

Article

Extending Inflatable Actuator with Spool Mechanism Incorporating Air Supply Tubes Within Its Body

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Abstract

Soft actuators provide a wide range of motion capabilities, allowing for the advancement of novel mobile robots. However, soft actuators that possess the capability required to achieve three-dimensional movement are limited. In addition, the presence of air supply tubes poses a challenge to utilizing pneumatic actuators as mobile robot components. This study presents a long inflatable actuator with a novel structure in which air supply tubes are arranged within its body. This structure enables the extension of the inflatable tube with minimal deformation. The proposed actuator comprises an inflatable tube and a spool mechanism. The length of the actuator is controlled by a motor. The performance of the actuator was evaluated experimentally, validating its alignment with our proposed models. The results showed that the proposed actuator exerted extension and contraction forces of 28 N and 87 N, respectively. Furthermore, the proposed actuator can be equipped with a gripper at its tip, enhancing its functionality. In a demonstration, this gripper-equipped actuator successfully extended to grasp a bar at a height of 1.3 m and contracted while lifting a 1.0 kg base. This demonstration indicated that the proposed actuator could provide the required arm motions of a bi-arm climbing robot.

Keywords: soft actuator; soft robot; inflatable actuator; extension and contraction mechanism; spool mechanism; gripper

1. Introduction

Actuators are crucial in the function of robots. Several actuators have been developed to suit different applications. For example, electromagnetic motors are commonly utilized in robots of various sizes, whereas hydraulic actuators are preferred for applications requiring high power output. In addition to conventional rigid actuators, many soft actuators have been developed recently, providing robots with new flexible motions that were previously unattainable with conventional rigid actuators.

Soft actuators are characterized by their flexibility and lightweight design. The former is achieved by utilizing flexible materials, such as silicone rubber, allowing the actuator to adapt to different objects and environments [1,2]. The latter was achieved using a pneumatic cavity structure. The interior of the actuator is filled with air, which provides the actuator with a significant deformation, despite its light weight [3,4]. The motion types between conventional rigid actuators and soft actuators also differ. Most electromagnetic motors produce rotary motion. Some hydraulic actuators offer linear motion, and others offer rotary motion. By contrast, soft actuators typically exhibit bending motion. Extending and contracting motions are also commonly offered by soft actuators.



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The aforementioned advantages of soft actuators enhance the capabilities of small mobile robots, such as legged robots and climbing robots and provide a novel movement method. For example, utilizing extending motion allows a climbing robot to efficiently approach and grasp an object located at a distance, whereas contracting motion enables the robot to smoothly move its body toward the grasped object. Some climbing robots that can move through objects composed of pipes or move by hanging on a ladder have been developed [5,6]. These are examples of robots that have performed complex-flexible motions that are difficult for conventional rigid robots. The flexibility of soft robots also has positive implications for movement in complex environments. This flexibility makes them well-suited for tasks that require interaction with intricate structural objects, setting them apart from unmanned aerial vehicles, which struggle with physical contact.

Soft robots can move by interacting with their surroundings due to their flexibility, whereas their movements in complex environments involve problems stemming from their driven mechanism. As mentioned above, many soft robots are pneumatically driven, and they move while carrying tubes for air supply. In complex environments, snagging of these tubes can impede the movements of robots. In addition, the tension caused by the weight of the air supply tube or the tube caught on surrounding objects may apply force to the actuator and cause undesired deformation [5]. To overcome this issue, some untethered soft mobile robots, such as crawling robot and jumping robot, equipped with pneumatic circuits have been developed [7,8]. While such mechanisms further enhance the adaptability of soft robots to their environment, to the best of our knowledge, no climbing robot capable of both three-dimensional movement and untethered operation has yet been developed.

Soft actuators require the following capabilities to achieve three-dimensional climbing movement utilizing structural objects as described above: (1) The actuator must maintain its shape during the extending motion to reach the target object, (2) it generates a significant contraction force to lift its own body incorporating a pneumatic circuit for untethered movement, (3) it has a large ratio of length change owing to its extending motion, and (4) it allows controlled length adjustment both during extension and contraction motions. However, to the best of our knowledge, few actuators satisfy all these capabilities. Pneumatic artificial muscle is the most common example of a soft actuator [9–11]. Although they can generate a significant contraction force despite their compact size, they cannot generate sufficient extending force or allow controlled length adjustment during extension because their extending motion depends on the elastic deformation of their material. Other soft actuators that perform well in bending and contraction deformations cannot extend linearly while maintaining their shape because they require gravitational force for extension [12,13]. The inverse pneumatic artificial muscle, which undergoes extending deformation when subjected to high pressures, can generate a significant extending force [14,15]. However, their amount of deformation is largely affected by the magnitude of the external force because they rely on an elastic force to produce contraction deformation. Furthermore, applications to climbing robots, as mentioned above, require larger deformation.

Several actuators besides artificial muscle-type actuators can extend deformation. Actuators that employ origami structures to induce contracting deformation have been developed [16–18]. Some origami-based actuators utilize the restoring force caused at the folded edges to contract [16,17]. These actuators can generate contraction motion with a simple structure alone, but they are strongly affected by external force. Other origami-based actuators that utilize a negative pressure for contracting motion [18]. The mechanism with negative pressure allows motion control through internal pressure, minimizing the

effect of external forces. However, contraction involves the uniform deformation of the entire body. Consequently, fine-tuning the length by combining extending and contracting motion is difficult. A reel-type pneumatic actuator is very lightweight and has a large extension ratio [19]. The length of this actuator is also easily altered by external forces and internal pressures because it uses a torsion spring for its motion. Some soft-growing robots have a retraction mechanism and can be utilized as an extendable soft actuator [20–22]. In recent years, although complex shape control methods have been developed based on fundamental mechanisms previously proposed [23], the designs of these robots are unsuitable for use as components of climbing robots because they require a sealed container for their base and some actuators, which are quite bulky. The research, which minimizes components and mounts them as an extendable arm on a quadrotor, has also been conducted [24]. The weight of the arm is extremely light, under 0.65 kg. However, its load capacity is not mentioned, possibly because their primary purpose is inspection. Thus, an actuator that fully satisfies the aforementioned capabilities has yet to be developed. We believe that developing actuators that satisfy these capabilities and employ a structure where the air supply tubes do not affect motion will contribute to the realization of novel climbing robots.

This study aims to develop a novel soft actuator capable of generating force and controlling its length during the extension and contraction motions. In addition, we propose a design in which the air supply tube does not obstruct the motion of the actuator. The main contributions of this study are as follows: (1) An actuator that allows easy length control was developed by combining an electromagnetic motor with an inflatable structure. (2) Models of the extending force and contracting force were developed. (3) A configuration incorporating the air flow path internally to deduce the effect of the air supply tube on actuator motion was developed. Moreover, some experiments were conducted to validate the performance of the proposed actuator. We confirmed that the extension and contraction forces generated by the actuator agreed with the developed models. The extension force was 28 N, and the contraction force was 87 N under the operating conditions applied. The experimental result indicated the proposed design reduced the effect of the air supply tube on the actuator deformation. In addition, the demonstration showed that the proposed gripper-equipped actuator can be operated as a climbing robot arm.

The remainder of this paper is organized as follows: Section 2 presents the design of the extension and contraction mechanism. The force and tube deformation models are outlined in Section 3. The fabricated actuator is outlined in Section 4, and Section 5 presents the experiments conducted using the fabricated actuator. A sample application is shown in Section 6. Section 7 discusses the performance of the proposed actuator. Finally, Section 8 presents the conclusion.

2. Extension and Contraction Mechanism

2.1. Inflatable Tube and Spool Mechanism

First, an inflatable tube is utilized for the proposed actuator, as in previous studies [18,19], owing to its light weight and elongated body. While telescopic actuators composed of rigid components and have large extension ratios have been developed [25,26], they are unsuitable for the objective of this study owing to their weight. Conversely, an inflatable structure with thin plastic film is considerably lighter because air occupies most of the body. Hence, an inflatable tube is suitable for this study.

In the case where the inflatable tube is composed of plastic film, elastic deformation does not occur in the body compared with pneumatic artificial muscles. Thus, the actuator with inflatable tube requires a mechanism to induce contraction. Based on previous studies, a spool (reel) mechanism or an origami structure is useful for inducing contraction. Fine-tuning the length is difficult because the contracting deformation with an origami structure results in uniform deformation of the entire body, as mentioned above. Conversely, the spool mechanism allows for easy length control by adjusting the amount of rotation. Therefore, the proposed actuator employs a spool mechanism.

The actuator with a spool mechanism developed by Hammond et al. employs a torsion spring for winding up the inflatable tube [19]. The length of the actuator is dependent on the balance between the tensile force from the torsion spring and the internal pressure within the tube. Hence, the length can be controlled based on the magnitude of the internal pressure under no-load conditions. However, when external forces are applied, length control is difficult because the relationship between the internal pressure and actuator length varies. This characteristic is undesirable considering a climbing robot transporting objects. Hence, this study controls the amount of rotation of the spool and actuator length using an electromagnetic motor. The tube is fed out and wound up by applying torque from the motor to the spool. This mechanism enables length control unaffected by external forces.

2.2. Structure Incorporating Air Supply Tubes in the Body

An extendable actuator must have the capability to gradually deform from its tip while approaching an object at a distance. The air must be supplied to the actuator tip to enable extension from the tip. In a previous study by Hammond et al., the air supply port was positioned on the fixed side, and the spool was located at the extension tip [19]. However, the spool should be positioned on the fixed side to reduce the weight of the tip. When the spool is positioned on the fixed side and the air supply tube is connected to the end of the inflatable tube, the unfixed section of the air supply tube may apply force to the tip of the inflatable tube and impede actuation owing to its own weight or snagging on surrounding objects. The same issue occurs with the tube supplying air to the gripper mounted at the tip of the actuator.

This study addressed this issue by proposing a structure that incorporates the airflow pass in its body. An overview of the proposed structure is shown in Figure 1a. Air supply tubes for the actuator and gripper are fixed to the inner surface of the inflatable tube. The air supply tubes are connected to the rotary shaft of the spool, which has an internal airflow pass, as shown in Figure 1b,c. Both ends of the shaft are connected to the pneumatic circuit. Since the position of the rotary shaft remains unchanged even when the spool rotates, the actuator can be driven with no movement of the connection point to the pneumatic circuit. The shaft is enclosed within the spool cylinder, and the end of the inflatable tube is fixed to it. In addition, the actuator is enclosed within the outer cover to prevent the expansion of the wound tube. The shaft receives torque input from the motor. The inflatable tube extends by rotating the shaft in the tube-unwinding direction when air is supplied and contracts by rotating the shaft in the tube-winding direction when the air is exhausted.

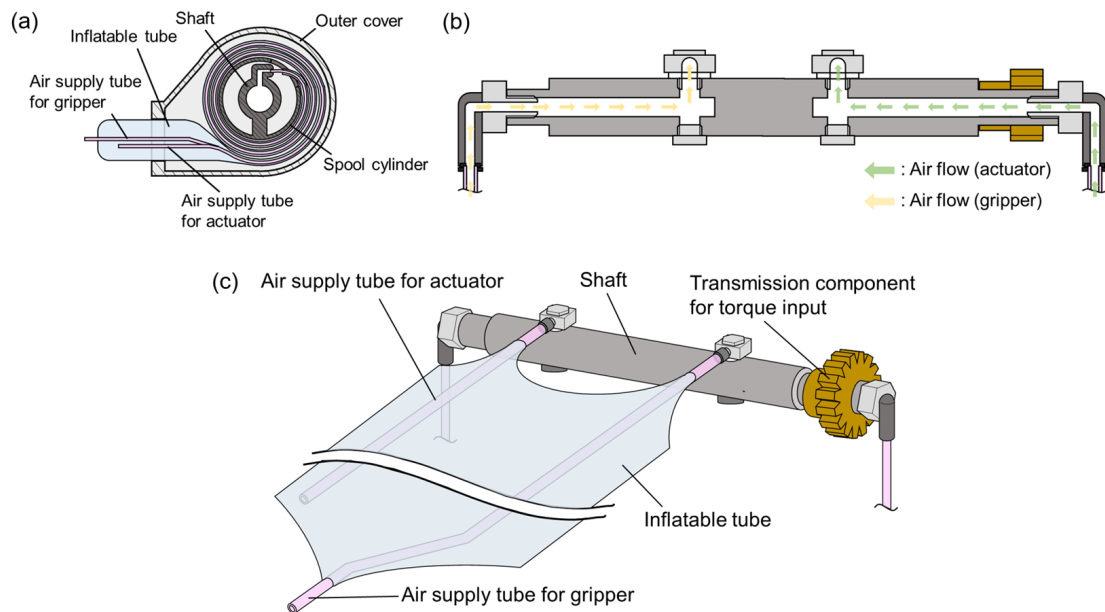


Figure 1. Proposed structure that incorporates an airflow pass in its body. (a) Overview of the actuator with the proposed structure. (b) Internal structure of the rotation shaft. (c) Arrangement of air supply tubes.

3. Models

3.1. Model of Extension Force

The actuator extends by unwinding the inflatable tube and filling it with air. Hence, the extension force produced by the actuator primarily depends on the internal pressure of the inflatable tube.

The extension state model in contact with an object is shown in Figure 2. When the tip of the inflatable tube contacts an object and the tube is unwound, the tube initially inflates to fill the space inside the outer cover. Once the spaces are filled, the tube extends, generating force to push the object by unwinding the tube and filling it with air. Because the tube is subjected to resistant forces, such as the friction between the film and surface of the outer cover of the actuator and the force required to bend the tube in the outer cover, the force F_{extend} exerted by the tube on the object is expressed as follows:

$$F_{\text{extend}} = \pi p_{\text{tube}} r_{\text{tube}}^2 - R_{\text{tube}}, \quad (1)$$

where p_{tube} represents the internal pressure of the inflatable tube, r_{tube} represents the radius of the cross-sectional area of inflatable tube, and R_{tube} represents the sum of the resistance forces to which the tube is subjected. The sum of resistance forces R_{tube} consists of the frictional force occurring between the inflatable tube and the outer cover, and the force required for the bending deformation of the tube. According to Comer and Levy, the force causing transverse buckling in an inflatable tube is proportional to the magnitude of the internal pressure [27]. The frictional force between the tube and the cover is also proportional to the magnitude of the internal pressure. Thus, R_{tube} is assumed to be proportional to the internal pressure and described as

$$R_{\text{tube}} = \alpha_{\text{resist}} p_{\text{tube}}, \quad (2)$$

where α_{resist} represents the resistance coefficient based on factors such as the friction and tube deformation. Based on these models, the actuator generates a constant push force that is independent of the actuator length.

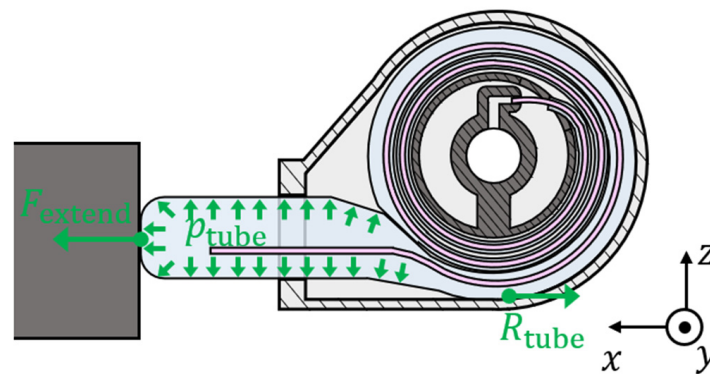


Figure 2. Model of the extension motion with a pushing object.

While the actuator pushes the object, the actuator receives a compressive force in the axial direction due to the reaction force. When this axial load exceeds the buckling load, buckling occurs in the inflatable tube. Fichter developed a buckling load model for axial load as follows [28]:

$$F_{cr} = \frac{E_{film} I_{tube} \frac{\pi^2}{L_{tube}^2} (\pi r_{tube}^2 p_{tube} + G_{film} \pi r_{tube} t_{film})}{E_{film} I_{tube} \frac{\pi^2}{L_{tube}^2} + \pi r_{tube}^2 p_{tube} + G_{film} \pi r_{tube} t_{film}}, \quad (3)$$

$$I_{tube} = \pi r_{tube}^3 t_{film}, \quad (4)$$

where F_{cr} is the buckling load, E_{film} is Young's modulus of the inflatable tube, I_{tube} is the second moment of area for the inflatable tube, L_{tube} is the length of the inflatable tube, G_{film} is the shear modulus of the inflatable tube, and t_{film} is the thickness of the film in the inflatable tube. Hence, the extension force of the actuator expressed by Equation (1) when $F_{extend} < F_{cr}$.

3.2. Model of Contraction Force

The actuator contracts by winding an inflatable tube around the spool. Hence, the contraction force is primarily determined by the torque applied to rotate the spool.

The contracting state model for pulling an object is shown in Figure 3. Notably, this model assumes that the inflatable tube is fully exhausted, as any remaining air in the tube may impede contraction and reduce the contraction force. When the extended length of the inflatable tube is L_{extend} , the outer radius of the spool with the wound tube r_{spool} is expressed as follows:

$$r_{spool} = \sqrt{\frac{t_{tube} (L_{max} - L_{offset} - L_{extend})}{\pi}} + r_{spool_0}^2, \quad (5)$$

where r_{spool_0} represents the radius of the spool with no inflatable tube, L_{max} represents the length of the inflatable tube mounted on the actuator, L_{offset} represents the distance between the spool and the exit of the outer cover, and t_{tube} represents the thickness of the inflatable tube, including the air supply tubes given by

$$t_{tube} = 2(t_{film} + t_{supply}), \quad (6)$$

where t_{film} and t_{supply} represent the film thickness of the inflatable tube and the wall thickness of the air supply tube, respectively. The relationship between the contraction force $F_{contract}$ and the input torque to the spool T_{spool} is described as

$$F_{contract} = T_{spool} / r_{spool}. \quad (7)$$

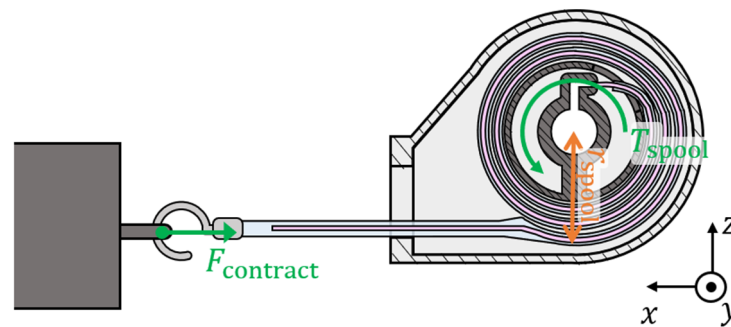


Figure 3. Model of the contraction motion with a pulling object.

Then, T_{spool} is expressed as follows:

$$T_{\text{spool}} = \eta_{\text{trans}} \eta_{\text{gear}} T_{\text{motor}}, \quad (8)$$

where η_{trans} is the transmission efficiency to the spool, η_{gear} is the reduction ratio by gears, and T_{motor} is the output torque by the motor. Thus, F_{contract} is expressed as

$$F_{\text{contract}} = \frac{\eta_{\text{trans}} \eta_{\text{gear}} T_{\text{motor}}}{\sqrt{\frac{t_{\text{tube}}(L_{\text{max}} - L_{\text{offset}} - L_{\text{extend}})}{\pi}} + r_{\text{spool}_0}^2}. \quad (9)$$

This model shows that F_{contract} increases with the extension of the actuator.

3.3. Influence of the Air Supply Tube

The arrangement of the air supply tube affects contact with surrounding objects. Even when no contact occurs, the weight of the air supply tube causes deformation in the inflatable tube. While the study simulating the deformation of inflatable tubes under external forces with finer resolution have been conducted [29], this research employs the traditional and simple method of treating them as cantilever beams [27]. This subsection shows the effectiveness of fixing the air supply tube inside the inflatable tube by comparing the differences in deformation between the case where the air supply tube is connected outside to the tip of the inflatable tube and the case where it is fixed inside the inflatable tube.

Figure 4a shows the actuator with the air supply tube connected to the tip. When the actuator extends in L_{extend} , the force F_{tip} acting on the actuator tip is given by

$$F_{\text{tip}} = P_{\text{supply}}/2, \quad (10)$$

where P_{supply} is the magnitude of the gravitational force acting on the air supply tube, described as follows:

$$P_{\text{supply}} = \rho_{\text{supply}} L_{\text{extend}} g, \quad (11)$$

where ρ_{supply} and g represent the mass per unit length of the air supply tube and gravitational acceleration, respectively. Since the actuator is considered to have a concentrated load acting at its tip, the displacement δ_{outside} is expressed as

$$\delta_{\text{outside}} = \frac{F_{\text{tip}} L_{\text{extend}}^3}{3EI} = \frac{\rho_{\text{supply}} L_{\text{extend}}^4 g}{6EI}. \quad (12)$$

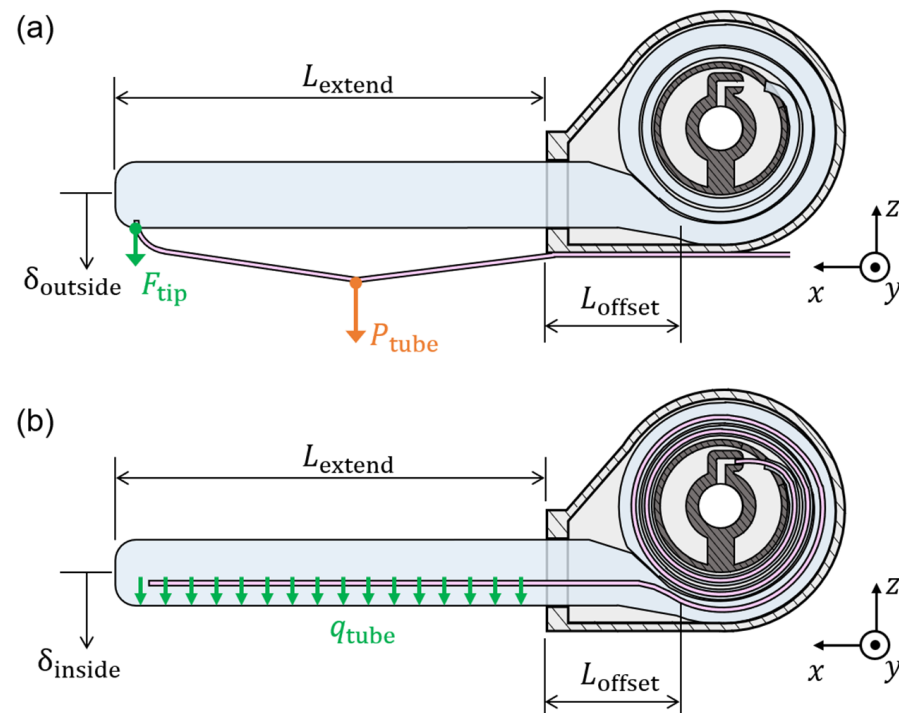


Figure 4. Influence of the air supply tube on actuator deformation. (a) The case where the air supply tube is connected to the tip of the actuator. (b) The case where the air supply tube is fixed inside the actuator.

Figure 4b shows the actuator with the air supply tube fixed inside. The force exerted by the gravitational force on the air supply tube is considered a distributed load q_{supply} , and it is given by

$$q_{\text{supply}} = \rho_{\text{supply}} g. \quad (13)$$

The displacement δ_{inside} of the actuator when a distributed load is applied is described by

$$\delta_{\text{inside}} = \frac{q_{\text{supply}} L_{\text{extend}}^4}{8EI} = \frac{\rho_{\text{supply}} L_{\text{extend}}^4 g}{8EI}. \quad (14)$$

From the above equations, the relationship between δ_{inside} and δ_{outside} can be expressed as follows:

$$\delta_{\text{inside}} = \frac{3\delta_{\text{outside}}}{4}. \quad (15)$$

Therefore, the displacement is smaller when the air supply tube is fixed internally than when it is connected to the tip. However, since this model approximates the inflatable tube as a general cantilever beam, the actual deformation of the inflatable tube in the actuator cannot be quantitatively estimated from this model.

4. Fabrication

4.1. Inflatable Tube Incorporating Air Supply Tubes

The laminated film comprising a 0.015 mm-thick nylon and a 0.040 mm-thick low-density polyethylene is used for the film of the inflatable tube ($t_{\text{film}} = 0.055$ mm). While a low-density polyethylene film offers good thermal processability due to its low melting point, its tensile strength is low. On the other hand, a nylon film has higher tensile strength, though its high melting point causes poor heat processability. The laminating film used in this study offers both of these advantages. Low-density polyethylene is placed on the inside of the tube and nylon on the outside, and they are adhered directly together with adhesive.

The Young's modulus of the laminated film E_{film} is 751 MPa and the shear modulus of the laminated film G_{film} is 254 MPa.

A silicone tube with a diameter and wall thickness of 4 mm and 0.75 mm, respectively, was used as the air supply tube inside the inflatable tube. The method for attaching the air supply tube to the inflatable tube is shown in Figure 5. Within the inflatable tube, the supply tubes were fixed to the left and right edges in the folded state. The supply tubes were secured by thermally bonding with a piece of laminated film. At both the tip and base ends of the inflatable tube, the air supply tubes were fixed via thermal bonding. A piece of laminate film (with the polyethylene side facing outward) was attached to the supply tube using double-sided tape and then sealed by thermal bonding. These thermal bonding procedures were carried out using a soldering iron.

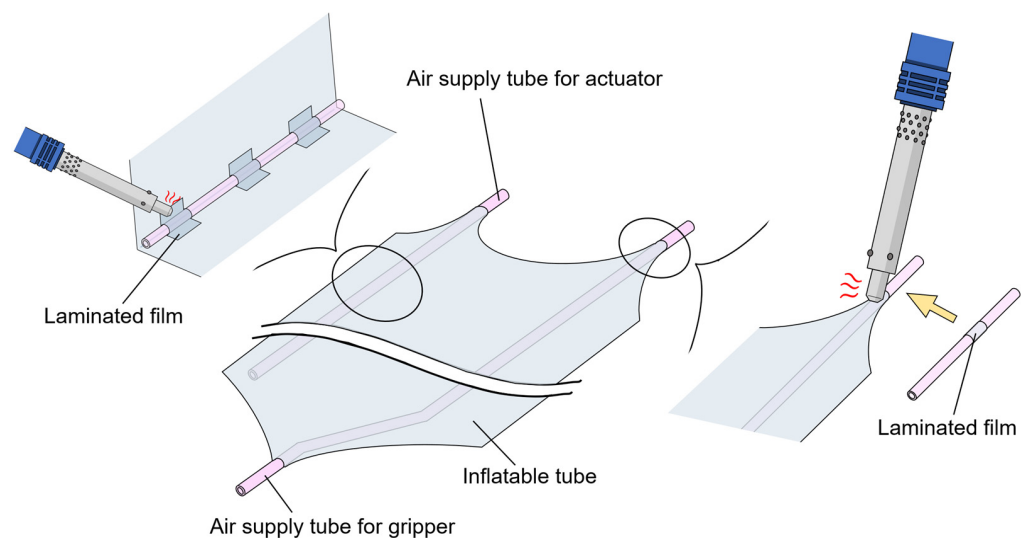


Figure 5. Fabrication method for attaching air supply tubes to the inflatable tube.

4.2. Shaft and Spool Connected to Which the Inflatable Tube Is Connected

The details around the shaft are shown in Figure 6. The shaft was made of aluminum. As shown in Figure 1b, the shaft incorporates an internal air flow pass. Two fittings were mounted on the shaft as air outflow ports. A spool for winding the inflatable tube was attached to the shaft. The inflatable tube was fixed to the spool using bolts. A non-inflatable section was installed at the base side of the inflatable tube. The boundary of the non-inflatable section was created by thermal welding.

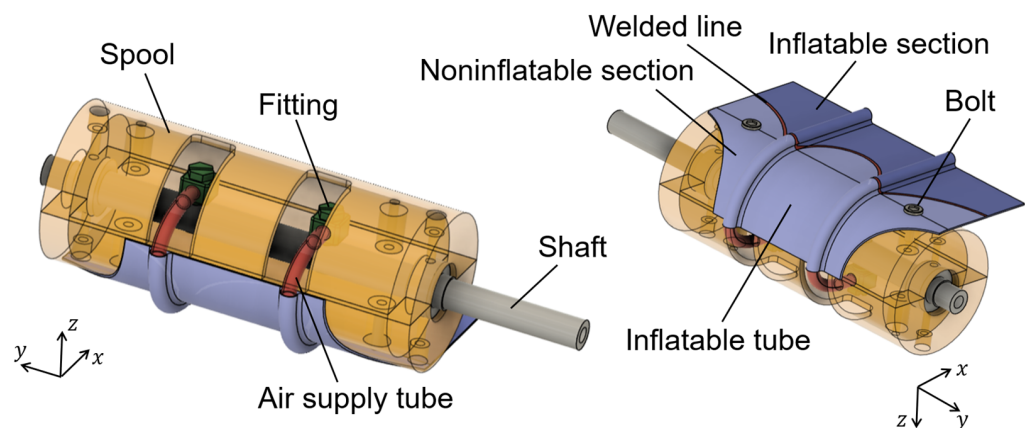


Figure 6. Structure of the shaft and spool.

4.3. Assembled Actuator

The assembled actuator is shown in Figure 7. The shaft was rotated using a motor equipped with a worm gear. A DC-gear motor of 2.0 W (pololu-3720, Pololu Corp., Las Vegas, NV, USA) was used. The gearhead attached to the motor featured a reduction ratio of 250:1. The relationship between the torque output from the motor with gearhead, and the input current is expressed by

$$T_{\text{motor}} = \frac{i_{\text{in}} - 0.13}{2.3}, \quad (16)$$

where i_{in} represents the current supplied to the motor. The worm gear provided an additional reduction ratio of 30:1. The transmission efficiency to the spool η_{trans} was 0.2. Rotary fittings are attached at both ends of the shaft. They allowed for continuous rotation and connected seamlessly to the pneumatic circuit.

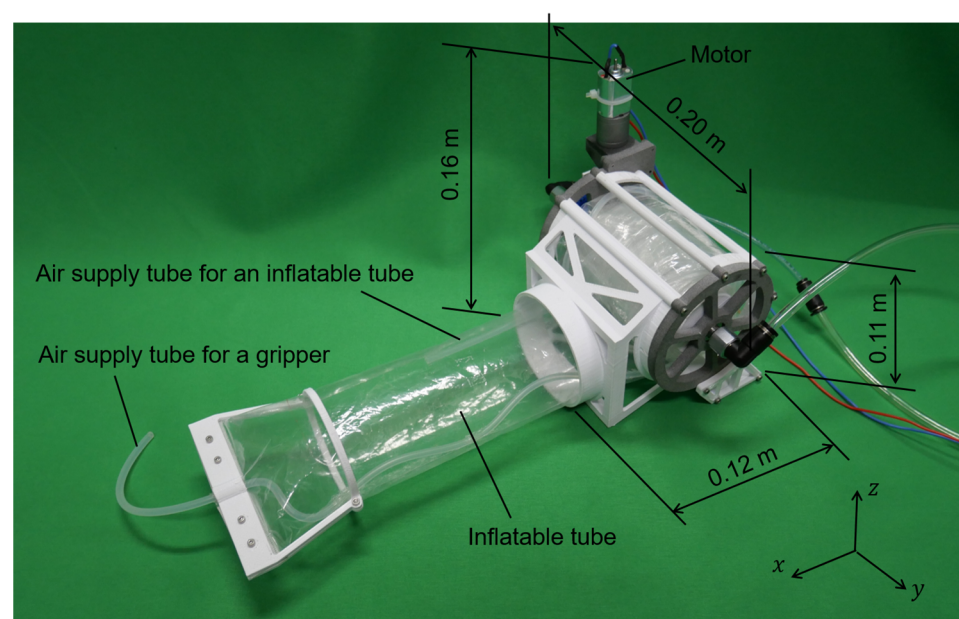


Figure 7. Fabricated actuator.

The side plates of the outer cover were made of polyamide, and other components of the outer cover were made of polylactic acid using a 3D printer. The overall weight of the actuator, excluding the inflatable tube and pneumatic circuit, was 0.42 kg. The weight per unit length of the inflatable tube with an air supply tube is 36 g/m. The length of the inflatable tube mounted on the actuator (L_{max}) was 1.1 m, and the distance between the spool and the exit of the actuator (L_{offset}) was 0.1 m.

5. Experiments and Results

5.1. Experiment on the Extension Force

The experiment conducted to evaluate the extension force involved measuring the resistance force R_{tube} and extension force F_{extend} . First, an experiment to measure R_{tube} was conducted. We removed the front cover of the actuator and secured the actuator to the stand with no inflatable tube to measure R_{tube} . An inflatable tube was then inserted in a way that it folded back inside the case around the shaft. Once inflated, one end of the tube was pulled, and the force required for the tube to move through the case was measured using a digital force gauge (ZTS-500N, IMARA Co., Ltd., Aichi, Japan). The inner pressure was varied from 6 to 18 kPa in 2 kPa increments, with each measurement repeated six times. Figure 8 shows an overview of the experiment.

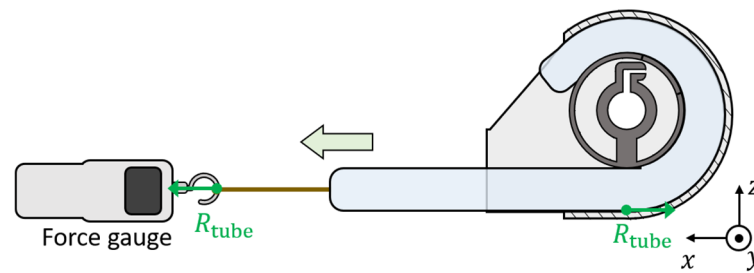


Figure 8. Overview of the experiment for measuring the R_{tube} .

The measured resistance forces are shown in Figure 9. Using this result for obtaining α_{resist} for model (2), as $\alpha_{\text{resist}} = 1.61 \times 10^{-3}$ N/Pa. This value was derived from fitting a line to the measured data. The broken line in Figure 9 represents the model (2) with this α_{resist} .

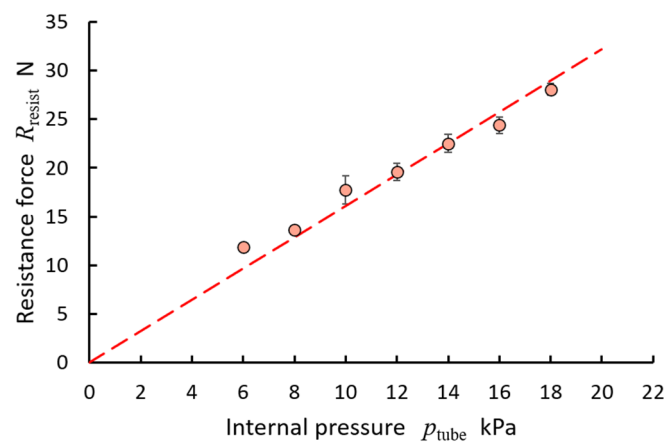


Figure 9. Plot of resistant forces against internal pressure. Each plot represents the average, and the error bar represents the standard deviation. The broken line shows model (2), with α_{resist} derived from fitting a line.

Next, an experiment to measure F_{extend} was conducted. The actuator was secured to the stand constructed from an aluminum frame. The actuator was supplied with 10 kPa of air, and the tube was extended by 0.20 m. The force gauge was positioned so that the tip of the gauge and that of the tube made contact. Subsequently, the actuator was slightly contracted. After that, the actuator was extended, and the maximum extension force F_{extend} was measured. The tube length was varied from 0.20 to 0.90 m in increments of 0.10 m, with the internal pressure varied at 10, 14, and 18 kPa. Each experiment was repeated six times under each condition. The experimental equipment is shown in Figure 10.

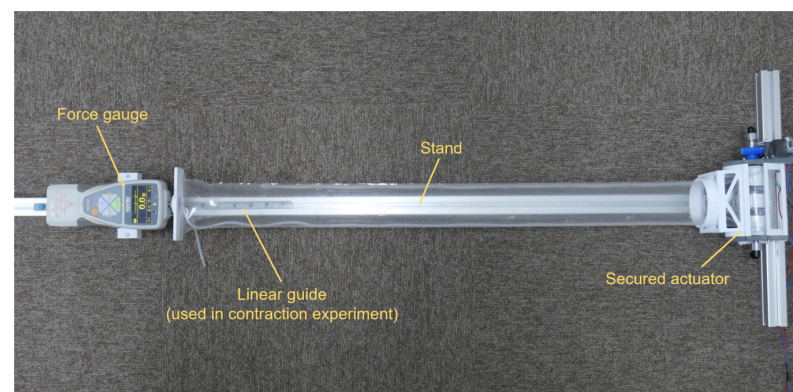


Figure 10. The experimental equipment used in extension experiment and contraction experiment.

The measured extension forces are represented as plots in Figure 11. The extension forces were almost identical regardless of the tube length from 0.20 to 0.80 m. The theoretical values of the extension force obtained from these results and models (1) and (2) are represented by solid lines in the figure. The extension forces were increased significantly at 0.9 m. When the length was 0.80 m or less, the actuator halted extension due to resistance. On the other hand, when the length was 0.90 m, the inflatable tube was buckled. The average lengths of the inflatable tubes when buckling occurred at pressures of 10 kPa, 14 kPa, and 18 kPa were 0.97 m, 0.98 m, and 1.00 m, respectively.

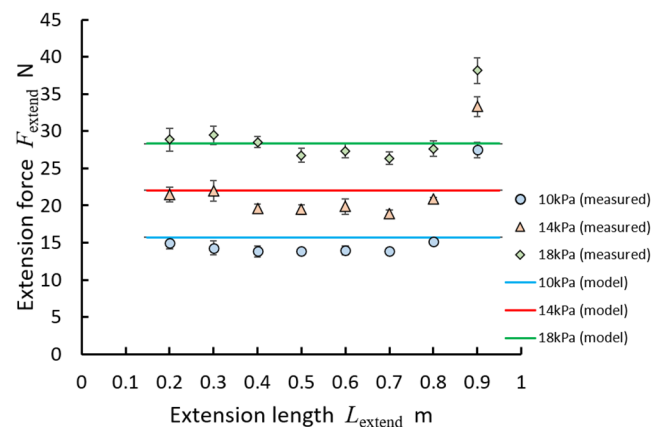


Figure 11. Plot of extension forces against tube length. Each plot represents the average, and the error bar represents the standard deviation. The solid lines show the theoretical values obtained from models (1) and (2).

5.2. Experiment on the Contraction Force

An experiment was conducted to evaluate the contraction force acting on the fabricated actuator. Initially, the inflatable tube was completely exhausted, and the actuator was fixed to a stand. The tube length L_{extend} was set to 0.20 m, and the tip of the tube was connected to a force gauge. Subsequently, the actuator contracted, and the maximum contraction force F_{contract} was measured. The tube length was varied from 0.20 to 0.80 m in increments of 0.10 m, with upper current limits set to 0.4, 0.6, and 0.8 A. The measurements were repeated six times under each condition.

The results of the experiment are shown in Figure 12. The contraction force increased as L_{extend} and the input current increased. The solid lines in the figure represent theoretical values obtained from models (9) and (16).

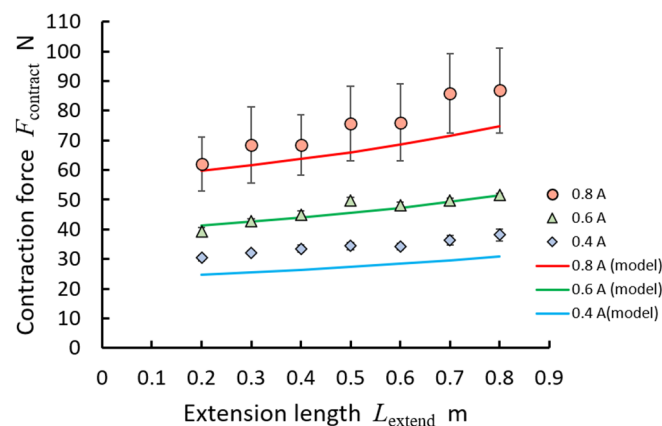


Figure 12. Plot of contraction forces against tube length. Each plot represents the average, and the error bar represents the standard deviation. The solid lines represent model (7).

5.3. Experiment on the Influence of the Air Supply Tubes

An experiment was conducted to evaluate the influence of the air supply tubes. Here, two types of inflatable tubes were prepared: one with an air supply tube fixed inside and another with an air supply tube connected outside, as shown in Figure 4. The inflatable tube with an air supply tube incorporated internally was attached to the actuator. Next, the actuator was fixed to a stand. Subsequently, the actuator was extended horizontally by 0.10 m, and the vertical displacement at the tip of the inflatable tube was measured. The tube length was varied from 0.10 to 0.90 m in increments of 0.10 m. The same measurements were conducted on inflatable tubes with the air supply tube connected outside. The measurements were repeated six times under each condition.

The results of the experiment are shown in Figure 13. The displacements of the inflatable tube increased as L_{extend} increased. The inflatable tube, with the air supply tube connected outside, exhibited greater displacement than that with the air supply tube fixed inside. The broken line represents δ_{inside} derived from model (15) using the value of δ_{outside} obtained in the experiment.

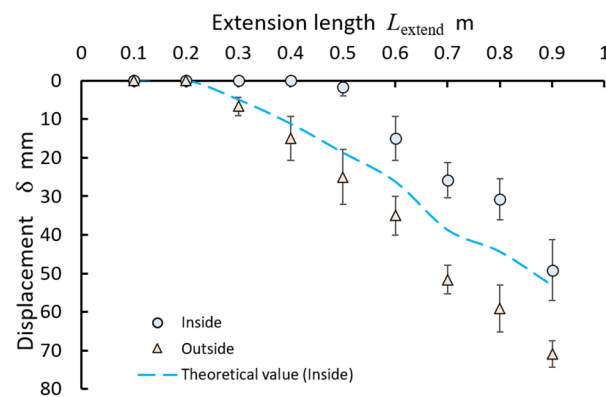


Figure 13. Vertical displacement against tube length. Each plot represents the average, and the error bar represents the standard deviation. The broken line shows model (15).

5.4. Experiment on the Speed

Some experiments were conducted to measure the extension and contraction speed of the actuator under various conditions. First, extension speed response to changes in input voltage to the motor was investigated. Initially, the actuator was fixed to a stand. The actuator was supplied with 10 kPa of air, and the tube was extended by 0.20 m. Then, the actuator was extended vertically by applying a 2.0 V voltage to the motor, and the time required for 0.50 m of extension was measured. The supplied voltage was varied from 2.0 to 8.0 V in increments of 0.5 V, with the internal pressure varied at 10 and 18 kPa. Each experiment was repeated six times under each condition.

Extension speed response to changes in tip weight was also investigated. Initially, a 0.1 kg weight was attached to the tip of the actuator. The actuator was fixed to a stand, and supplied with 10 kPa of air. The actuator was supplied with 10 kPa of air, and the tube was extended by 0.20 m. The actuator was extended vertically by applying a 6.0 V voltage to the motor, and the time required for 0.5 m of extension was measured. The tip weight was varied from 0.1 to 0.5 kg in increments of 0.1 kg. Each experiment was repeated six times under each condition.

In addition, contraction speed response to changes in input voltage to the motor was investigated. Initially, the actuator was fixed vertically downward to a stand. The inflatable tube was completely exhausted, and the tube length was set to 0.7 m. Then, the actuator was contracted by applying a 2.0 V voltage to the motor, and the time required for 0.50 m of

contraction was measured. The supplied voltage was varied from 2.0 to 8.0 V in increments of 0.5 V. Each experiment was repeated six times under each condition.

At last, contraction speed response to changes in tip weight was also investigated. Initially, a 0.1 kg weight was attached to the tip of the actuator. The actuator was fixed vertically downward to a stand. The inflatable tube was completely exhausted, and the tube length was set to 0.7 m. Then, the actuator was contracted by applying a 6.0 V voltage to the motor, and the time required for 0.50 m of contraction was measured. The tip weight was varied from 0.1 to 0.5 kg in increments of 0.1 kg. Each experiment was repeated six times under each condition.

The results of the first and third experiments are shown in Figure 14. The speed increased as input voltage increased. Under the same input voltage conditions, the contraction motion exhibited the highest speed, while the extension motion at 18 kPa exhibited the lowest speed.

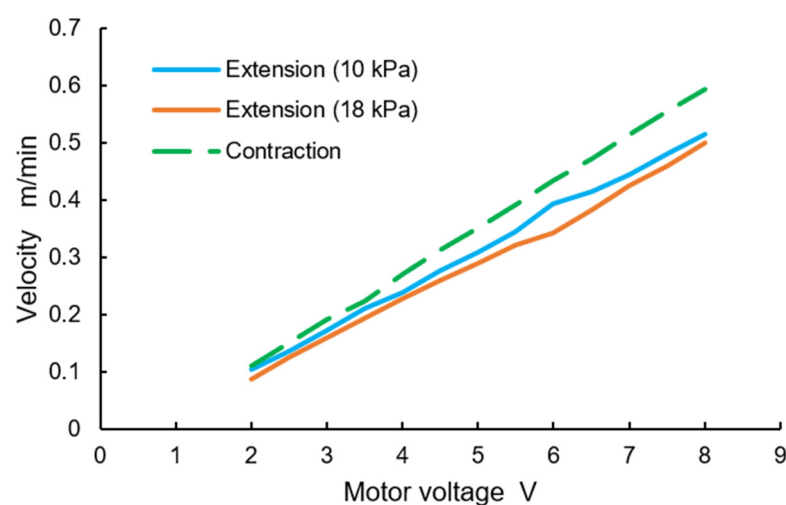


Figure 14. Speed responses to change in input voltage to the motor.

The results of second and fourth experiments are shown in Figure 15. In the contraction motion, the speed decreased at a nearly constant rate as the tip weight increased. In the extension motion, the speed remained nearly constant until the tip weight reached 0.3 kg, and then decreased significantly when the tip load exceeded 0.3 kg. When the tip weight was 0.4 kg and 0.5 kg, the inflatable tube inflated fully inside the outer cover.

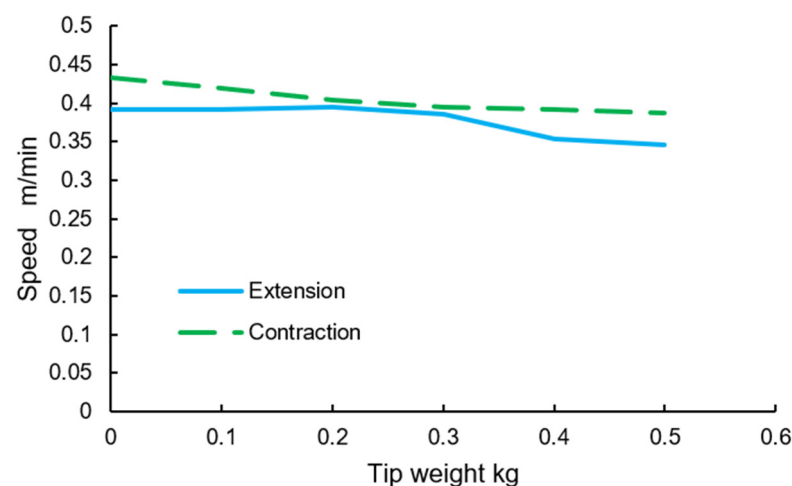


Figure 15. Speed responses to tip weight.

5.5. Experiment on Electrical Power Consumption

We conducted an experiment to measure electrical power consumption of the actuator. The actuator was fixed vertically downward to a stand. The inflatable tube was completely exhausted, and the tube length was set to 0.7 m. Then, applying a 6.0 V voltage to the motor, and the actuator contracted by 0.50 m. The current supplied to the motor was measured during the contraction motion. We applied weights ranging from 0.1 to 0.5 kg in 0.1 kg increments to the tip and conducted the same measurements. Each experiment was repeated six times under each condition. A current sensor (ACS712ELCTR-05B-T, Allegro MicroSystems, Manchester, NH, USA) was used to measure the current, with measurements taken at 10 Hz frequency. The tip weight varied from 0.1 to 0.5 kg in increments of 0.1 kg. Each experiment was repeated six times under each condition. Furthermore, efficiency was calculated from the results obtained.

The average electrical power consumption and efficiency are shown in Figure 16. The electrical power consumption increased as tip load increased. The efficiency also increased as tip load increased.

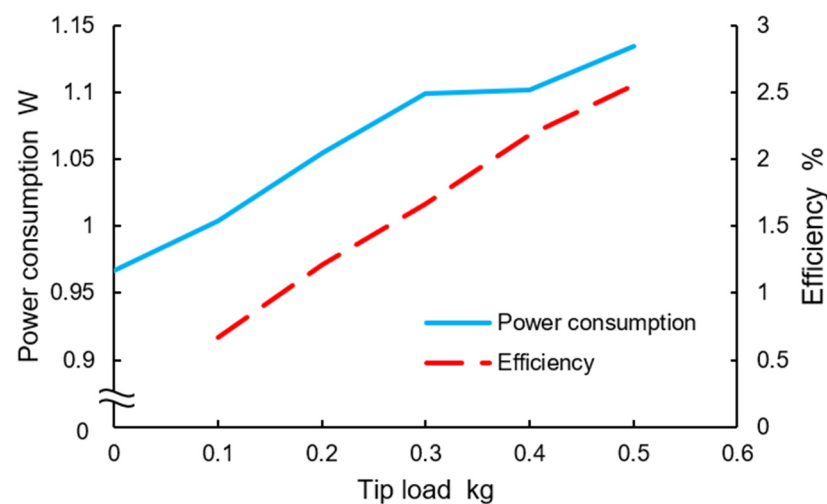


Figure 16. Average electrical power consumption and efficiency in contraction motion.

6. Demonstration

We demonstrated that the proposed actuator can be utilized as an extendable arm for climbing robots. A pneumatic gripper for grasping objects was attached to the tip of the actuator, and a servo motor was attached to control the extending direction. The actuator grasped an object at a distance and lifted itself by contracting.

6.1. Setup

The gripper attached to the actuator was designed with reference to previous research conducted by Tago et al. [5]. The actuator consisted of three fingers, and each finger was fabricated using an inflatable tube. The inflatable tube was folded to create pleats on one side, and the pleats were secured by thermal bonding. Due to the difference in longitudinal length between the pleated and non-pleated sides, the finger forms a circular shape when it is inflated, as shown in Figure 17a. To prevent slippage during grasping, a vinyl chloride sheet was affixed to the pleated side. On the side without pleats, a rubber band was placed to allow the finger to unbend when not inflated. Each finger was positioned as shown in Figure 17b to configure the gripper. The weight of the gripper was 0.09 kg.

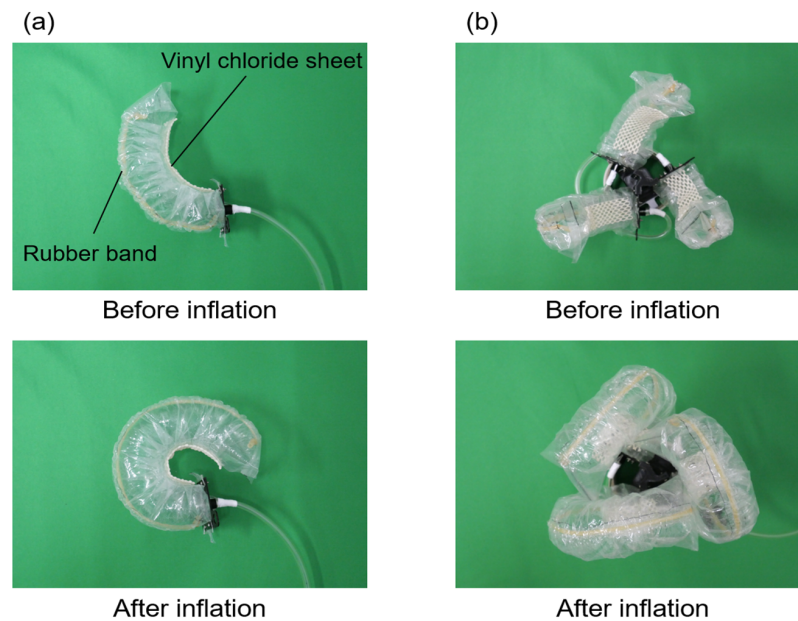


Figure 17. Fabricated gripper. (a) Inflatable finger with folded pleats. Due to the difference in longitudinal length between the pleated and non-pleated sides, the finger forms a circular shape when it is inflated. (b) A gripper composed of three fingers. Each finger was mounted in a 120° rotated position.

The proposed actuator was mounted on a base for directional control. The base was constructed from aluminum frames, and the section connecting to the actuator featured a servo motor (KRS-2572R2HV, Kondo Kagaku Co., Ltd., Tokyo, Japan) for rotation around the pitch axis. The weight of the base was 1.07 kg.

The integrated actuator utilized as an extendable arm is shown in Figure 18. The motor for actuator extension and contraction was powered by 6 V, and the servo motor for direction control was powered by 9 V. The pulse signal for the angle of the servo motor was sent from the Arduino, and we input the target value of the angle via a potentiometer. The direction of extension was visually controlled without using any sensors. Two switches were implemented to transition states to either extension or contraction. The pneumatic circuit was composed of regulators, solenoid valves, a hand valve and an ejector. The ejector was introduced to exhaust air from the actuator during contraction and was driven at 50 kPa. The pressure of the air supplied to the actuator and gripper was 15 kPa. The system configuration was shown in Figure 19.

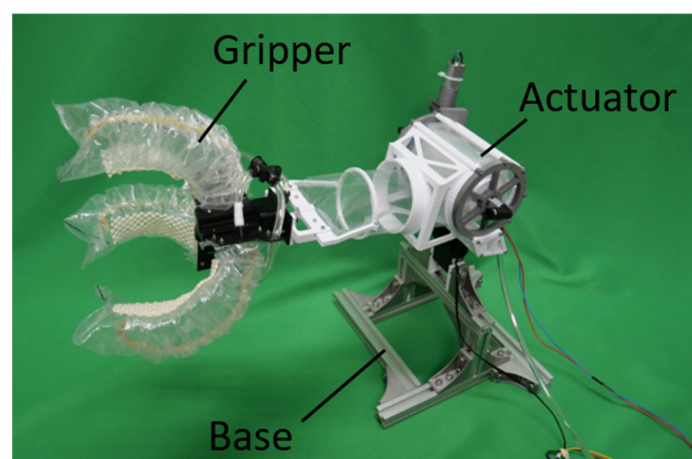


Figure 18. Integrated actuator with the gripper and base.

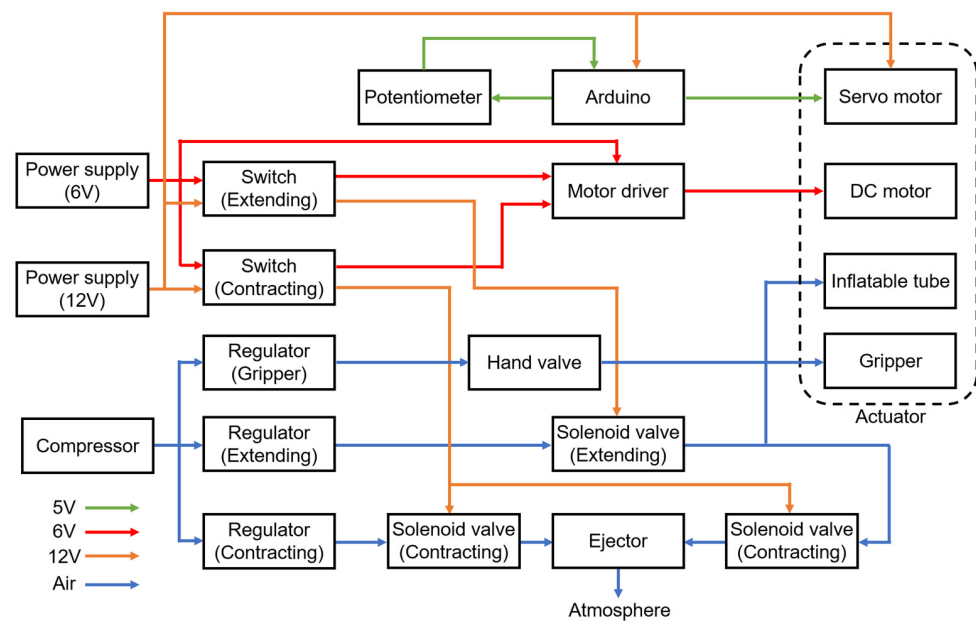


Figure 19. System configuration. Voltages of 6 V and 12 V are supplied from the power supply unit. The 5 V electrical signal is provided by the Arduino.

6.2. Operation

A 1.3 m high structural object was constructed with aluminum frames, and a pillar at the top of the structural object was used as the grasping target. This structural object is shown in Figure 20a. The operations are shown in Figure 20b and Supplementary Video S1. First, air was supplied to the actuator, and the inflatable tube was inflated. Second, the actuator was rotated in the direction of the upper frame. The actuator was subsequently extended. During the extension motion, the extension was paused several times to modify the direction of extension. Once the gripper was near the upper frame, the actuator ceased extending and securely gripped the frame. Following this, the actuator expelled air using the ejector and lifted itself.

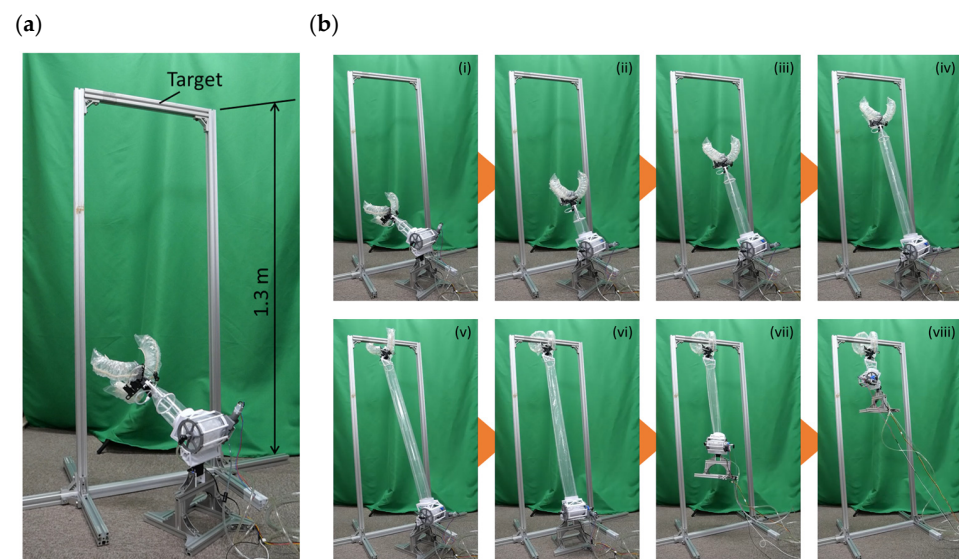


Figure 20. Demonstration of the extension and contraction motion of the actuator with the gripper. (a) Object to be grasped. (b) Operation of actuator. (i) Initial state. (ii) The actuator is controlled in the extension direction. (iii) Extension motion. (iv) Pausing extension and controlling an extension direction. (v) Extension completed. (vi) Grasping motion. (vii) Contraction motion. (viii) Operation completed.

7. Discussion

The primary contribution of this study is the development of an inflatable-extendable actuator with a novel structure that removes the influence of the air supply tube. This innovative actuator exerts a 28 N extension force at a pressure of 18 kPa, regardless of its length, and an 87 N contraction forces at an input current at 0.8 A. In addition, its length is easily controlled because extension and contraction motion can be stopped at any desired time and unaffected by external forces. This easy controllability is a characteristic not found in existing passive reel actuator [19] or an actuator with an origami structure [18]. Proposed spool mechanism incorporating air supply tubes within its body is also highly novel and not found in other inflatable robots. This actuator also enables the grasping of objects from a distance by attaching a gripper to its tip. The contraction motion of the actuator enables it to pull itself toward the grasped object, making it a valuable tool for both manipulators and climbing robots.

We proposed the model for the extension force, revealing that these forces remain largely unaffected by the length of the tube. The experimental results almost corroborate this finding, demonstrating that the forces are consistent regardless of tube length. This characteristic allows the magnitude of the force to be estimated independent of the state of the actuator, thereby facilitating a more intuitive operation. The extension force when $L_{\text{extend}} = 0.9$ m was significantly larger than in other cases. In this case, the extension of the inflatable tube did not stop until buckling occurred. This is presumably because the tube length wound on the spool was extremely small, resulting in R_{resist} being approximately zero. When $R_{\text{resist}} = 0$ N, the extension force F_{extend} derived from model (1) is 32 N, 45 N, and 57 N for internal pressures of 10 kPa, 14 kPa, and 18 kPa, respectively. Comparing these values with the experimental results, the results at 10 kPa are close to the theoretical values. In addition, the buckling loads F_{cr} derived using model (3) are 43 N, 42 N, and 41 N for internal pressures of 10 kPa, 14 kPa, and 18 kPa, respectively. Comparing F_{cr} and F_{extend} , F_{cr} is smaller for internal pressure of 14 kPa and 18 kPa. Therefore, the tube was presumed to have buckled before F_{extend} reached its theoretical value. Hence, unless the actuator is used near its maximum length, the extension force can be estimated from the proposed models. The R_{resist} used in the extension force model (1) is determined experimentally. Since R_{tube} consists of the frictional force occurring between the inflatable tube and the outer cover, and the force required for the bending deformation of the tube, R_{resist} changes when the actuator size changes. For example, when the curvature of the tube inflated inside the outer cover becomes smaller, the R_{resist} increases because the tube requires a larger bending. If a model for estimating R_{resist} under various conditions is successfully developed, we believe that the utility of the proposed actuator is significantly improved.

Furthermore, we developed the model for the contraction force. These models indicated that the force F_{contract} increased as L_{extend} increased and depends on the input torque from a motor. The experimental results agreed with these models. Thus, these models enable us to select the motor for designing the actuator and determine the operating parameters of the current based on the usage situation.

The fabricated actuator generated extension and contraction forces of 28 N and 87 N, respectively, under experimental conditions. The force-to-weight ratios of the extension and contraction forces were 67 N/kg and 185 N/kg, respectively. Compared with other actuators with a large extension ratio, the contraction force-to-weight ratio of the actuator with an origami structure was 52 N/kg [18]. Hence, the proposed actuator demonstrated a significantly higher contraction force-to-weight ratio. Conversely, the contraction force-to-weight ratio of the pneumatic reel actuator was 278 N/kg [19], which is higher than that of the proposed actuator. The pneumatic reel actuator was very light because it comprised only passive components. However, the length of this actuator is easily altered by external

forces and internal pressures. Conversely, the length of the proposed actuator can be easily controlled by sensing the rotation of the spool regardless of external forces. Hence, the proposed actuator is characterized by its ability to achieve both easy controllability and high output power.

The weight of the fabricated actuator excluding the inflatable tube and pneumatic circuit, was 0.42 kg. The weight of the soft vine arm mounted on the quadrotor is approximately 0.65 kg, which is not significantly different from the weight of proposed actuator. This result indicates that the proposed actuator can be mounted on mobile robots such as drones, meaning it can be used as a component of climbing robots. As described in Section 1, its load capacity is not mentioned, but we believe that our proposed actuator can generate extension and contraction forces equal to or greater than that of the vine arm.

The length of the fabricated actuator with outer cover was 0.12 m, and the length of the mounted inflatable tube was 1.1 m. Therefore, the strain of the fabricated actuator considering the offset length L_{offset} was approximately 800%. This value was almost the same as the value of the actuator used as the extendable arms of the climbing robot [5,18]. Hence, the fabricated actuator was also applicable as extendable arms for climbing robots.

This study proposed a novel structure for an inflatable actuator that removes the influence of the air supply tube. The experimental results showed that the proposed structure reduced the amount of deformation caused by gravity acting on the air supply tube. The proposed structure exhibited smaller values compared with the theoretical values obtained from model (15). This result is because the end of the inflatable tube was not perfectly fixed. Since the unfixed end of the tube cannot receive a counterforce, the tube is easily deformed by external forces. Therefore, the tip load caused by the air supply tube arranged outside the inflatable tube results in greater deformation than in the ideal cantilever beam model. Because the deformation was large when the air supply tube was arranged outside, the theoretical value for the deformation when the air supply tube was arranged inside, which was calculated using model (15), was greater than the experimental value. As mentioned previously, model (15) is not intended to predict the precise deformation of the inflatable tube, but rather to demonstrate the effect of the arrangement of the air supply tubes on deformation. Although we observed a difference between the theoretical and experimental values, the result demonstrated that the proposed structure reduced the influence on the inflatable tube, as we had expected. If a model that accurately estimates deformation is required, a coefficient to correct for the influence of non-fixed ends must be determined using finite element analysis or experimental analysis.

We investigated the extension and contraction speed of the actuator under various conditions. Both extension and contraction speed increased as the input voltage to the motor increased. Hence, the speed can be controlled by varying the input voltage. Since the motor used in this experiment had a rated voltage of 6.0 V, the maximum voltage was set to 8.0 V. If the rated voltage of the motor is higher, the range of controllable speeds will also be greater. However, a large air flow rate is required to immediately fill the extended tube with air. Under the same input voltage conditions, the contraction speed was the highest, while the extension speed at 18 kPa was the lowest. This difference in speed was due to deformation and friction occurring in the inflated tube inside the outer cover of the actuator, which impeded rotation. The extension speed and contraction speed showed different responses to the tip weight. While the contraction speed decreased at a nearly constant rate as the tip weight increased, the extension speed remained nearly constant until the tip weight reached 0.3 kg. The reason no change in extension speed was observed is thought to be because the resistance force exerted on the inflatable tube inside the outer cover of the actuator had a larger influence than the tip weight. Since speed is affected by disturbances such as tip weight, an encoder should be attached to the

actuator to obtain the feed amount of the inflatable tube when precise control is required. Under no-load conditions, the extension speed at 6.0 V voltage and 18 kPa internal pressure was 0.34 m/min, and the contraction speed at 6.0 V was 0.45 m/min. These speeds are not sufficient for the operational speed of a climbing robot, but the slow operating speed is expected to be less of an issue if the operation is automated. In addition, operational stability is more important than operational speed for automation. The proposed actuator offers stability through its ability to finely control length. If the actuator requires a higher speed, as mentioned above, a motor capable of higher rotational speeds and an air supply with a higher flow rate are necessary.

We investigated the electrical power consumption and efficiency in contraction motion. We confirmed that the efficiency is far from high. Potential factors contributing to this low efficiency include the fact that the maximum efficiency of the motor used in fabricated actuator is only 28%, and the use of a worm gear, which is known for their low efficiency. We believe that this data on electrical power consumption and efficiency will contribute to the selection of a power source for the climbing robot.

In the demonstration, we successfully executed a sequence of motions for controlling the extension direction, extension, grasping, and contraction. This indicates that the proposed actuator can provide the required motions for one arm of a bi-arm climbing robot. Notably, the proposed actuator offers the advantage of being able to stop extending and contracting at any time, as well as the ability to contract with significant force, distinguishing it from other actuators. Although its mass is larger than those of other inflatable actuators [18,19], the proposed actuator generates sufficient contraction force to compensate for the increased weight. Furthermore, the demonstration illustrated that directional control by the servomotors remained unaffected by the increased weight, showcasing the valuable ability of this actuator. The combined use of two of these actuators is expected to facilitate the design of a climbing robot. Although the proposed actuator is free from the influence of the air supply tube on the inflatable tube, the tubes connecting the actuator to the pneumatic circuit and the wires supplying current to the motor still exist. Removing these tubes and wires would further enhance mobility. For this purpose, mounting batteries and compact pumps directly onto the actuators is considered an effective approach.

In this study, the maximum pressure applied to the inflatable tube was set to 18 kPa because applying pressure exceeding 28 kPa caused deformation in the outer cover. Improving the rigidity of the outer cover allows the actuator to use higher pressure. However, the demonstration showed that the inflatable tube of the fabricated actuator has sufficient rigidity to function as the arm of a climbing robot. Therefore, we have investigated the characteristics of the actuator within the pressure range suitable for our objectives.

8. Conclusions

We proposed a novel inflatable actuator in which air supply tubes are arranged inside its body. This actuator can extend and contract with significant force, and these movements can be halted at any desired moment. In addition, we developed models to determine the force involved in the extension and contraction processes. These models are essential for estimating the operational range of the actuator and the forces exerted during extension and contraction. During our demonstration, we successfully showcased a series of movements enabling control over the extension direction, extension, grasping, and contraction. These capabilities demonstrate the potential for this actuator to be utilized in developing climbing robots.

In future studies, we intend to integrate this actuator into developing a climbing robot. We will explore the feasibility of incorporating a small pump onto this actuator, enabling

untethered operation. If successful, these advancements will result in a climbing robot whose movement is minimally impacted by the air supply tube.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/act15030176/s1>: Video S1: The demonstration of the actuator.

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