discussion; and Section 6 concludes the paper.



Figure 1: YU-Bibot planar robot platform.

2 FOOT DESIGN AND ELASTIC PAD IMPLEMENTATION

To improve ground compliance and reduce joint torques during walking, we extend the flat-foot design of the planar biped robot by integrating elastic pads under each foot. The approach is motivated by the human foot's ability to adapt to ground

irregularities and absorb impact through soft tissue structures.

2.1 Flat-Foot with Pads Concept

The base configuration of YU-Bibot uses rigid flat feet without passive or active foot degrees of freedom (see Figure 2). To enhance compliance while retaining structural simplicity, three modular elastic pads are mounted beneath each foot — two forefoot pads and one heel pad — mimicking the key contact regions of the human foot: the big toe mound, base of the little toe, and centre of the heel. Each pad acts as a passive elastic element with adjustable stiffness and damping.

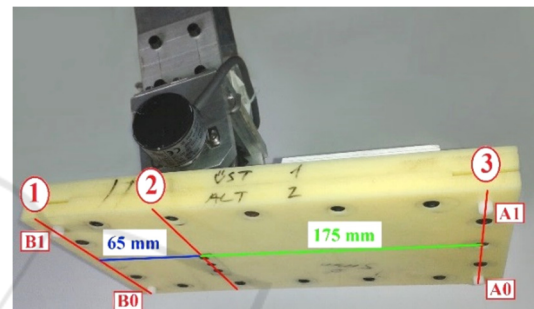


Figure 2: Existing foot structure and sensors.

The geometry of the pad layout is illustrated in Figure 3. Each pad acts as a passive elastic element and can be independently varied in stiffness and damping. This parametric configuration enables targeted tuning of impact absorption and dynamic stability.

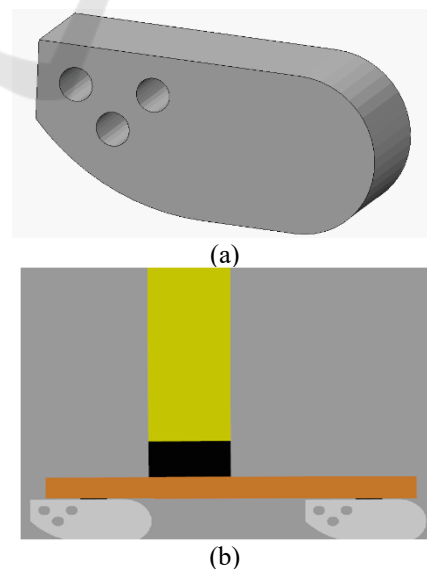


Figure 3: (a) CAD drawing of elastic pads, (b) Implementation of pads underneath rigid foot.

2.2 Pad Fabrication and Material Selection

Pads are fabricated using thermoplastic polyurethane (TPU) via 3D printing. Two variants were tested: orange (Shore-A 90, lower grid density) and white (Shore-A 80, higher grid density).

Both designs use a sandwich-like internal structure for lightweight compliance. The orange pad weighed 36.5 g and measured $88 \times 26 \times 40$ mm. The grid pattern and material thickness were varied to modify mechanical properties. These prototypes were not the final optimized configuration but served as experimental references for material properties.

2.3 Compression Testing and Characterization

Quasi-static compression tests were performed using a universal testing machine at velocities ranging from 0.5 to 3 mm/s (orange) and up to 5 mm/s (white). The load-displacement curves were analyzed to extract spring constants and damping coefficients.

Results confirmed light damping behavior in all cases (i.e., $\zeta_{eq} < 1$). The white pads exhibited higher stiffness and lower damping compared to the orange pads, making them more suitable for forefoot implementation. Average values used in simulation were:

- $k \approx 65,000$ N/m, $c \approx 4$ Ns/m for white pads
- $k \approx 4,800$ N/m, $c \approx 4.2$ Ns/m for orange pads

These parameters were input into the robot simulation model to represent contact dynamics accurately.

3 SIMULATION AND OPTIMIZATION FRAMEWORK

3.1 Bipedal Robot Simulation Environment

To evaluate the effect of compliant foot design on joint loading, a detailed simulation model of the planar bipedal robot was constructed using MATLAB Simulink (Simscape Multibody). The model incorporates six actuated joints and simulates single and double support phases using realistic contact dynamics (see Figure 4).

Elastic pads are modelled as compliant elements beneath each foot, with separate stiffness and

damping coefficients for forefoot and heel pads. Contact interactions are defined using spatial contact force blocks, and walking motions are driven by predefined joint angle trajectories based on previous gait studies.

Each simulation run evaluates whether the robot maintains balance and measures maximum joint torques at ankle, knee, and hip. A fall condition is detected if the hip height drops below a threshold.

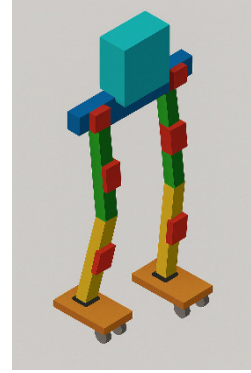


Figure 4: Visualization of robot simulation model.

3.2 Optimization Objective and Constraints

The main goal is to minimize joint torque spikes during walking by tuning pad stiffness and damping. The objective function is defined as the squared sum of joint torque peak values divided by each joint actuator's maximum continuous torque limits:

$$J = \left(\frac{\tau_{\text{ankle}}}{\tau_{\text{max,ankle}}} \right)^2 + \left(\frac{\tau_{\text{knee}}}{\tau_{\text{max,knee}}} \right)^2 + \left(\frac{\tau_{\text{hip}}}{\tau_{\text{max,hip}}} \right)^2 \quad (1)$$

where τ_{max} values are motor torque limits (5A rated). The squared terms place stronger emphasis on torque values approaching or exceeding actuator limits. The optimization criterion is based on maximum normalized torques at ankle, knee, and hip joints over the gait cycle, rather than mean values.

3.3 Genetic Algorithm Optimization

A genetic algorithm (GA) is used to find optimal pad parameters:

- $k_{\text{fore}}, k_{\text{heel}} \in [20000, 300000]$ N/m
- $c_{\text{fore}}, c_{\text{heel}} \in [10000, 150000]$ Ns/m

These ranges were established from the experimentally measured stiffness and damping of 3D-printed pad prototypes, which served as a basis and starting point for the optimization rather than fixed values. GA uses population size 50, crossover

probability 0.8, with convergence based on stall for 100 generations. Each evaluation runs a full walking simulation.

3.4 Gait Generation

To simulate realistic walking dynamics, the robot's joint trajectories were defined based on a previously generated walking gait for YU-Bibot. The gait was developed through offline trajectory planning using human-inspired profiles and validated in an earlier work (Şafak & Baturalp, 2023).

The walking cycle consists of distinct stance and swing phases for each leg, with ankle, knee, and hip joints actuated via time-based reference profiles. The gait assumes walking on flat terrain at constant velocity and does not use feedback control during this study. The same gait is used across all foot configurations to ensure fair comparison between the baseline and optimized feet.

Although the gait was initially tuned for the baseline flat foot, the simulation revealed that the compliant foot with pads improved torque distribution without compromising the overall kinematics or balance.

4 RESULTS AND DISCUSSION

4.1 Simulation Setup

The walking simulation was run using predefined joint trajectories based on flat-ground walking gait. Each simulation covered one full step cycle, with joint torques monitored throughout. Two foot configurations were compared: baseline flat-foot (rigid sole, no compliance) and flat-foot with optimized elastic pads (using GA-tuned stiffness and damping).

Motor torque limits were taken as $\tau_{\max, \text{ankle}}=24.2$ Nm, $\tau_{\max, \text{knee}}=17.7$ Nm, and $\tau_{\max, \text{hip}}=11.8$ Nm, based on hardware specs.

4.2 Torque Reduction Results

The simulation showed that the optimized pad configuration substantially reduced joint torque peaks, especially at the ankle and knee. The comparative results are summarized in Table 1.

Table 1: Max and RMS Joint Torques – Baseline vs. Optimized Pad Design.

Joint	Metric	Baseline (flat foot)	Optimized (with pads)
Ankle	Max (Nm)	13.8	11.6
	RMS (Nm)	4.6	4.7
Knee	Max (Nm)	31.3	20.4
	RMS (Nm)	12.1	8.6
Hip	Max (Nm)	57.2	30.8
	RMS (Nm)	22.1	14.2

The optimized foot with elastic pads significantly reduced maximum joint torques across all joints, most notably at the hip (46%) and knee (35%). These reductions indicate improved impact buffering and smoother load transfer during the stance phase.

RMS torques also decreased substantially at the knee (30%) and hip (36%), which suggests a reduction in sustained joint loading over the gait cycle. Interestingly, the ankle RMS torque slightly increased, likely due to the redistribution of force during heel-strike and push-off with the compliant pads. This trade-off appears acceptable given the larger reductions elsewhere and the peak torque at the ankle still remaining well below motor limits.

These results confirm that pad-based compliance can mitigate peak loads while also reducing overall energy demand on major joints, particularly at the knee and hip — both of which are commonly critical in robotic actuation systems.

4.3 Contact Force and Stability

The total vertical ground reaction force (GRF) and zero moment point (ZMP) were analyzed for both the baseline flat-foot and the optimized foot with elastic pads. ZMP stability analysis follows established approaches in (Kajita et al., 2003; Erbatur et al., 2002). As shown in Figure 5, the rigid flat foot produced sharp GRF peaks at heel-strike and toe-off, with abrupt changes in load transfer. The corresponding ZMP trajectory (Figure 6) exhibited rapid shifts, occasionally approaching the edge of the support polygon. These behaviors reflect the limited compliance of the rigid sole, leading to higher impact forces and reduced stability margins.

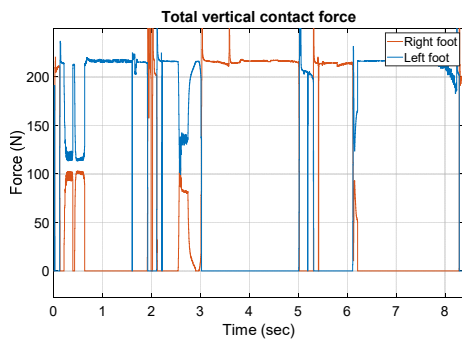


Figure 5: Total contact forces for flat foot (baseline).

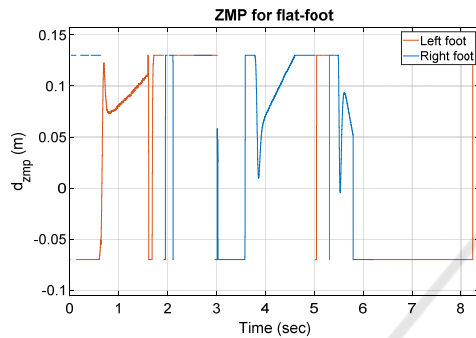


Figure 6: ZMP for flat foot (baseline).

The addition of elastic pads resulted in smoother contact force profiles with fewer sharp transients compared to the baseline. The total ground reaction forces (Figure 7) remained within expected limits. To assess dynamic stability during walking, the Zero Moment Point (ZMP) was tracked throughout the gait cycle (Figure 8). The ZMP represents the point on the ground where the net moment due to gravity and inertia forces is zero, and it must remain within the foot's support area to ensure stable motion (Kajita et al., 2003; Erbaturo et al., 2002). For both the baseline and optimized foot designs, the ZMP remained inside the support polygon during the stance phase, confirming that the robot maintained balance throughout the simulated steps.

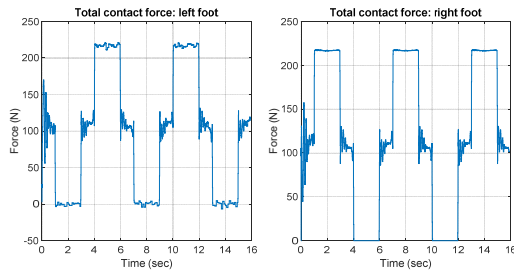


Figure 7: Total contact forces for flat foot with pads.

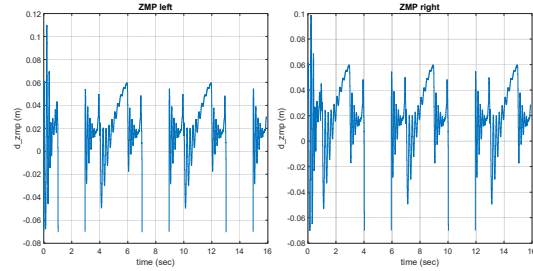


Figure 8: ZMP for flat foot with pads.

Notably, the forefoot pads converged to much higher stiffness values than the heel pads in the optimization, echoing the biomechanical distribution in the human foot. This natural-like stiffness gradient appears to enhance impact buffering at heel-strike while maintaining push-off stability.

4.4 Discussion and Implications

The results support the effectiveness of simulation-driven foot design using parametric compliance. Even in a planar biped without active foot control, passive elasticity can significantly reduce actuator demand, improve gait stability, and protect mechanical components.

The trade-off is a slight increase in ankle RMS torque, possibly due to dynamic coupling effects introduced by the pads. This could be addressed in future work via adaptive gait tuning or a hybrid passive-active compliance approach.

5 CONCLUSION

This study presented a simulation-driven approach to improving the foot-ground interaction of the YU-Bibot planar biped robot. A modified flat-foot design with elastic pads was introduced, inspired by human foot contact regions. Prototype pads were fabricated and experimentally characterized to provide baseline stiffness and damping ranges, which served as inputs to a genetic algorithm-based optimization framework.

Walking simulations were conducted in MATLAB Simulink on flat terrain for two configurations: a baseline rigid flat foot and a flat foot with optimized elastic pads. Comparative analysis showed that the optimized design reduced peak torques by up to 46% at the hip and 35% at the knee, with RMS torques also significantly reduced at these joints. While ankle RMS torque slightly increased, the overall load distribution across joints improved.

Ground reaction force analysis indicated that the elastic pads smoothed impact transients compared to the rigid baseline, while Zero Moment Point (ZMP) trajectories remained well within the support polygon, confirming stable walking. These results demonstrate that introducing passive compliance at the foot level can mitigate joint loads and enhance stability without requiring additional actuation or complex control.

The findings also suggest a natural-like distribution of compliance—stiffer forefoot and softer heel—as an effective configuration for impact absorption and propulsion, similar to human foot mechanics. Future work will include hardware implementation of the optimized pad design on the physical robot.

The proposed approach demonstrates the value of coupling simulation, experimental characterization, and optimization in advancing bio-inspired robotic design.

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