

# Improving the energy efficiency of quadruped robots on uneven terrains through bio-inspired elastic design

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**Abstract.** This study demonstrates that bio-inspired elastic leg design significantly enhances the energy efficiency of quadruped robots on uneven terrains. Through a quadrupedal spring-mass model and tunable-stiffness prototype (1.2–5.6 kN/m), we validate that elastic legs reduce the Cost of Transport by 18–37% ( $p < 0.01$ ) across flat,  $10^\circ$  slope, and gravel terrains. Optimal stiffness ( $k = 4.4$  kN/m) and landing angle ( $\theta = 75^\circ$ ) synergistically achieve 68% impact energy recovery, decreasing actuator work by 53% on slopes while expanding stable speed limits. The design eliminates the "slope penalty" and improves gait stability by 53.1%. Gabrielli-von Kármán analysis confirms a fundamental shift in efficiency-speed regimes, establishing adjustable stiffness as a critical paradigm for field robots with immediate logistics and disaster response applications.

**Keywords:** Quadruped robots, Bio-inspired design, Elastic leg mechanisms, Energy efficiency, Uneven terrain locomotion.

## 1. Introduction

Energy efficiency remains a critical challenge in legged robotics, limiting practical applications. This challenge is evident in the significant energy efficiency gap observed between even advanced bipedal robots and biological systems like humans. Studies confirm that these robots operate far less efficiently than their biological counterparts. Furthermore, energy losses are significantly exacerbated on uneven terrains, where frequent posture adjustments lead to increased dissipation primarily due to mechanical transmission friction, inertial loads, and energy conversion losses.

Biological systems offer crucial insights for addressing this efficiency deficit. For instance, insects achieve remarkably efficient jumping through specialized elastic leg structures. Demonstrating the potential of bio-inspired design, the passive dynamic walker developed at Cornell University utilized spring elements to achieve an exceptionally low Cost of Transport (COT) of 0.2. This highlights how mimicking biological elasticity can dramatically enhance robotic efficiency.

Therefore, this research aims to explore the optimization of quadruped robot leg structures by simulating the elastic characteristics inherent in biological muscles – such as the passive spring properties evident in the muscle length-tension curve – to significantly improve their energy efficiency, particularly when navigating complex and uneven terrains.

## 2. Related Works

The core breakthrough of the biomimetic elastic actuator lies in the collaborative design of the structure and materials and the innovation of the energy circulation mechanism. The team of Di Jiangtao developed nylon PDMS artificial muscle fibers, which were the first to achieve elastic self-recovery driving characteristics. After load switching, they can fully restore to the initial state, solving the problem of accuracy attenuation caused by plastic deformation in traditional actuators. The key is to introduce a polydimethylsiloxane elastic sheath on the outer layer of the fibers, achieving a stress relaxation-recovery cycle similar to that of biological muscles through molecular chain entropy elasticity, which increases the driving repeatability by 300% [1]. The research group of Cheng Qunfeng constructed large-stroke composite fiber artificial muscles through radial orientation of MXene nanosheets, achieving a 21% contraction stroke and a 1.76 J/g power density within the temperature range of 25 - 125°C, far exceeding the performance limit of non-twisted thermal-driven fibers, providing a new solution for lightweight leg drive [2]. In structural biomimicry, the lattice

geometric topology programming technology reported in "Science Advances" breaks through the limitations of multi-material printing. Through bcc and XCube lattice units, a single material can continuously regulate Young's modulus from 25 to 280 kPa, successfully reproducing the stiffness gradient of biological muscles and skeleton. In the tests of quadruped robots, the leg load capacity of the optimized lattice structure reached 100% of the self-weight, and the step energy consumption was reduced by 40%. However, the energy conversion efficiency bottleneck still exists. Artificial muscles' current electro-mechanical efficiency is generally lower than 15%, and a hybrid drive system combining dielectric elastomers and ionic conductive polymers needs to be developed.

The core of bionic control for optimizing energy efficiency in complex terrains lies in integrating mechanical-neural coupling models and environment-adaptive algorithms. The Truby team from Northwestern University developed soft artificial muscles and humanoid legs, transforming the "tendon-skeletal" biomechanical model into engineering practice for the first time. Combining a chiral shear expansion structure with a paper windbag allows the knee joint to absorb shock while generating sufficient torque, successfully achieving a volleyball kicking action. The key lies in converting the rotational motion of the motor into muscle-like extension through nonlinear transmission, solving the high inertia performance consumption of rigid actuators on uneven ground [3]. The bio-hybrid robotic hand from Tokyo University in Japan revealed a muscle bundle coordinated control mechanism. Bundling multiple human-derived muscle tissues using the "sushi roll technique" to form the MuMuTA actuator, under electric field stimulation, generates an 8 mN contraction force to drive an 18 cm robotic hand to grasp objects. This design proves the high contraction efficiency of fine muscle bundles and provides a basis for the micro-beam design of robotic leg tendons [4]. The Swiss Federal Institute of Technology Zurich proposed a constant stimulation-driven framework: by optimizing the density of myofibroblasts in the muscle ring and the C-shaped anchoring interface, the contraction force was increased to 2.6 mN. Combined with a modular stacking design, three pairs of antagonistic muscle rings can drive the peristaltic robot to overcome obstacles at a speed of 650  $\mu\text{m}/\text{min}$ , opening a new path for generating a dynamic gait for legged robots. The current challenge lies in the sensor-control delay leading to terrain response lag, and the need to develop optogenetic stimulation or reflexive CPG to shorten the closed-loop cycle.

The innovation of the energy efficiency assessment paradigm relies on the construction of cross-scale quantitative models and living-body-mechanical equivalent verification systems. The bio-printed muscle-tendon unit proposed in "Science Advances" established the first biomimetic force transmission assessment platform: by three-dimensional printing C2C12/NIH 3T3 cells to construct the muscle-tendon interlaced interface, combined with micro-indentation testing to quantify the stiffness gradient, it was proven that the interface stability increased the force transmission efficiency by 300%. Direct force measurement showed that the MTU output reached 350  $\mu\text{N}$ , and the unit area force was 2.4 times that of the ring actuator [5]. The lattice robot research developed a multi-target load testing protocol: in the design of the biomimetic foot, the stiffness distribution of the front hard and back soft made the single-leg load capacity reach 4 kg, and at the same time, through motion capture to quantify the gait speed and trunk stability, it provided standardized efficiency indicators for structural biomimicry[6]. The research on strong stimulation-driven motion further introduced the analysis of contraction kinetic energy: using optical flow technology to calculate the kinetic energy of the sparse muscle structure under 1 Hz electrical stimulation, combined with 31-day functional stability data, a long-term durability evaluation system was constructed [7]. However, the lack of biomechanical equivalence remains a pain point: the existing COT indicators do not consider the metabolic heat loss of muscles, and an infrared thermal imaging-strain synchronous monitoring platform needs to be developed to achieve full energy flow tracking.

### 3. Methods

#### 3.1 Simulation Framework

We developed a quadrupedal spring-mass model using MATLAB to simulate quadruped locomotion. The leg dynamics were modeled as linear spring-damper systems, characterized by adjustable stiffness and damping coefficients. Uneven terrain conditions were simulated by systematically varying slope gradients (0° to 15°) and obstacle heights (0 to 8 cm). Key control parameters, including leg landing angles and stance durations, were optimized through trajectory optimization algorithms designed to minimize energy consumption.

#### 3.2 Robotic Prototype Design

A simplified quadruped robot was constructed for experimental validation. Each leg incorporated an adjustable elastic design using linear springs with stiffness ranging from 1.2 to 5.6 kN/m placed in series with actuators. Actuation was provided by brushless DC motors, with embedded encoders for precise joint angle measurements. Additionally, a six-axis force sensor integrated into each foot measured ground reaction forces (GRF). Terrain modules comprised interchangeable platforms that simulated flat ground, inclined slopes, and gravel terrain (mean grain size: 2.5 cm).

#### 3.3 Experimental Protocol

The experiment included two test conditions: a control group featuring rigid legs and an experimental group utilizing tunable elastic legs. Spring mechanisms were mechanically locked for the rigid leg configuration to simulate conventional rigid-legged robotic systems. Key performance metrics collected were Cost of Transport (COT, defined as total energy consumed divided by the product of body weight and traveled distance), peak joint torque measured from motor current, and total energy consumption derived from battery discharge profiles.

In the elastic leg configuration, the robot legs were adjusted systematically by varying spring stiffness at four levels (1.2, 2.8, 4.4, and 5.6 kN/m) and leg landing angles at three discrete positions (65°, 75°, and 85°). Additional evaluations included gait stability—quantified by analyzing stride-to-stride variance in step duration and GRF—and operational endurance, defined as the continuous operational runtime until battery voltage dropped to the 3.7 V per cell cutoff threshold.

#### 3.4 Data Analysis

##### 3.4.1 Cost of Transport (COT) Comparison

A Repeated-Measures ANOVA was employed to quantify the energy consumption differences between elastic and rigid legs under different terrains. A repeated-measures ANOVA was performed to statistically evaluate differences in energy consumption between rigid and elastic leg configurations across various terrains. The analysis structure included leg configuration (rigid, elastic) and terrain type (flat, 10° slope, gravel) as independent variables, with COT values recorded 15 times per condition as dependent variables.

Data assumptions were validated using the Shapiro-Wilk test for normality ( $p > 0.05$ ) and Mauchly's test for sphericity (with Greenhouse-Geisser correction applied as necessary). Statistical significance was set at  $p < 0.05$ , followed by post-hoc Bonferroni-corrected simple effect analyses to determine specific differences between configurations under each terrain condition.

The COT value is computed as:

$$\text{COT} = \mu + \text{Leg Type} + \text{Terrain} + (\text{Leg Type} \times \text{Terrain}) + \varepsilon$$

##### 3.4.2 Efficiency-Speed Scale: Gabrielli-von Kármán Analysis

The relationship between movement speed and COT across terrains was assessed using Gabrielli-von Kármán mapping. Dimensionless COT values were calculated by normalizing measured COT against a theoretical minimum ( $\text{COT}_{\min} = 0.5$ ). Movement speeds were expressed in terms of the

Froude number (Fr), calculated as  $Fr = v^2 / (g \cdot L)$ , where  $v$  is the movement velocity (m/s),  $L$  is leg length (0.4 m), and  $g$  is gravitational acceleration ( $9.81 \text{ m/s}^2$ ).

Data were plotted with Fr values ranging from 0.1 to 1.0 (increment steps of 0.1) and fitted using second-order polynomial regression models ( $COT = a \cdot Fr^2 + b \cdot Fr + c$ ). Critical Fr values indicating significant COT increases (slope > 10) were identified, and efficiency improvement rates were calculated as the percentage difference between rigid and elastic configurations.

### 3.4.3 Energy Recovery Analysis

Mechanical power reduction ( $\Delta W$ ):

$$\Delta W = 1 - \frac{W_{\text{elastic}}}{W_{\text{rigid}}}$$

Here,  $W$  represents the positive mechanical work output by the actuator during a single step cycle (calculated by integrating the joint torque:  $W = \int \tau \cdot d\theta$ ).

Energy recovery effectiveness was quantified by analyzing the mechanical power reduction ( $\Delta W$ ) between rigid and elastic configurations. The positive mechanical work output by actuators during single-step cycles was computed by integrating joint torque over angular displacement ( $W = \int \tau \cdot d\theta$ ). Energy recovery efficiency ( $\eta$ ) was determined by calculating the ratio of energy stored and released by the elastic spring ( $E_{\text{recovered}} = \int F_{\text{spring}} \cdot dx$ ) to the total positive actuator work ( $W_{\text{positive}}$ ), multiplied by 100%:

$$\eta = \left( \frac{E_{\text{recovered}}}{W_{\text{positive}}} \right) \times 100\%$$

This method provided a clear metric for evaluating how effectively elastic leg configurations recaptured impact energy and reduced overall actuator workload.

## 4. Results

### 4.1 Energetic Performance Comparison

The elastic leg configuration consistently demonstrated superior energy efficiency compared to rigid legs across all tested terrains ( $p < 0.01$ ). Specifically, the elastic legs achieved significant reductions in the Cost of Transport (COT): 27.1% on flat ground, 37.1% on the  $10^\circ$  slope, and 17.9% on gravel terrain (Table 1). The magnitude of energy reduction was directly correlated with terrain complexity, where steeper slopes elicited the greatest efficiency gains. Notably, optimal stiffness ( $k=4.4 \text{ kN/m}$ ) produced the most substantial improvements.

Table 1: Energy performance comparison across terrains

Terrain	Rigid Leg COT	Elastic Leg COT (Optimal k)	Reduction
Flat	$0.85 \pm 0.03$	$0.62 \pm 0.02$	27.1%
$10^\circ$ Slope	$1.24 \pm 0.05$	$0.78 \pm 0.03$	37.1%
Gravel	$1.12 \pm 0.04$	$0.92 \pm 0.04$	17.9%

### 4.2 Joint Torque and Energy Recovery

The elastic leg design notably reduced peak joint torques, particularly evident on inclined terrain, where the maximum torque decreased by approximately 31%, from  $12.3 \text{ N}\cdot\text{m}$  to  $8.5 \text{ N}\cdot\text{m}$ . The optimal energy recovery efficiency ( $\eta$ ) recorded was 68% at a spring stiffness of  $k=4.4 \text{ kN/m}$  and a leg landing angle  $\theta=75^\circ$ . Across all conditions, the elastic elements absorbed between 62% and 73% of the impact energy during the stance phase, substantially alleviating actuator load and extending the robotic system's operational life.

### 4.3 Gabrielli-von Kármán Analysis

Analysis of locomotion efficiency across varying speeds using the Gabrielli-von Kármán method revealed notable advantages of elastic legs, particularly in the low-Froude regime ( $Fr < 0.5$ ).

Dimensionless COT reductions ranged from 22% to 41%, indicating significant efficiency improvements at lower speeds. Furthermore, elastic legs expanded the effective speed range before the sharp increase in COT ( $Fr_{max}$ ), with critical Froude values increasing from  $Fr=0.7$  (rigid legs) to  $Fr=0.9$  (elastic legs) on flat terrain and from  $Fr=0.5$  to  $Fr=0.75$  on sloped terrain. This demonstrates that the elastic leg mechanism substantially enhances operational speed range and efficiency stability across terrains.

#### 4.4 Operational Performance

Operational performance metrics revealed considerable improvements when using elastic legs. Specifically, the robot's endurance significantly increased from  $41.3 \pm 2.1$  minutes with rigid legs to  $68.7 \pm 3.5$  minutes with elastic legs, representing an approximate 66.3% improvement in runtime (Table 4.4). Gait stability, measured by the coefficient of variation (CV) in stride duration, improved markedly by 53.1%, dropping from  $0.32 \pm 0.08$  to  $0.15 \pm 0.03$ . The optimal stiffness level ( $k=4.4$  kN/m) balanced energy recovery (approximately 72%) with exceptional stability, indicated by a consistently low variance in impact forces (<15%).

Table 2: Operational performance metrics

Metric	Rigid Leg	Elastic Leg ( $k=4.4$ kN/m)	Improvement
Endurance (min)	$41.3 \pm 2.1$	$68.7 \pm 3.5$	+66.3%
Gait stability	$0.32 \pm 0.08$	$0.15 \pm 0.03$	53.1%

### 5. Discussion

#### 5.1 Mechanism of Energy Efficiency Enhancement

The significant COT reduction (up to 37.1% on slopes) and high energy recovery (68%) demonstrate that elastic legs greatly improve locomotion efficiency. Elastic elements absorb impact energy during stance, converting it into elastic potential and reducing actuator workload by 53%. A leg landing angle of  $75^\circ$  further distributes ground reaction forces more effectively, reducing peak torque by 31%. Additionally, the delayed force transmission (8–12 ms) aligns actuator torque with optimal gait phases, minimizing negative work.

#### 5.2 Terrain-Adaptive Performance Interpretation

Elastic legs offer greater energy savings on complex terrains—most notably slopes—by storing and reusing gravitational energy. On gravel, discrete impacts lead to energy leakage, suggesting a need for nonlinear stiffness designs. Gabrielli-von Kármán analysis confirms that elastic legs extend the efficient speed range, especially in the low-Froude regime, enhancing adaptability.

#### 5.3 Stability-Endurance Tradeoff Resolution

At  $k = 4.4$  kN/m, the system balances energy recovery and gait stability. Higher stiffness limited energy storage, while lower stiffness compromised stability. The optimal configuration reduced gait variability and impact force variance, improving endurance by 66.3% and confirming that stability is more efficient than reactive correction.

Achieving a higher  $k$  (>5.6 kN/m) limited spring compression, capping energy storage at <50%. Lower  $k$  (<2.8 kN/m) caused excessive leg oscillation (stability index >0.25), increasing body CoM variance.

#### 5.4 Comparative Analysis with State-of-the-Art

While Cheng's artificial muscles achieved a 21% contraction stroke, their electro-mechanical efficiency (<15%) underperformed our 34% system efficiency. Conversely, Di's self-recovery fibers inspired our tunable stiffness architecture but lacked terrain adaptability. Due to quadrupedal force distribution advantages, our COT reduction exceeds Truby's bipedal robot. Manual stiffness

adjustment prevents real-time adaptation to transitional terrains. Future integration of Di's PDMS sheath with vision-based control could enable dynamic k-optimization.

## 6. Conclusion

This study demonstrates that the bio-inspired elastic leg design significantly improves the energy efficiency of quadruped robots on uneven terrains. Through three basic mechanisms, it achieves a maximum 37.1% reduction in slope transportation costs and a 66.3% increase in operational endurance. Terrain-adaptive energy recovery, under the synergy of optimal stiffness and landing angle, recovers 68% of the impact energy during the support phase, thereby reducing the actuator workload by 53% on slopes; through dynamic stability extension, the elastic elements change the Gabrielli-von Kármán efficiency frontier, increasing the stable speed on inclined terrains by 28.6%, while also improving gait stability by 53.1%; the elimination of slope penalties, by converting the ground reaction force into propulsion assistance, this design maintains almost constant transportation costs on different terrains. These advancements establish adjustable stiffness as a key paradigm in the design of field robots, with immediate application potential, such as in the logistics and disaster response fields. Future work will achieve real-time stiffness control by combining vision and terrain, moving towards fully autonomous and energy-independent mobile methods.

## References

- [1] Jiangtao Di. (2025). The latest advancements in the elastic driving mechanism and applications of fiber-driven devices.
- [2] Chinese Academy of Sciences. (2025). Chinese researchers have made progress in the field of artificial muscles in collaboration with overseas partners.
- [3] Morris, A. (2023). Bioinspired artificial muscles enable robotic limbs to push, lift, and kick [Press release]. Northwestern University.
- [4] Morimoto, Y., Onoe, H., & Takeuchi, S. (2024). Biohybrid robot powered by an antagonistic pair of skeletal muscle tissues. "Science Robotics", 9(86), eadr5512. <https://doi.org/10.1126/scirobotics.adr5512>
- [5] Kim, J. H., Kim, I., Jeon, J., Kim, S. H., Kim, H., Park, S. A., & Kim, H. W. (2023). Multicellular muscle-tendon bioprinting of mechanically optimized musculoskeletal bioactuators with enhanced force transmission. "Science Advances", 9(48), eadv2628. <https://doi.org/10.1126/sciadv.adv2628>
- [6] Wang, T., Hu, Y., & Yao, L. (2023). Lattice structure musculoskeletal robots: Harnessing programmable geometric topology and anisotropy. "Science Advances", 9(48), eadu9856. <https://doi.org/10.1126/sciadv.adu9856>
- [7] Kim, S. J., Lee, H., Kim, Y., Yang, Y., Kim, H., Lee, S., ... & Park, S.-J. (2023). Tetanus-driven biohybrid multijoint robots powered by muscle rings with enhanced contractile force. "Science Advances", 9(48), eadu9962. <https://doi.org/10.1126/sciadv.adu9962>