Adaptive Soft-Body Robot with Pneumatic Actuation and Bistable Spine for Locomotion

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Abstract: *Soft-bodied robots offer advantages in adaptability and safety, but their locomotion speed and stability remain key challenges. This project explores the use of a bistable actuation system to enhance movement efficiency and optimize the interaction between pneumatic actuation and structural design. By incorporating a spring-reinforced spine and different limb structures, the robot aims to achieve controlled, high-speed motion with improved environmental adaptability. The purpose of this study is to investigate how limb shape, inflation frequency, and terrain type affect the mobility of the robot. Results show that limb shape significantly impacts stability and speed, with the bionic-inspired design achieving higher velocity while the high-friction model provides better balance. Inflation frequency is critical, as excessively low frequencies lead to overinflation and instability. The robot performs well on firm surfaces but experiences reduced mobility on sand and inclined planes. These findings demonstrate that bistable mechanisms and limb optimization can improve the speed and control of soft robots.*

Keywords: *Soft-Body, Pneumatic System, Bistable Mechanisms, Optimizing Locomotion*

1. Introduction

Soft-structured robots, made of compliant materials, have gained traction for their safe human-environment interactions and unique functions like delicate manipulation—capabilities beyond traditional rigid robots. However, their locomotion speed (0.02–0.8 BL/s) remains a key challenge. A 2020 paradigm shift inspired by quadruped spinal mechanics led to tunable bistable soft robots, underexplored due to prior focus on unimodal stability. Bistable mechanisms show promise in boosting soft robot speed/stability, particularly for nuclear-contaminated zones. Their radiation-resistant materials ensure long-term functionality, as shown in Figure 1, while flexibility enables navigation through debris to monitor radiation/air quality in hazardous areas [1-3].

Current soft robot designs, like caterpillar-inspired peristaltic robots (1.8–4 mm/min speed) and multi-stable origami structures, are constrained by material compliance and snap-transition dynamics, highlighting the need for optimized bistable solutions.

Figure 1 The Environmental Effect of Nuclear Pollution, nterfaithsustain.com, 10 Dec. 2021, interfaithsustain.com/nuclear-pollution/.

While current solutions each address unique challenges in hazardous HRIs, limitations remain. Bistable soft robots offer significant advantages through their snap-action dynamics, reducing reliance on external sensors and computational resources. The mechanism also helps recover energy during cyclical tasks, alleviating material fatigue by redistributing stress from viscoelastic components to preloaded springs. While miniaturizing these designs to fit into confined spaces remains a challenge, the integration of compliance, power, and mechanical autonomy makes bistable architectures a transformative advancement in hazardous environment robotics.

The purpose of my project is to design a structure that exploits mechanical bistability to provide high-performance and versatile adaptability to soft robotic systems for a variety of applications such as rapid

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locomotion and high-force manipulation. Inspired by the high-speed quadruped mammalian spine flexion-extension dynamics, I hypothesize a soft robotic architecture with an adjustable bistable spine that rapidly stores and releases energy[4-6].

The core design of our innovation lies in a biomimetic hybrid structure that combines spring-reinforced bistable links that act as artificial vertebrae with pneumatic bending actuators that mimic spinal muscles. This synergistic integration enables energy storage via preloaded linear springs with tunable stiffness. The snap-instability mechanism can be used as a force amplifier, demonstrating baseline force enhancement while maintaining material compliance. The design of fast and powerful soft machines is guided by the physics of elastic bistability. This bistability enables two different dynamic operation modes, namely a bistable transition state and a monostable bending state, which not only expands the potential applications of soft robots but also establishes a new performance benchmark for multifunctional actuator design, especially in scenarios requiring simultaneous high-speed movement and forceful interaction with the environment.

2. Methods

Based on the biological structure of quadrupedal species, my design mainly contains an extendable and inflatable silicone airbag, an adjustable spring-reinforced bistable spine, a system consisting of an electrical circuit, an air pump, and air valves, and the rubber tubes that connects the pump and the airbag.

2.1. Design of Silicone Mold

To begin my design process, I focused on the design of the silicone mold, ensuring that it was both feasible for casting and capable of incorporating air chambers within the structure. The mold's dimensions were carefully considered to ensure that it would fit the necessary components and allow for appropriate deformation during inflation. The mold was designed using 3D modeling software and then printed using a 3D printer. As shown in Figure 2.

Figure 2 3D model of the first version of the silicone mold and Silicone airbags cooled and removed from external supports

After printing the mold, I proceeded with the assembly of the silicone mold, mixing the silicone according to the desired hardness levels (0, 5, and 10) and then pouring it into the mold. Once the silicone is removed from the mold, I connected it to an air pump that could constantly inflate the silicone. As shown in Figure 2,Data on the silicone's deformation during inflation was recorded by observing the bending and deformation patterns as the mold was inflated.

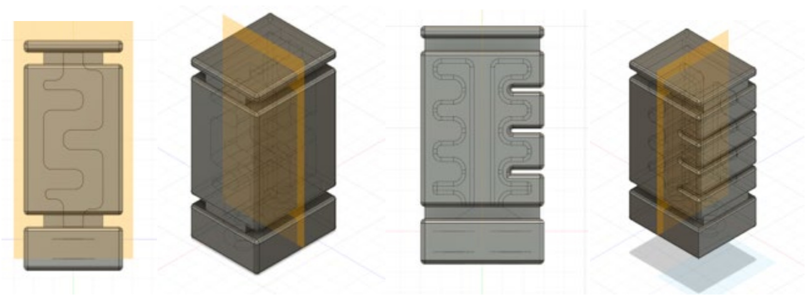

Figure 3 3D front and side view of the second version

Upon observing that the deformation was insufficient, I redesigned the silicone mold to improve the performance of the bending mechanism. This involved creating two new designs for the mold: one with an increased cavity volume and altered shape, and another with dual-sided air chambers instead of a single cavity. Additionally, grooves were added to facilitate easier bending. The support structures were

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also modified to ensure that the inner support could be easily removed after molding. Figure 3 shows one version of my model with grooves added only to one side. Comparing the effect of inflation on bending angle by inflating each airbag, it is shown that the grooves are able to increase bending angle and bending speed.

Experiment 1: investigation on correlation of silicone type and flex angle

The purpose of this experiment is to determine how varying silicone hardness affects the extent of deformation and flexibility, which are crucial factors in the robot's performance. The independent variable is the type of silicone used for modeling, and the dependent variable is the flex angle when inflated. The airbags are connected to the pumps and first deflated for 1.0 second, then inflated for 3.0 seconds. The flex angle is then observed and calculated using an online protractor.

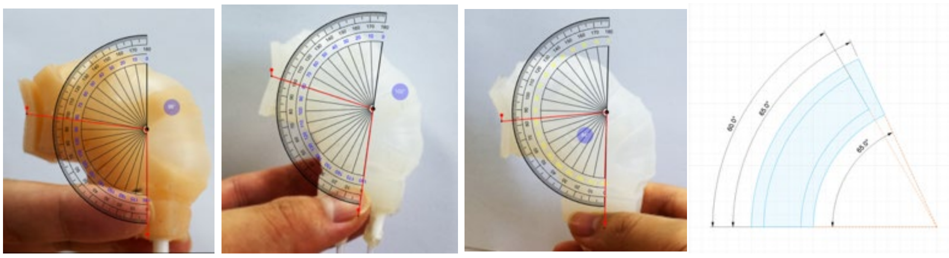

Figure 4 Bending angle of inflated shore 0-10silicone

The bending angle of each silicone can be calculated by subtracting the measured angle in figure 4 from 180 respectively. The angles for shore 0, 5, and 10 are therefore shown as below.

Observing the results, airbags made of all three silicone grades showed significant flexibility. After inflation, the model made of the models were easily deformed and had a large bending angle. The material showed high elastic stretch, and the inflated airbag walls expanded smoothly outward. However, since the surface of grooves are relatively thin and could pop during high air pressure, the models should not be fully inflated during actual operations.

Bending stiffness (S) in a structure is proportional to both the elastic modulus (E) and the moment of inertia (I).

$$S = EI \tag{1}$$

For thin-walled silicone structures, the moment of inertia is more dependent on the cross-sectional geometry than on material stiffness. As shown in Figure4, Since the silicone airbag deforms primarily due to its hollow structure and air pressure, its structural geometry plays a more dominant role in bending than its hardness grade. However, while the results show that all models are suitable for applications where they must achieve large-scale bending and deformation envisioned in our design concept, further experiments should be conducted to test if they could maintain a fixed shape under high force, movement and pressure[7].

2.2. Design of Exoskeleton, Base and Sealing Plug

Next, an exoskeleton connecting two airbags was added to serve as the soft robot's framework and connection point for the spring-reinforced bistable spine. The exoskeleton has two parts, each with two rectangular loops fitting into the airbags' concaves, connected by screws for free bending during inflation.

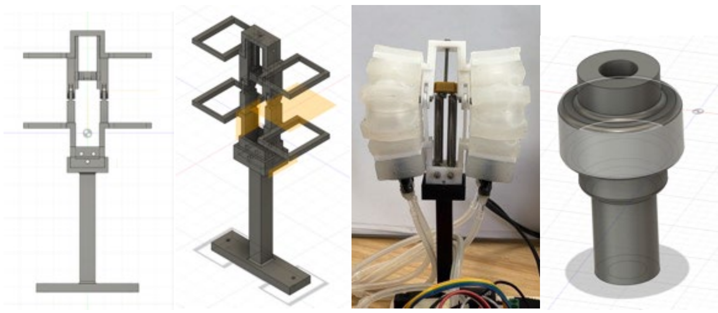

Figure 5 3D front and side view of exoskeleton

During testing, hand-holding the model during inflation caused bending angle measurement errors,

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while tube insertion led to varying air leakage across models, hindering consistent comparisons. To resolve this, a vertical base was designed to fix the exoskeleton and a silicone-glued sealing plug improved airtightness, enabling accurate bending angle comparisons without leakage interference. As shown in Figure 5.

When inflating airbags within the exoskeleton, Shore 0 and 5 silicone models lacked sufficient tenacity to rebound under exoskeleton pressure. Their extreme softness and low elastic modulus meant they stored less elastic energy, failing to generate strong restoring forces. This caused permanent wall thinning—even after deflation, reduced thickness prevented shape recovery, indicating elastic limit exceedance. Thus, Shore 10 was chosen for its higher stiffness and elastic modulus, ensuring robust resilience and shape recovery under exoskeleton constraints. As shown in Figure *6.*

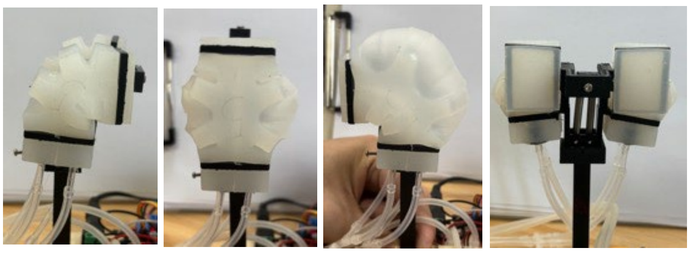

Figure 6 Deformed shore 5 airbag under high pressure and string tension

2.3. Design of Electronic Modules and Pneumatic System

To achieve the regular bending and straightening of the model, a detailed study was made on the principle and assembly method of the pneumatic valve. As shown in Figure 7. I designed a pneumatic system incorporating two pumps and a control valve. The system was designed to allow the model to switch between three states: inflation, maintenance of inflation, and deflation. I mapped out the air path in a schematic and tested the system using an output control valve to manage the air flow, while the pumps were connected to two different outputs, each controlling one pump during inflation or deflation. The advantage of this system is that it utilizes one single pump to control two air chambers simultaneously, reducing energy required.

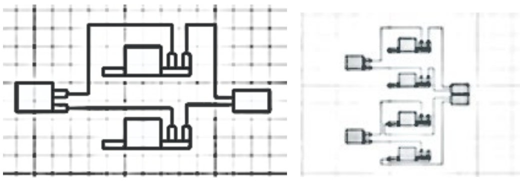

Figure 7 2D Pneumatic system map

My choice of other components for the complete electronic module is based on efficiency, compatibility with my robot's movement and pneumatic system, and adaptability to specific functional requirements. Two separate modules are built for different scenarios: one optimized for high power and pressure to maximize velocity, and one designed with micro-components and low weight for onboard integration, allowing the robot to operate without external tubes[8-9].

Module 1 (Fig 8 is designed to maximize performance, focusing on rapid inflation and deflation to achieve the highest possible velocity. The key characteristics of this module include a high-pressure air pump capable of delivering strong airflow, 12V power supply to sustain the energy demand, ESP32 for advanced control and wireless connectivity, A4950 motor driver to ensure smooth and powerful actuation, and an external Tubing System to connects the robot to a centralized air pump. This module is particularly suitable for laboratory testing and high-speed performance experiments, where maximizing velocity is the main objective. However, it also has certain limitations, including excessive heat loss due to high voltage and limited maximum displacement due to the length of tubes.

In comparison, Module 2 (Fig 8) prioritizes self-sufficiency and mobility, allowing the robot to operate independently without external connections. The design includes a lightweight pump small enough to be embedded within the exoskeleton, a 4.5V control board ensuring energy efficiency, and minimal tubing integration that reduces external dependencies. This setup enables the robot to navigate real-world environments with greater autonomy, making it more adaptable to field applications. The integration of all components in Module 2 reflects a balance between compactness and functionality, ensuring that the robot maintains both flexibility and performance without being constrained by external equipment.

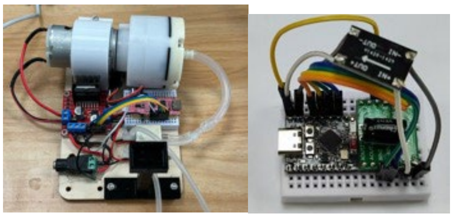

Figure 8 Electronic module 1 and 2

The silicone-spring composite structure used in this project offers inherent radiation resistance, which can be a key advantage in harsh environments. Future developments could focus on enhancing energy efficiency. The potential applications of this robot are vast, particularly in autonomous exploration of hazardous areas like nuclear disaster sites, where its mobility is essential.

To further refine the system, I used an Arduino program to control the pneumatic system through Bluetooth via a mobile app. The program allowed for switching between inflation and deflation states. A slider on the app controlled the inflation frequency, while two buttons were used to activate the switching of states. When pressed, it sent a signal to the Arduino board, which then activated the relevant control circuits to start the pumps and open the control valve.

2.4. Design of adjustable spring-reinforced bistable spine

Due to constant bending, springs are consumable. To ease replacement, they're secured to a small component with a headless screw. One end has a nut attached to a long screw, allowing vertical movement within exoskeleton slides. Turning the long screw adjusts spring length: shorter lengths enhance bending angle but risk overloading the system. As shown in Figure 9.

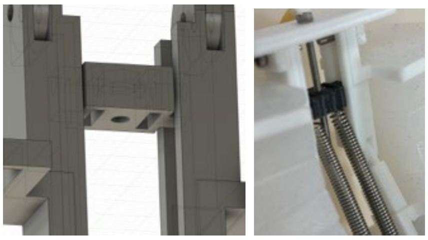

Figure 9 3D model of spring component

To investigate the effect of spring hardness on the deformation and bending of the silicone, I tested various spring hardness levels and adjusted the spring length using a screw. I then recorded the resulting bending angles and compared the effects across different spring configurations.

2.5. Design of Paw Component

To investigate the influence of paw morphology on the locomotion performance of a soft robot, two terminal paw designs were devised: As shown in Figure 10. one replicating the curvature of a leopard's hind-limb skeleton and the other optimized for maximum contact angle. Trials were conducted on silicone pads emulating natural terrain, using per-cycle displacement and 40-cm average speed as metrics. Results indicate that the large-contact-angle configuration (Type 2) increases static friction and propulsive force while reducing backward slip, raising per-cycle displacement from 1.38 to 1.64 body lengths and average speed from 0.86 to 0.98 body lengths per second. The bionic configuration (Type 1, As shown in Figure 11) sacrifices this speed for superior stability through more even load distribution and shock-absorbing curvature.

Subsequent investigation of actuation frequency revealed that a 300 ms inflation period enables the robot to traverse 40 cm in 7 s (≈0.98 bl/s). Extending the period to 500 ms causes rollover due to prolonged airbag residence, whereas continuous inflation (0 ms) yields the lowest speed (≈0.45 bl/s).

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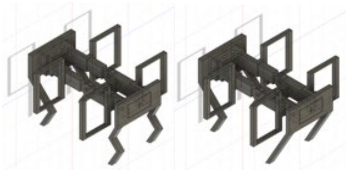

Figure 10 3D side view of exoskeleton with type 1 and 2 paw components

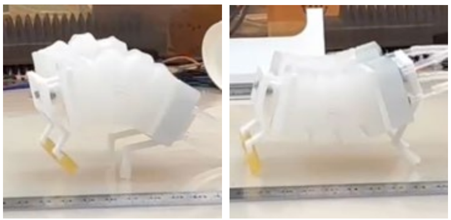

Figure 11 Stage 1, 2 movement of robot with paw type 1

Experiment 2: Mobility of robot on different surfaces

Figure 12 Movement of robot on sandground and inclined sandground

Table 1 Mobility of robot on different surfaces

Surface	Silicone	Sand	Sand + inclined
Time to travel 40cm (s)	7.0	19.0	22.0
Average velocity (cm/s)	5.71	2.11	1.82
Average velocity (/bl)	0.98	0.36	0.31

Different surfaces introduce varying levels of friction and resistance, which can impact the effectiveness of the robot's movement. This experiment demonstrates that the robot can move across multiple surfaces, maintaining effective locomotion on smooth and moderately rough terrains. However, it exhibits reduced mobility on loose surfaces like sand, where decreased traction limits displacement per cycle. As shown in Figure 12. Similarly, on tilted surfaces, gravity and uneven weight distribution affect its ability to maintain stability and consistent movement. As shown in Table 1.

3. Discussion

These results match theoretical predictions for soft-bodied robotic locomotion, where movement efficiency relies on surface traction, inflation control, and stability. Reduced mobility on sand validates friction principles, as loose particles hinder grip and energy transfer. Inclined surface performance aligns with gravitational force and weight distribution impacts on soft structures.

Errors may arise from air pressure fluctuations, slight material property variations, or environmental factors like airflow. Repeated trials showed minor displacement/velocity differences due to inflation response or material deformation nuances, plus unexpected issues like limb misalignment or leaks.

Future work should prioritize surface adaptability optimization via active grip materials or adaptive limbs, refine inflation control with real-time feedback, and investigate environmental impacts (e.g., temperature, humidity) on silicone properties. These insights will drive more resilient soft robots for challenging/hazardous environments.

4. Conclusion

These results contribute to the broader field of soft robotics by addressing key challenges in locomotion efficiency, surface adaptability, and stability. Compared to existing work, which often focuses on crawling or peristaltic motion with limited speed, my study explores bistable actuation mechanisms to enhance both movement precision and velocity. The findings align with previous research indicating that soft-bodied robots struggle with mobility on loose and inclined surfaces, but they also demonstrate that design optimizations—such as limb shape and inflation control—can mitigate some of these limitations.

The results directly address my research question by demonstrating the effectiveness of different limb structures, inflation frequencies, and surface interactions in influencing the robot's movement. The data supports the hypothesis that optimizing actuation timing and limb design improves both speed and stability, while also highlighting certain limitations, such as instability at low inflation frequencies and reduced traction on soft terrain.

This work has potential applications in autonomous environmental monitoring, particularly in hazardous or unpredictable terrains where traditional rigid robots struggle. The ability to operate independently without external air supply makes it suitable for long-term deployment in challenging environments, such as disaster-stricken areas, nuclear-contaminated zones, or extraterrestrial exploration. Additionally, further improvements in material selection and control algorithms could enhance its adaptability for search-and-rescue missions or infrastructure inspections in complex environments.

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