

Experimental Assessment of the Performance of the Snake Robot

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Abstract:

A snake robot is a bio-inspired robotic system that mimics the form and motion of a snake. The present research presents pressure-bending angle and the pressure-applied force relationships for three metamaterial-based pneumatic robot actuator models of different sizes, designed in SolidWorks and manufactured using a 3D printer. The practical results showed a direct proportionality between chamber size and bending angle. At the same time, it was noted that there is an inverse relationship between chamber size and the applied force when the pressure is held constant, as a basic design criterion. The experimental results also showed a linear direct proportionality between the pressure and the bending angle and a non-linear direct proportionality between the pressure and the applied force. The bending angle of the system with a large chamber was large, whereas that of the snake robot with a small chamber was small.

Keywords:

Assessment; Experimental; Metamaterial; Performance; Snake Robot.

Highlights:

- The relationship of pressure with the bending angle is linear, and the relationship of pressure with the applied force is quadratic.
- When the volume of the chamber is large, it leads to a large deformation of the material.
- Inverse proportionality between chamber size and applied force, and direct proportionality between chamber size and bending angle.

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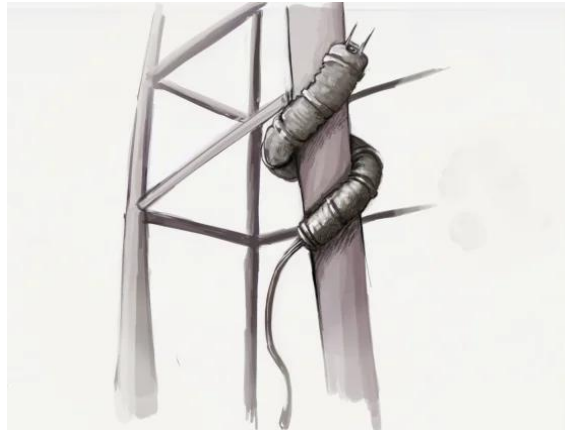
1. INTRODUCTION

Snake robots, also known as serpentine robots, are bio-inspired machines designed to mimic the movement and flexibility of real snakes. These robots are made up of multiple articulated segments connected by joints, allowing them to perform a wide range of motions, including slithering, climbing, rolling, and swimming [1,2]. The range of potential applications for this new generation of robots is medium-sized. It includes, among other things, exosuits to rehabilitate patients or help the elderly [3], surgical assistance [4], and ocean exploration [5]. For example, several recent survey articles have addressed key areas of this interdisciplinary domain—associated manufacturing techniques [6], applications [7], and control strategies [8]. However, the lack of analysis and simulation tools slows down progress in this field [9]. A metamaterial is any material engineered to have a property that is

not found in naturally occurring materials. They are made from assemblies of multiple elements fashioned from composite materials such as metals and plastics. The materials are usually arranged in repeating patterns at scales that are smaller than the wavelengths of the phenomena they influence. Metamaterials derive their properties not from the properties of the base materials but from their newly designed structures. Their precise shape, geometry, size, orientation, and arrangement give them smart properties that enable them to manipulate electromagnetic fields [10]. According to [11], metamaterials can be divided into two major classes based on the mathematical approaches used to describe them. The first class includes DNG and SNG structures, whereas the second class includes PBG (photonic crystal) structures, also known as photonic bandgap materials.



(a) The Use of the Snake Robot in Medicine and Rescue.



(b) Check Piers and Scaffolding in Dangerous Environments Using Snake Robots.



(c) Robot Snakes Used in Firefighting.



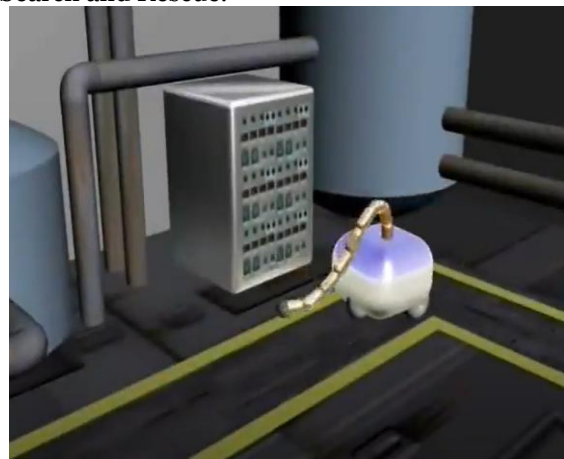
(d) Robot Snakes Used in Nuclear Sites.



(e) After an Earthquake, Search and Rescue.



(f) A snake Robot Used to Inspect Pipelines.



(g) Inside-Process Plant Inspection and Maintenance.



(h) Pipeline Inspection Using a Snake Robot.



(i) The Snake Robot is Set up at the Location.

Fig. 1 Different Uses of the Snake Robot.

The operator control unit and rainwater pipe are shown being inserted by the robot in two different positions in the image above. The snake robot is used for storm sewer pipe inspection [16]. Zhou et al. [17] present a new flexible snake robot with several motion gaits and a rigid-flexible connection system. A bending model was built to help the soft understand the robot's behavior. Moreover, a dynamic model is constructed to map the link between joint torque and input air pressure, therefore providing a basis for efficient robot control. Seyidoglu and Rafsanjani [18] reported on a modular soft robot with rectilinear movement composed of outdoor cloth. With an eye on the skin's role in propulsion, the design captures the snakes' flexibility. It offers a weight- and material-cost-effective method for a robot to navigate limited environments. With possible uses ranging from search-and-rescue operations to field inspection and space exploration, integrating lessons from snake biology into soft robotic designs promises to produce more intelligent, flexible, and efficient robotic systems. This research primarily focuses on experimental curves from a practical perspective to describe relationships among several parameters, rather than on mathematical analysis. However, a few parts of the article include values that describe the relationship between these parameters, making the paper more accessible to researchers interested in applications who want to

understand how simulation contributes to this exciting and promising multidisciplinary field. The present study aims to develop a kinematic model of the flexible actuator and analyze it using the Kenovia program. In this method, each part of the soft actuator is designed using multi-stiffness links, connected by joints. This approach used a simple procedure to reduce the error between the desired end-effector position and the foreground kinematic equations. In this energy-saving method, a second desired task is added; e.g., to control the bending angle, additional constraints can be used. The presented method has been verified through various simulations and experimental results, demonstrating its applicability to different paths. One of the main advantages of the presented method is the ability to use any robot controller. The current research presents a fast and accurate method for designing, manufacturing, and analyzing soft robots, especially snake robots. This research presents a mechanical design for a snake robot in search, rescue, and exploration, particularly in light of recent crises the world has faced, such as earthquakes, fires, and others.

2.METHODOLOGY

Soft robots are robots that promise to enable the manipulation of existing objects. Their bodies are fragile and have widely varying shapes, making them prone to injury during safe interaction with humans in complex shared work environments, and during the

performance of complex tasks in difficult areas [19]. Recently, many articles have been published about snake robots. These articles discuss how to design mechanical structures, control algorithms, and select materials with desired properties. Snake robots have been researched and published over the past few decades. The amount of writing has increased dramatically [20-22]. This collection of literature is a comprehensive examination and discussion of snake robotics, with articles covering everything from mathematical modelling to control strategy to mechatronics design and implementation methods. Hence, they have conducted a comprehensive analysis of the development potential of different snake robots from diverse perspectives, which is remarkable and underscores the importance of researching classifications of snake robots. Specialized arrangement methods for snake robots based on movement elements capture the basic features of snake robots, including ergonomics, joint design, gait, control mechanisms, and operation. The present research addressed the following aspects:

- a) A brief introduction to the snake robot and metamaterials and their uses in manufacturing soft robots.
- b) Types of snake robots and their classifications and applications.
- c) The results and curves obtained in practice are discussed.
- d) Presents the conclusion of the paper.

3.Types of Snake Robots and Their Classifications

Snake robots are robotic devices that mimic the movement and flexibility of a snake. These robots are classified by design, movement mechanisms, and intended applications. Below are the main types and classifications [23]:

3.1.By Design

- 1) Modular Snake Robots: Composed of multiple identical modules, each with its actuator and sensor. The modules can be assembled in different configurations, allowing the robot to perform various tasks.
- 2) Wheeled Snake Robots: Feature wheels attached to the segments, enabling faster movement on flat surfaces. They can still perform serpentine motions; however, they are optimized for terrains where wheels are advantageous.
- 3) Jointed Snake Robots: Have a series of jointed segments, which provide a high degree of flexibility. The joints are typically powered by actuators that enable the robot to mimic a snake's undulatory motion.

3.2.By Movement Mechanism

- 1) Serpentine Locomotion (Lateral Undulation): Mimics the common side-to-side motion of real snakes. The robot

propels itself by generating waves that travel along its body.

- 2) Sidewinding: The robot lifts parts of its body off the ground and moves sideways, similar to how some desert snakes move, which is useful in sandy or loose terrains.
- 3) Rectilinear Locomotion: The robot moves in a straight line by alternately stretching and contracting its segments. It is similar to how some large snakes, like pythons, move.
- 4) Concertina Locomotion: The robot moves by anchoring part of its body while pulling or pushing the other segments, and it is used in confined spaces like tunnels.
- 5) Rolling: The entire body of the snake robot rolls like a wheel. It is a rare type of locomotion and is typically used for quick escapes or movements.

3.3.By Control Mechanism

- 1) Autonomous Snake Robots: Operate without human intervention, relying on onboard sensors and AI algorithms to navigate and perform tasks.
- 2) Semi-Autonomous Snake Robots: Require human input for certain tasks but can perform some operations autonomously.
- 3) Teleoperated Snake Robots: Controlled remotely by a human operator, who directly manipulates the robot's movements and actions.

3.4.By Power Source

- 1) Electrically Powered: Use electric motors or actuators to generate motion, which are common and can be powered by batteries or external power sources.
- 2) Hydraulically Powered: Use hydraulic actuators, which are powerful and suitable for heavy-duty tasks; however, they require a complex power system.
- 3) Pneumatically Powered: Use compressed air to move the segments. These are often used in environments where electric power might be hazardous.

3.5.By Material

- 1) Rigid Body Snake Robots: Made from rigid materials like metal or hard plastics, providing strength and durability.
- 2) Soft Body Snake Robots: Made from flexible materials, allowing for smoother and more adaptable movements, especially in delicate environments.

These classifications help in understanding the wide variety of snake robots and their potential applications in different fields [24].

4.EXPERIMENTAL WORK

The relationship between pressure and bending angle in a snake robot depends on the design of

its actuators. Typically, these actuators can be pneumatic, hydraulic, or based on smart materials such as electroactive polymers or shape memory alloys [25]. In the present research, the external structure of the snake robot was made of nylon fibers, while the internal components were made of silicon rubber type (RTV2). This section presents the overall system fabrication, including the fabrication of the snake robot and the experimental work steps. The experimental part includes manufacturing an exoskeleton for the snake robot from a metamaterial. The goal of this work is to control the robot's movement and analyze it under different conditions. Thus, the work began by designing the proposed components and assembling them to form the external structure of the snake robot. The external structure manufacturing process includes using CNC fiber laser technology to manufacture the internal links and joints, and a 3D printer to manufacture the soft pneumatic actuator. The soft pneumatic actuator is

designed in three pieces, each containing three stones with tubes inside. When air is pumped into these tubes, the actuator moves in several directions. The dimensions of this actuator are shown in Fig. 2. This actuator was then wrapped with nylon fibers to increase the applied force, as shown in Fig. 3. This section also includes experimental procedures, in which a comparison was made among three snake robot models designed from the same material. Still, the difference was only in chamber size (small, medium, and large), as shown in Fig. 4, and the effect of the chamber size on bending angle and the applied force was observed while keeping the chamber air pressure constant. After that, the components were connected to a platform, which is a compressor, a load cell, and a controller (Mega), and each manufactured model of the snake robot was connected to this platform so that when pumping the air from the compressor, the robot's finger touches the load cell and reads the value of the force applied to each model, as in the Fig. 5.

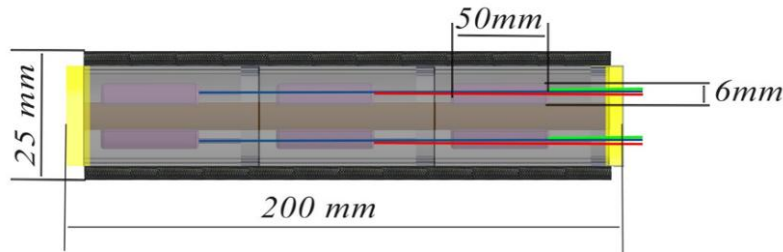


Fig. 2 Dimensions of Soft Pneumatic Actuators.



Fig. 3 Wrapping the Operator with Nylon Fibers.



Fig. 4 Chamber of the Snake Robot.

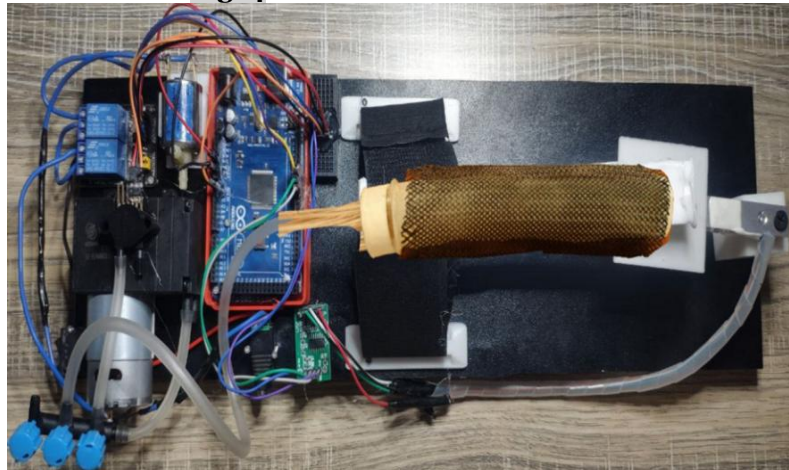


Fig. 5 Robot's Finger and the Load Cell.

5.RESULTS AND DISCUSSION

The relationship between the bending angle and the chamber size in the snake robot is direct: the bending angle increases with the chamber size for the soft pneumatic actuator. When the pump pressure is set to 16 Psi, the bending angle of the

actuator with a large chamber is 63.3° . The value of the bending angle for the actuator with a medium-sized chamber is 59.3° , while the bending angle of the small chamber size actuator is 48.5° , as shown in Fig. 6.



Fig. 6 Bending Angle Values for Three Different Chamber Size Models of the Pneumatic Actuator.

The relationship between pressure and the bending angle in the snake robot is direct: increasing pressure increases the bending angle [26, 27]. For a small-chamber soft pneumatic actuator, at the pressure value (2 Psi), the bending angle is (7°), and at pressure (6 Psi), the bending angle value is (18.6°). Thus, as the pressure increases, the bending angle increases until the pressure reaches 16 Psi, at which the bending angle is (48.5°), as shown in Fig. 7. As for the soft pneumatic actuator with a medium-sized chamber, at the pressure value (2 Psi), the bending angle is (7.1°), and at pressure (6 Psi), the bending angle value is (23.4°). Thus, as the pressure increases, the bending angle increases until the pressure reaches 16 Psi, which has a bend angle (of 59.3°), as shown in Fig. 8. Finally, for the soft pneumatic actuator with a large chamber, at the pressure value (2 Psi), the bending angle is (80°). At pressure (6 Psi), the bending angle value is (24°). Thus, as the pressure increases, the bending angle increases until the pressure reaches 16 Psi, which has a bend angle (63.3°), as shown in Fig. 9. The relationship between the applied force and the chamber size in the snake robot is inverse. Also, it has been observed that the applied force increases as the chamber volume decreases in the soft pneumatic actuator. At a pump pressure

of 16 Psi, the force applied to the actuator with a large chamber was measured at 6.6 N. The value of the force applied to the actuator with a medium chamber size is 7.9 N, while the force applied to the actuator with a small chamber size is 9.2 N. There is a direct quadratic relationship between the pressure and the applied force in the snake robot, such that both increase [28-30]. For a small chamber soft pneumatic actuator, at a pressure of 4 Psi, the applied force is 4.2 N, and at a pressure of 10 Psi, the applied force is 7.5 N. Thus, as the pressure increases, the applied force increases until the pressure reaches 16 Psi, at which point the applied force is 9.2 N, as shown in Fig. 10. As for the soft pneumatic actuator with a medium-sized chamber, at the pressure value 4 Psi, the applied force is 3.1 N, and at pressure 10 Psi, the applied force value is 6.5 N. Thus, as the pressure increases, the applied force increases until the pressure reaches 16 Psi, which has the applied force 7.9 N, as shown in Fig. 11. Finally, for the soft pneumatic actuator with a large chamber, at the pressure value 4 Psi, the applied force is 2.6 N. At a pressure of 10 Psi, the applied force value is 5.3 N. Thus, as the pressure increases, the applied force increases until the pressure reaches 16 Psi, at which point the applied force is 6.6 N, as shown in Fig. 12.

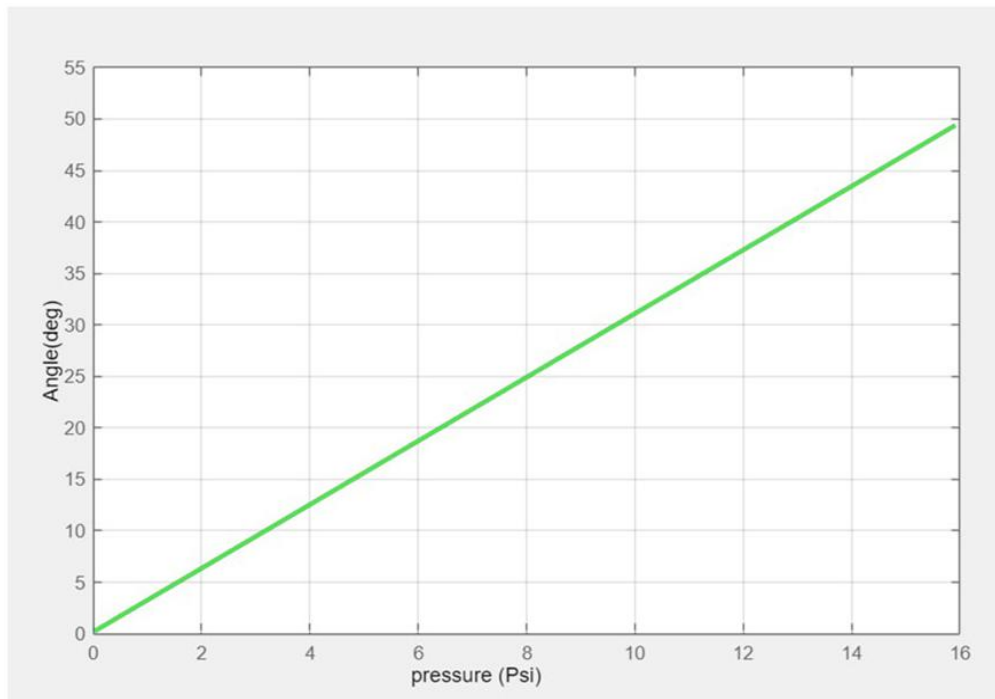


Fig. 7 Relationship of Pressure with Bending Angle of a Small-Chamber Pneumatic Actuator.

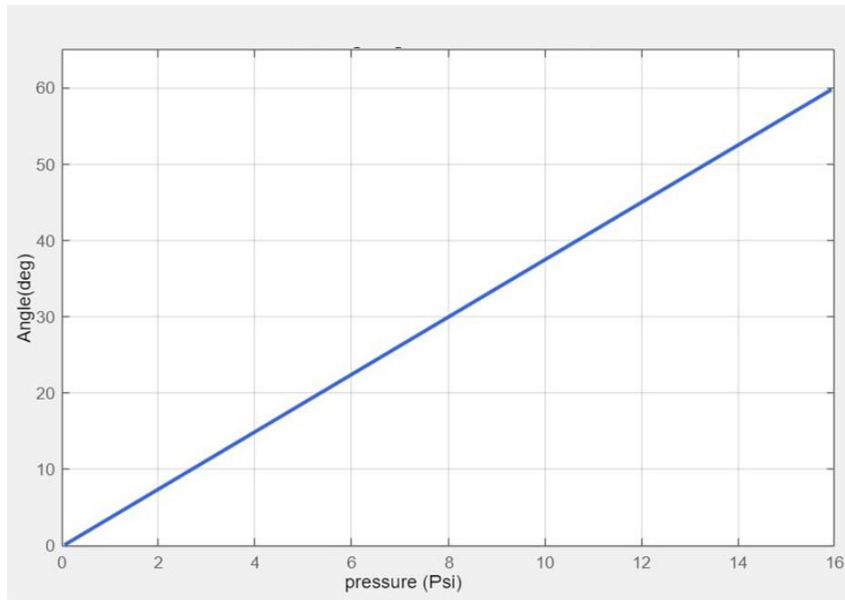


Fig. 8 Relationship of Pressure with Bending Angle of Medium-Chamber Pneumatic Actuator.

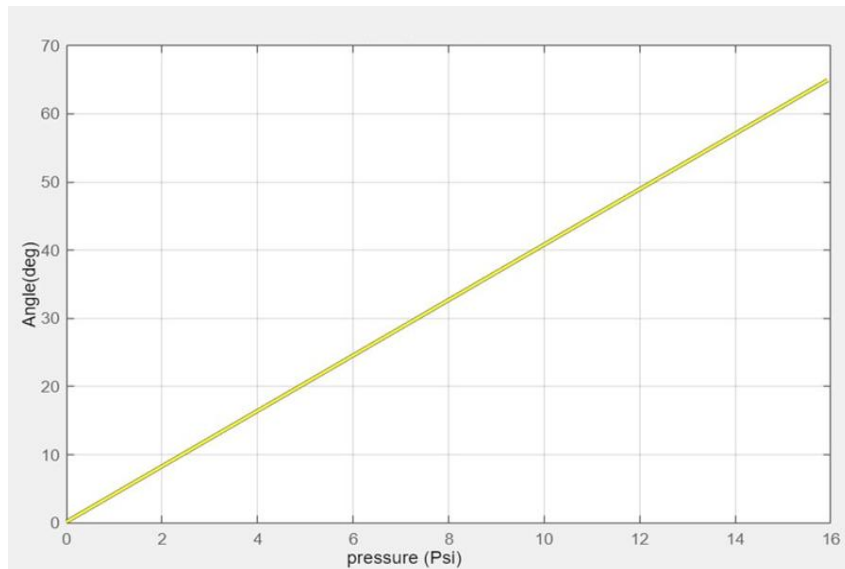


Fig. 9 Relationship of Pressure with Bending Angle of a Large-Chamber Pneumatic Actuator.

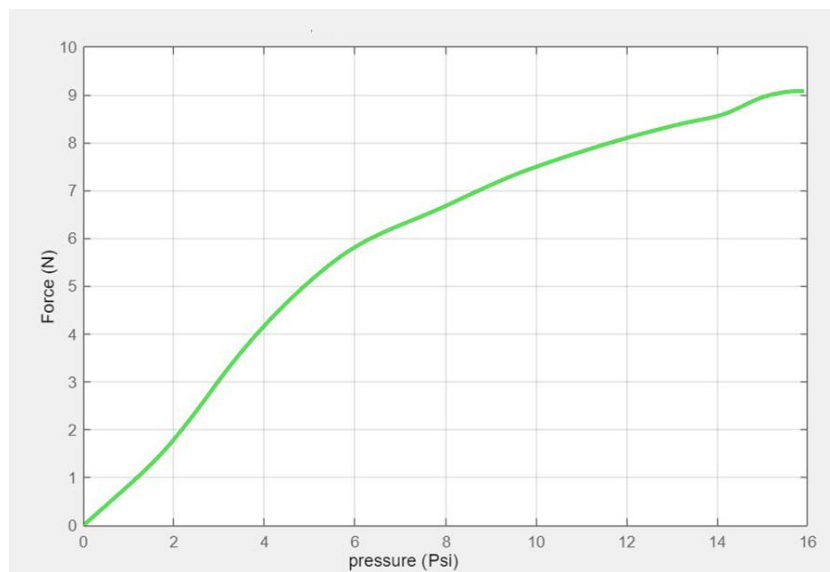


Fig. 10 Relationship of Pressure with Applied Force of Small-Chamber Pneumatic Actuator.

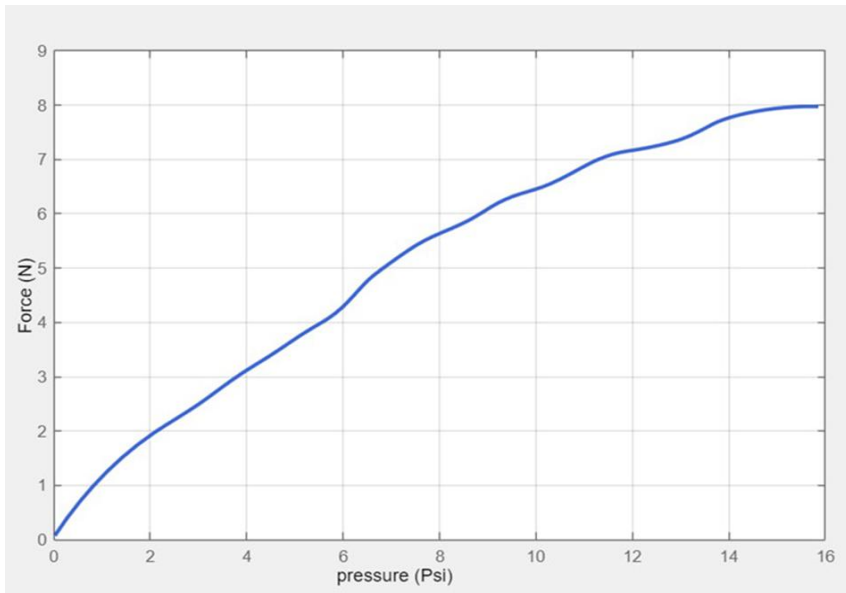


Fig. 11 Relationship of Pressure with Applied Force of Medium-Chamber Pneumatic Actuator.

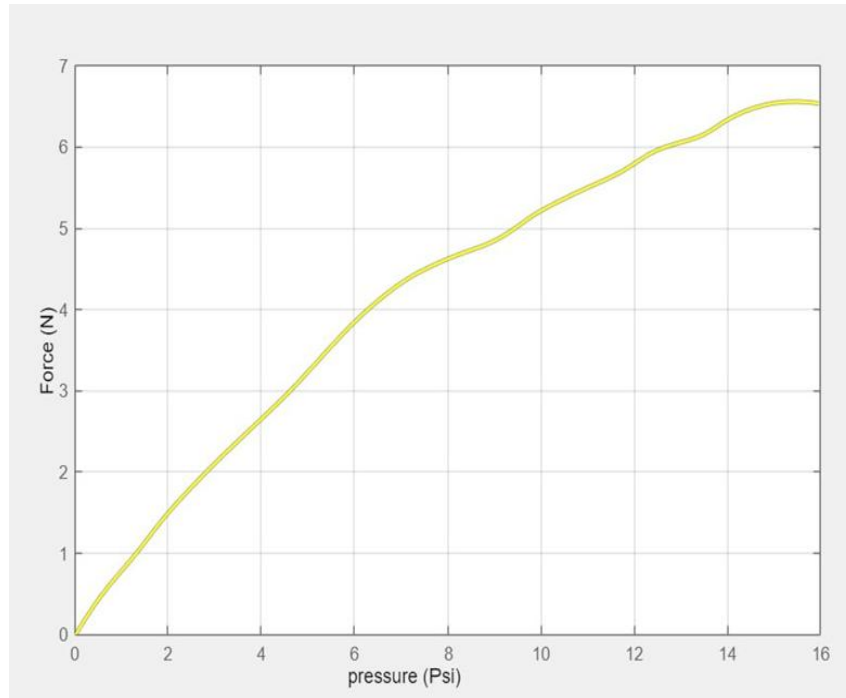


Fig. 12 Relationship of Pressure with Applied Force of Large-Chamber Pneumatic Actuator.

6. CONCLUSIONS

Several important points can be concluded that indicate the success of the electronic and mechanical design of the snake robot, as follows:

- The relationship between pressure and the bending angle is linear, and that between pressure and the applied force is quadratic.
- The relationship between pressure and bending angle in a snake robot is fundamental to its design and operation. By experimentally determining this relationship, the robot's movement can be accurately controlled, ensuring precise and reliable performance.
- For the snake robot with a small chamber, the applied force was greater, and vice versa:

for the large-chamber robot, the applied force was less.

- For the snake robot with a large chamber size, its bending angle was large; for the snake robot with a small chamber, it was small.
- Inverse proportionality between chamber size and applied force and direct proportionality between chamber size and bending angle.
- When the chamber volume is large, it leads to greater material deformation, and vice versa when applying the same pressures in ANSYS.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Hawazen N. Shubat: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. *Ali H. Mohammed*: Methodology, Investigation, Writing – review & editing, Investigation. *Omer K. Ahmed*: Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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