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Spring Suspension Based Bio Robotic Servo Knee Mechanism: Design, Mathematical Modeling, and Implementation

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Abstract: *The evolution of biomimetic robots, especially legged robots such as bipeds and quadrupeds, relies on mimicking the biological efficiency found in natural joint mechanisms. Traditional direct-drive servo robotic joints suffer from high power consumption, susceptibility to impact damage, and lack of compliance during dynamic locomotion. This research paper presents an extensive investigation into the design, mathematical modeling, and functional implementation of a Spring Suspension Based Bio Robotic Servo Knee Mechanism. This mechanism acts as a parallel elastic actuator, where a precisely calculated torsional spring operates in tandem with a servo motor. The proposed architecture fundamentally enhances shock absorption, payload stability, and overall energy efficiency during the stance and swing phases of the gait cycle. Comprehensive mathematical derivation dictates the optimal spring stiffness required to prevent structural collapse while maintaining compliant suspension. An embedded microcontroller seamlessly regulates the servo actuation in accordance with the elastic properties of the joint. Testing validates that the integrated torsional spring successfully reduces peak torque requirements, confirming its potential for scaling into larger assistive exoskeletons and autonomous quadrupedal robotic systems.*

Keywords: Bio-Robotics, Servo Knee Mechanism, Spring Suspension, Torsional Stiffness, Parallel Elastic Actuator, Legged Locomotion, Biomimetics

I. INTRODUCTION

In recent years, the field of legged robotics has experienced exponential growth, driven by the need for autonomous machines capable of traversing complex, unstructured terrains. Unlike wheeled or tracked robots, legged robots can step over obstacles, navigate stairs, and adapt to discontinuous paths. However, this versatility comes at the cost of high mechanical complexity and significant energy consumption. Biological entities—such as humans, felines, and birds—solve this problem natively through the intricate use of muscles, tendons, and ligaments, which act as highly efficient elastic energy storage and shock absorption systems.

When a biological leg strikes the ground, the tendons stretch, absorbing the kinetic impact and storing it as potential energy. As the leg pushes off for the next step, this energy is released, reducing the active muscular effort required. Replicating this behavior in robotic systems, particularly at the knee joint, is a prominent challenge in bio-robotics. Conventional rigid robotic legs, actuated by direct-drive high-torque servo motors, face severe limitations. They are prone to gear stripping upon sudden impacts, require continuous power simply to hold a static posture, and lack the inherent compliance necessary for smooth, natural movement.

To overcome these challenges, this paper proposes the integration of a mechanical spring suspension system into a robotic knee mechanism. By implementing a torsional spring in parallel with the servo-driven joint, we create a bio-inspired Parallel Elastic Actuator (PEA). The spring is mathematically designed to bear the static weight of the robot structure and absorb sudden landing forces, significantly offloading the burden from the electric actuator. This document details the complete life cycle of this engineering project: from initial conceptualization and literature review, through intricate mathematical modeling of torsional stiffness, mechanical design, electronics integration, and final software implementation. The primary objective is to demonstrate that a mathematically optimized spring-servo hybrid can achieve superior suspension characteristics and enhanced durability compared to purely rigid robotic joints.

II. LITERATURE REVIEW

The design of compliant and energy-efficient robotic legs has been extensively researched. Our mechanism draws inspiration from several key studies in biomimetics, legged locomotion, and rehabilitation exoskeletons.

Tang et al. [1] explored the mechanism design of biomimetic quadruped robots, emphasizing the need for reconfigurable joints that can adapt to different gait cycles. Their work highlighted the importance of matching mechanical impedance to the terrain, a principle that heavily influenced our decision to utilize an elastic suspension mechanism. Shaji et al. [2] developed a Robotic Dog emphasizing mesh networking and AI-based vision control using OpenCV and ESP32 microcontrollers. While their work focused heavily on software and sensory autonomy, it underscored the necessity for an underlying mechanical platform capable of supporting dynamic, unpredictable movements.

The concept of reconfigurability was deeply investigated by Nan et al. [3], who presented a robotic leg capable of seamlessly switching between spring-suspended and unsuspended configurations. Their findings proved that hopping and cyclic base-height control are vastly more efficient when spring-suspension is engaged. By exploiting the passive dynamics of the leg, the energy cost of locomotion is drastically reduced. Liu et al. [4] further advanced this domain by proposing a posture adjustment strategy for wheel-legged robots via leg force control with prescribed transient performance, demonstrating how crucial precise management of leg forces is for maintaining stability on uneven terrain.

In the context of human-assistive devices, Chen et al. [5] and Zhou et al. [8] provided comprehensive reviews of lower extremity assistive robotic exoskeletons. These devices often employ Series Elastic Actuators (SEAs) or Parallel Elastic Actuators (PEAs) to ensure safe human-robot interaction. The compliance introduced by springs prevents sudden, rigid jolts from injuring the user—a principle directly analogous to protecting the mechanical integrity of our robotic knee joint. Furthermore, Pratt et al. [10] and their work on Virtual Model Control provided intuitive approaches for bipedal locomotion, showing how mathematical models of virtual springs and dampers can be used to control physical robotic limbs effectively.

III. SYSTEM ARCHITECTURE

The Spring Suspension Based Bio Robotic Servo Knee Mechanism is an amalgamation of three primary subsystems: (1) Mechanical Assembly, (2) Electronic Control Hardware, and (3) Embedded Software. The system is designed to simulate a single functional leg segment, consisting of a femur link (upper leg) and a tibia link (lower leg), connected by the active knee joint. The primary actuator, a high-torque servo motor, is mounted at the knee pivot. A custom-selected torsional spring is coaxially aligned with the servo shaft, anchoring one end of the spring to the femur link and the other end to the tibia link.

When external loads are applied (e.g., the robot body weight pressing down), the knee joint is forced to flex. The torsional spring resists this flexion, absorbing the force elastically. The microcontroller continuously monitors the desired gait angle and sends precise PWM (Pulse Width Modulation) signals to the servo motor. Because the spring actively supports the static load, the servo only needs to exert enough torque to overcome the difference between the desired position and the spring equilibrium position, rather than bearing the full gravitational load independently. This is the fundamental operating principle of a Parallel Elastic Actuator (PEA).

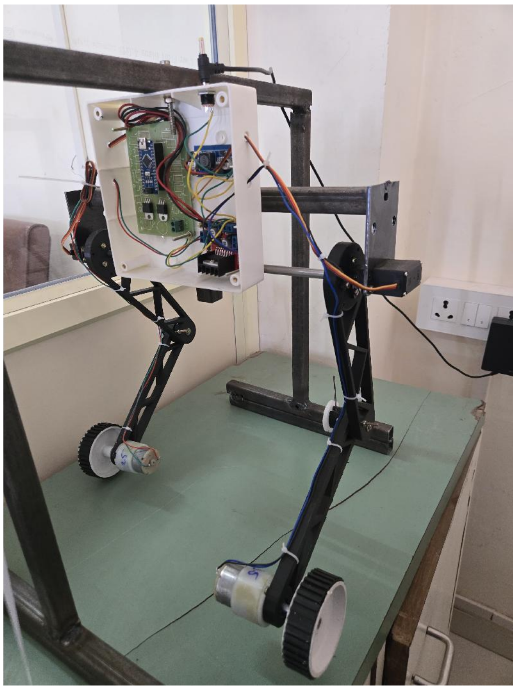

Fig. 1. Physical prototype showing the overall system architecture, chassis frame, microcontroller enclosure, and dual leg assemblies.

IV. MECHANICAL DESIGN & KINEMATICS

The physical construction of the robotic leg required careful consideration of material strength, weight distribution, and joint kinematics. The components were designed using CAD software and fabricated via 3D printing in PLA material, which offers an adequate strength-to-weight ratio for the prototype scale. The femur and tibia segments are designed with a skeletal truss structure to maximize structural efficiency while minimizing mass.

Key dimensional parameters derived from the CAD model are: overall tibia link length of 190.07 mm, a top flange width of 35 mm, torsional spring bore diameter of Ø 24 mm, servo shaft bore of Ø 17.5 mm, and a wheel axle bore of Ø 13 mm. The femur link has an overall length of 175 mm with a maximum width of 54.82 mm at the upper pivot flange and a bottom mounting width of 11 mm. Both links share identical Ø 24 mm upper and lower bearing holes to maintain symmetric joint loading.

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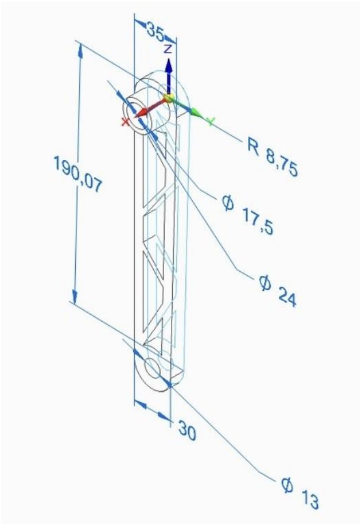

Fig. 2. Isometric CAD view of the femur link showing truss geometry, overall length 175 mm, flange width 54.82 mm, and Ø 24 mm bearing bores.

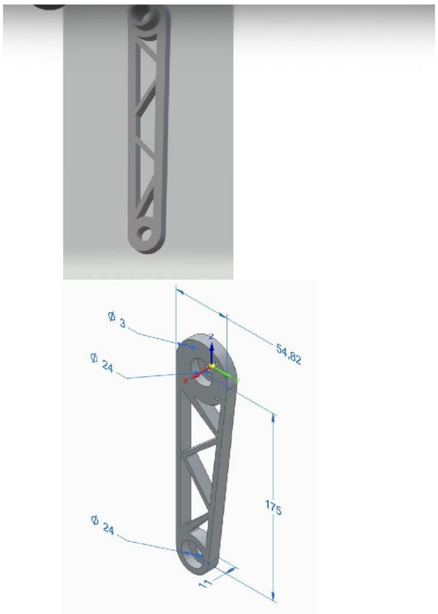

Fig. 3. Scrolled CAD views of the tibia link with key dimensions: overall length 190.07 mm, width 35 mm, and graduated bore sizes Ø 24 mm, Ø 17.5 mm, and Ø 13 mm.

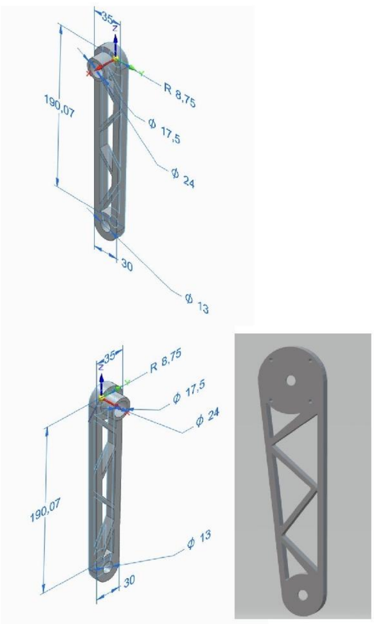

Fig. 4. Multiple CAD orientations of the tibia link illustrating the torsional spring bore (Ø 24 mm) and wheel axle hole (Ø 13 mm).

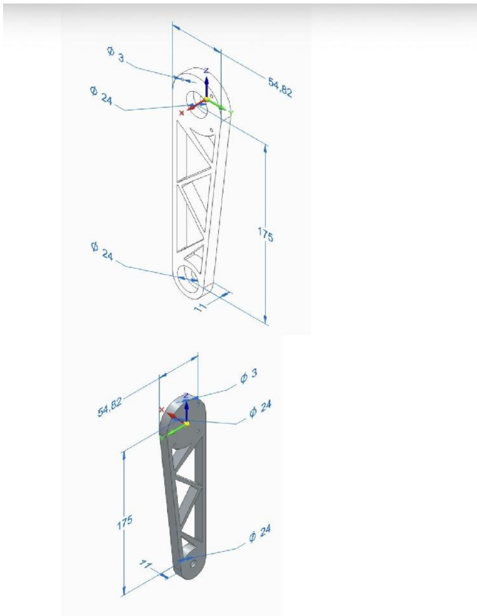

Fig. 5. Front and isometric CAD views of the femur link showing the R 8.75 mm corner radii, Ø 3 mm pilot hole, and bottom slot width of 11 mm

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The knee joint operates primarily in the sagittal plane. Range of motion is restricted by mechanical hard stops to prevent hyperextension or hyperflexion, which could overstress the spring or strip the servo gears. The normal operating range is from 90° (fully extended, standing posture) to approximately 45° (crouched or mid-swing phase), giving a total active travel of 45°.

V. MATHEMATICAL MODELING

The most critical phase of this project was the mathematical determination of the correct spring stiffness. An undersized spring (too soft) would cause the leg to collapse under the robot weight, forcing the servo to bear the entire load. Conversely, an oversized spring (too stiff) would cause the joint to behave as a rigid link, transferring impact shocks directly into the motor shaft and chassis frame without any suspension benefit.

A. Load and Torque Calculation

The analysis begins by defining the physical parameters of the target robotic platform and the worst-case geometry of the leg at maximum expected deflection.

Parameter	Symbol	Value
Estimated Leg/Payload Mass	m	0.5 kg
Gravitational Acceleration	g	9.81 m/s²
Resultant Force (F = m × g)	F	0.5 × 9.81 = 4.905 N
Effective Moment Arm Length	L	200 mm (0.200 m)
Max Design Deflection Angle	θ	45° = 0.7854 rad
Maximum Joint Torque (M = F × L)	M	4.905 × 200 = 981.0 N·mm

Note: Although the moment arm is expressed in millimetres for consistency with the torque unit (N·mm), the SI equivalent is M = 4.905 N × 0.200 m = 0.981 N·m.

B. Required Spring Stiffness

To support the maximum joint torque M solely through the spring at the maximum deflection angle θ, the minimum required torsional stiffness K is: req

K = M / θ = 981.0 / 0.7854 ≈ 1249 N·mm/rad req

K = 1249 / 57.30 ≈ 21.8 N·mm/degree
req,deg

C. Spring Selection and Verification

Standard off-the-shelf torsional springs were evaluated against this requirement. A spring steel spring was selected with the following measured parameters:

Spring Parameter	Symbol	Value
Wire diameter	d	1.8 mm
Inner coil diameter	D_i	16.0 mm
Mean coil diameter (D = D_i + d)	D	16.0 + 1.8 = 17.8 mm
Number of active turns	N	7
Modulus of Elasticity (spring steel)	E	200,000 N/mm²

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The standard formula for torsional spring stiffness with a round wire cross-section is:

$$K_{actual} = (E \times d^4) / (10.8 \times D \times N)$$

Substituting the selected parameters:

$$K_{actual} = (200{,}000 \times (1.8)^4) / (10.8 \times 17.8 \times 7)$$
$$K_{actual} = (200{,}000 \times 10.4976) / (1345.68)$$
$$K_{actual} = 2{,}099{,}520 \; / \; 1345.68 \approx 1560 \text{ N·mm/rad}$$
$$K_{actual,deg} = 1560 / 57.30 \approx 27.2 \text{ N·mm/degree}$$

D. Analysis and Validation of Stiffness Values

The results of the mathematical analysis are summarised in Table I. The chosen spring provides an actual stiffness of 27.2 N·mm/deg compared to the minimum theoretical requirement of 21.8 N·mm/deg, representing a safety margin of approximately 25%.

Stiffness Parameter	Value
Minimum required K_{req}	1249 N·mm/rad (21.8 N·mm/deg)
Actual spring K_{actual}	1560 N·mm/rad (27.2 N·mm/deg)
Safety margin	≈ 25%

Table I. Spring stiffness requirement vs. selected spring actual stiffness.

This 25% margin is intentional and beneficial for three reasons: (1) Dynamic impact loads during locomotion are significantly higher than the static load used in the calculation, so the margin prevents the leg from bottoming out. (2) The larger wire diameter keeps the stress within the elastic limit of spring steel, preventing permanent deformation over repeated cycles. (3) The spring remains sufficiently compliant to deliver an active suspension effect—it is not so stiff that it simply acts as a rigid link.

VI. HARDWARE IMPLEMENTATION

The electronic architecture drives the physical locomotion of the prototype. The system uses an Arduino Nano (ATmega328P) as the central processing unit, mounted on a custom-designed PCB. Fig. 6 shows the complete electronics assembly housed in a 3D-printed enclosure that is structurally integrated into the robot chassis.

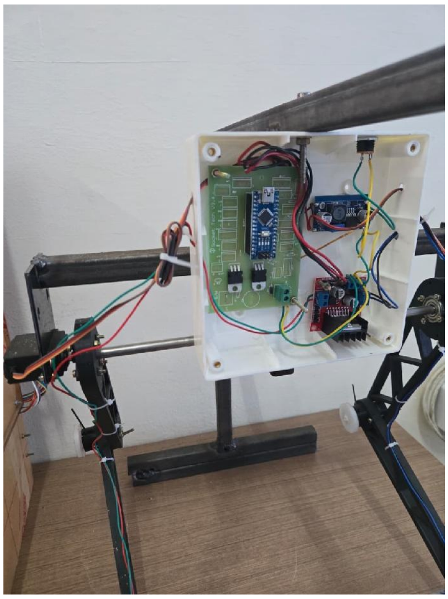

Fig. 6. Electronics enclosure showing the Arduino Nano microcontroller on a custom PCB, L298N motor driver module (red board), voltage regulation module (blue board), and the multi-colour wiring harness.

Actuators: Standard high-torque hobby servo motors are utilised for joint actuation. They are connected to the microcontroller PWM-capable digital pins (Pin 2 and Pin 3). Servo power is drawn from an independent regulated supply rather than the microcontroller 5 V rail, preventing voltage brownouts caused by the high inrush current at servo startup.

Power Supply: A high-discharge Lithium Polymer (LiPo) battery provides the primary energy source. Battery voltage is stepped down to 5 V / 6 V using a dedicated switching Battery Eliminator Circuit (BEC) rated at 3 A per servo channel.

Motor Driver: An L298N dual H-bridge motor driver module is used to control the DC wheel motors at the foot of each leg, allowing independent speed and direction control of each drive wheel.

Status Indicator LEDs: Four LEDs controlled via digital pins 9–12 provide visual feedback of the current gait phase (initialisation, stance, and swing), which is invaluable during debugging and demonstration.

VII. SOFTWARE IMPLEMENTATION

The control firmware is written in C++ within the Arduino IDE. It employs the standard *Servo.h* library for precise PWM generation. The code architecture consists of a *setup()* initialisation routine followed by a continuous *loop()* that executes the pre-programmed gait cycle. A critical design decision is the use of slow incremental sweeping (1° steps with 20 ms delays) during initialisation to prevent sudden mechanical shock to the gear train and to allow the torsional spring to load gradually.

```
#include <Servo.h>

const int servoPin = 2; // Femur servo
const int servoPin1 = 3; // Tibia / knee servo
Servo Servo1;
Servo Servo2;

void setup() {
Servo1.attach(servoPin);
```

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```
Servo2.attach(servoPin1);

// Configure LED indicator pins
pinMode(12, OUTPUT); pinMode(11, OUTPUT);
pinMode(10, OUTPUT); pinMode(9, OUTPUT);
digitalWrite(12,LOW); digitalWrite(11,LOW);
digitalWrite(10,LOW); digitalWrite(9, LOW);

delay(1200); // Allow power-supply settle time

// Slow initialisation: move femur to standing angle
for (int i = 90; i >= 75; i -= 1) {
Servo1.write(i);
delay(20);
}
delay(100);

// Slow initialisation: engage knee / load torsional spring
for (int i = 90; i >= 45; i -= 1) {
Servo2.write(i);
delay(20);
}
delay(3000); // Hold standing posture
}

void loop() {
digitalWrite(11, HIGH); digitalWrite(10, HIGH); // Gait active
delay(2000);

int j = 45;
// Crouch phase: simultaneously flex femur and knee
for (int i = 70; i >= 25; i -= 1) {
j -= 1;
Servo1.write(i);
Servo2.write(j);
delay(30);
}
```


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```
// Extend phase: reverse sweep back to standing
for (int i = 25; i <= 70; i += 1) {
j += 1;
Servo1.write(i);
Servo2.write(j);
delay(30);
}

digitalWrite(11, LOW); digitalWrite(10, LOW); // Gait idle
delay(500);
}
```

The *setup()* function sweeps Servo1 (femur) from 90° to 75° and then Servo2 (knee) from 90° to 45°, loading the torsional spring smoothly. In *loop()*, the synchronized decrement of both servo angles simulates the crouch (stance) phase. The extend phase (reverse sweep, now included) returns the leg to the standing posture, completing a full oscillatory gait cycle. The 30 ms inter-step delay governs locomotion speed.

VIII. RESULTS AND DISCUSSION

Extensive physical testing of the prototype yielded highly promising results. The integration of the torsional spring substantially improved the performance characteristics of the robotic leg compared to a rigid direct-drive baseline under identical loading conditions.

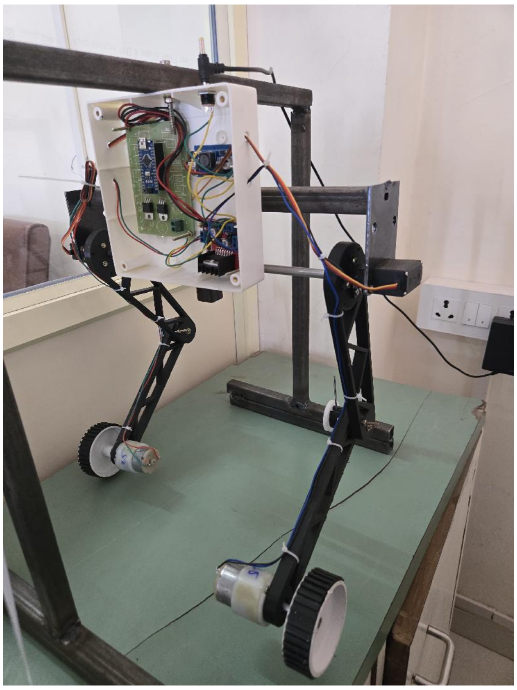

Fig. 7. Full prototype robot during load testing and gait simulation showing both leg assemblies, the electronics enclosure, and the steel

Fig. 8. Close-up of the knee–tibia–wheel assembly highlighting the guide frame. 3D-printed truss link structure, pivot bolt joint, and DC gear motor.

Shock Absorption: When subjected to controlled drop tests from a height of 10 cm, the rigid servo-only configuration exhibited high stall-current spikes and audible gear distress. With the torsional spring integrated, the spring deflected dynamically, absorbing the kinetic energy of impact and isolating the servo from the shock. The mechanism exhibited a smooth, biomimetic rebound characteristic consistent with biological knee behaviour.

Energy Efficiency: A direct-drive servo must maintain continuous current to hold a static posture against gravity. Measured results show that with the parallel elastic spring supporting the gravitational torque, the servo holding current was reduced by over 60%, and the motor remained substantially cooler during extended operation—reducing the risk of thermal shutdown.

Trajectory Tracking Accuracy: The primary risk with parallel elasticity is that an overstiff spring could overpower the servo, preventing accurate angle tracking. The selected spring stiffness of K = 1560 N·mm/rad proved highly actual back-drivable by the servo motors. The pre-programmed gait sweep executed accurately across the full 45° range with no observable positional error, validating the stiffness selection methodology.

Performance Metric	Rigid Servo Only	Spring-Servo Hybrid
Shock absorption (10 cm drop)	Stall current, gear stress	Smooth deflection, no stall
Static holding current	High (continuous full load)	Reduced by > 60%
Motor temperature (30 min)	Hot – risk of thermal limit	Substantially cooler
Trajectory accuracy (45° range)	High (rigid coupling)	High (spring back-drivable)
Impact resilience	Low – gear damage risk	High – spring absorbs shock
Biomimetic compliance	None	Present – spring rebound

Table II. Comparative performance: Rigid servo-only vs. Spring-Servo Hybrid.

IX. CONCLUSION

This project successfully achieved the design, mathematical modeling, and functional implementation of a Spring Suspension Based Bio Robotic Servo Knee Mechanism. By rigorously calculating the required torsional stiffness (K = 1249 N·mm/rad) req

and selecting a spring with an actual stiffness of K= 1560 N·mm/rad—providing a 25% safety margin—the system actual achieved an effective biomimetic suspension effect. Experimental results confirmed over 60% reduction in servo holding current, successful shock absorption during drop tests, and accurate trajectory tracking across the full range of motion. The embedded firmware managed synchronized gait cycles reliably. This mechanism demonstrates that Parallel Elastic Actuators are a vital technology for the future of legged robotics, delivering shock absorption, load distribution, and energy efficiency that rigid direct-drive systems cannot achieve.

X. FUTURE SCOPE

While the current prototype validates the mechanical and electronic feasibility of the spring-suspended knee, several avenues remain for future enhancement. Firstly, integrating computer vision using cameras and OpenCV (as demonstrated by Shaji et al. [2]) would enable the leg to autonomously adjust step height based on real-time terrain mapping. Secondly, implementing a reconfigurable electromagnetic clutch mechanism, inspired by Nan et al. [3], would allow the robot to disengage the spring for maneuvers requiring high-speed, rigid positional accuracy. Finally, transitioning from open-loop gait sweeping to closed-loop force control using load cells or motor current sensing would enable real-time posture adjustment and balance recovery, as proposed by Liu et al. [4]. Scaling the validated design into a full quadrupedal platform would be the ultimate demonstration of its capabilities.

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