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Inflated Bendable Eversion Cantilever Mechanism with Inner Skeleton for Increased Stiffness

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Abstract—**Inflatable structures used in soft robotics applications have unique characteristics. In particular, the tip-extension structure, which extends the structure from its tip, can grow without creating friction with the environment. However, these inflatable structures need high pressure to maintain their stiffness under various conditions. Excessive inner pressure limits their application in that it prevents the structure from maintaining its curved shape and from complying with specifications. This study aimed to simultaneously lower the pressure and increase the rigidity of the structure. Our work resulted in the proposal of a mechanism that combines a skeleton structure consisting of multi-joint links with functions to increase the rigidity. Insertion of this mechanism into an inflatable structure obviates the need for high inner pressure, yet enables the structure to bend and maintain the intended shape. We devised a design based on rigid articulated links and combined it with a membrane structure that utilizes the advantages of the tip-extension structure. The experimental results show that the payload of the structure designed to operate at low pressure increases compared to that of the membrane-only structure. The findings of this research can be applied to long robots that can be extended into open space without drooping and to mechanisms that enable structures to wrap around the human body.**

Keywords—Soft Robot Materials and Design, Mechanism Design, Compliant Joint/Mechanism

I. INTRODUCTION

Soft robotics, in which a soft, compliant part is in contact with the environment, has many advantages that cannot be realized using conventional rigid mechanisms. One such advantage is that the body is deformable; hence, precise positioning is unnecessary [1]. In addition, their performance is highly stiff (equivalent to that of rigid materials) by applying huge pressure in a limited application, even though they are fabricated using soft materials.

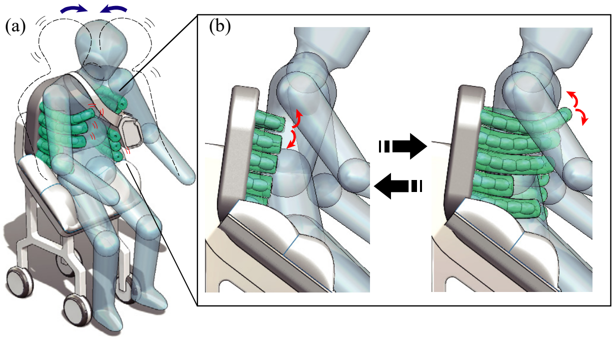

Figure 1. (a) High payload eversion mechanism to support human body posture (b) Low frictional insertion into under arm by tip extension

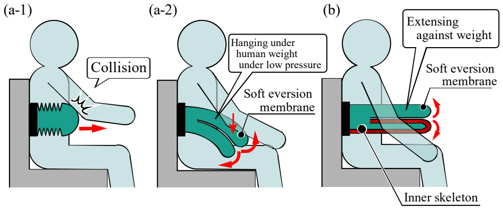

Figure 2. (a-1) Bellows type extension actuator (a-2) Eversion membrane (b) Eversion membrane with skeleton

Among soft robotics, inflatable structures, which are composed of flexible membranes, allow a large body to be stored in a small space [2], as shown in the concept in Fig. 1. An inflatable structure consists of a flexible membrane that is pressurized in an enclosed space in order to expand to form a structure that is more rigid than the membrane. In particular, in contrast to the bellow-like extension mechanism shown in Fig. 2 (a-1), the tip-extension structure [3][4] can extend into a narrow space without friction between the structure and the object (Fig. 2 (a-2)).

Several methods have been proposed to improve the functionality of advanced structures; for example, by installing actuators and devices with rigid bodies inside an eversion robot. Coad et al. [5] showed that the membrane structure experienced buckling during retraction; they solved this problem by attaching a tip-winding mechanism. Haggerty et al. [6] proposed a method for expanding the workspace in which a bending motion is added to the winding mechanism. The design of these methods is more complicated than that of methods that use only a membrane structure (intended to extend through a confined space). However, these methods can be applied to a wide range of possible applications of advanced inflatable structures. Our research group previously proposed a tip-extension structure, the extension of which is driven by a liquid, to increase the friction against the floor and maintain the shape of the structure [7]. The soft structure was equipped with an internal tube-type steering mechanism to select a path with an arbitrary shape [8]. Structures such as

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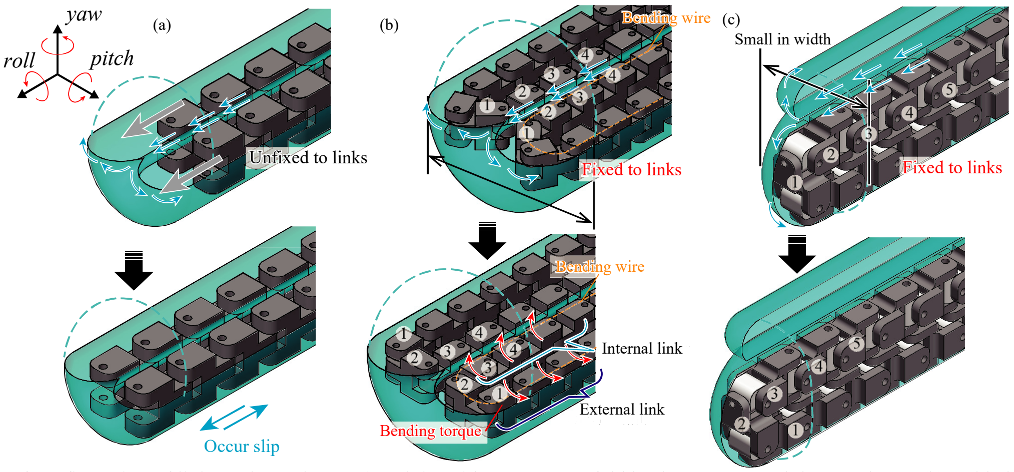


Figure 3. Example of configuration of links and membrane: (a) Links without separate fold back move toward the membrane (b) Folded links with yaw rotation, but with difficulty bending both ways with only a single wire (c) Proposed structure with folded links that enable pitch rotation

these have been shown to be effective in search applications in narrow areas, owing to their particular characteristics. Conversely, compliance and movements, such as the extension and curvature of the tip, are considered to be effective for applications that preclude the use of excessive force, such as those involving structures that make contact with the human body. These applications entail wrapping a soft structure around an irregularly shaped object to support the object. We conceived a mechanism to assist human walking using an inflatable structure as a cantilever to support a person's weight to enable them to stand upright or to hold them in position in a chair, with the final concept shown in Fig. 1.

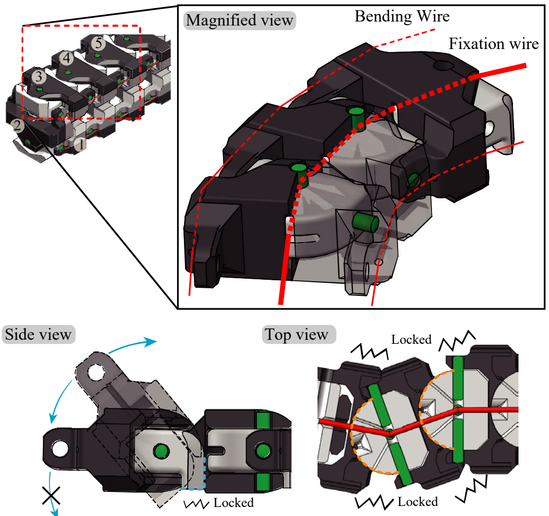
However, an inflatable structure driven by liquid or air requires considerably greater pressure to acquire the necessary stiffness or force in situations where firm support such as the ground is not available to provide a reaction force similar to that of a cantilever. This is because the mostly inflatable structure is composed of a thin sheet material, which requires high pressure to suppress wrinkling and greatly reduces rigidity. For example, a cantilever with a diameter of 110 mm and length of 450 mm, supporting a 60 kg human at the tip, requires a pressure of 1.01 MPa (Eq. (40) in [9]). However, an increase in stiffness via pressurization inhibits compliance and bending capability. Inflatable structures exhibit isotropic stiffness; therefore, if they are less likely to bend in the direction of the load application, they are also unlikely to bend in other directions. Although it is possible to integrate a bending mechanism with an eversion robot [10][11], a strong force is required to deform a large curvature under pressure sufficiently high to support the strong force, and the structure exhibits low compliance with respect to contact with the object. This can be solved by changing the structure to a preprogrammed bending shape. However, the inability to accommodate human bodies of different sizes remains problematic. Do et al. [12] proposed a method for increasing the stiffness of the membrane structure after it undergoes eversion. In this structure, the membrane itself has the shape of a bag, multiple sheets are inserted into the bag, and the stiffness of the membrane changes according to the friction generated when the pressure inside the bag is changed. Although this method enables the payload to be increased compared to the conventional single-layer membrane structure, part of the structure must be soft to allow the body to bend. In addition, the curvature of the robot is limited by the number and size of segments. Loh et al. [13] and Nakamura et al. [14] proposed a finger structure that uses this tip-extension structure mainly in nursing care. However, the structure had a limited range of motion because it was limited to the tip and assumed contact with the floor.

In this study, we propose a mechanism that combines a skeleton structure consisting of multi-joint links with functions to increase the rigidity and bending motion of a soft structure (Fig. x(b), Fig. 1). This mechanism can achieve the same level of load-bearing capacity as a robot with a rigid structure, and it also combines the softness of the surface and the features of the motion tip-extension structure, enabling an extension of the structure with a low degree of sliding in the environment. This structure includes a rigid articulated link inside the membrane structure, as shown in Fig. 3(c), which acts according to the membrane during the extension motion. The use of articulated links does not interfere with the flexible movement of the membrane and assists the load-bearing capacity at low pressures. To enable the structure to support heavy objects and to undergo extension and bending motion without contacting the ground, this structure has the ability to engage in three types of motion, as shown in Fig. 4 and Fig. 5: withstanding a gravitational load, actively bending in the horizontal direction, and maintaining the curved shape of the body. We devised a method to design rigid articulated links and combined these links with a membrane structure that utilized the advantages of the tip-extension structure. In addition, we experimentally verified the basic characteristics of the function of the proposed mechanism by constructing a prototype.

The remainder of this paper is organized as follows. Section II explains the design theory of the articulated links of the proposed tip extension structure. In Section III, we describe the design of the robot with articulated links and the fabricated membrane. Section IV presents the experiments using the robot, and Section V discusses the results and limitations of the robot as well as the scope for future improvements. Section VI summarizes the results and concludes the paper.

II. EVERSION MECHANISM WITH SKELETON

To realize the functions shown in Fig. 4, the proposed tip-extension structure includes custom-designed joints in the



Mechanical rotation limit Shape holding by friction

Figure 4. Basic function of articulated links

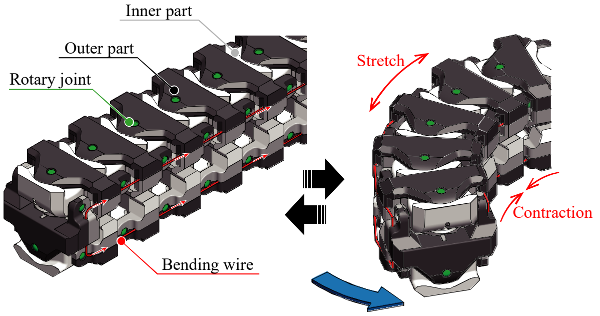


Figure 5. Bending motion enabled by articulated links

articulated links, as shown in Fig. 6. This motion is intended for situations in which a heavy, soft object with an undefined shape, such as a human body, is gently clasped and held, as shown in Fig. 1. In this situation, low-friction extension of the tip is necessary while the tip is in contact with the object, particularly when it is difficult to contact the bottom of the mechanism to support its own weight. After the structure has curved and deformed to fit around the object, it should maintain its curved shape such that force does not need to be applied continuously and damage to the object can be prevented. A method for changing the interjoint angle of an articulated link using a tip-mounted mechanism was proposed [15][16]. However, the tip-mounted mechanism increases the deflection because of its weight, and the size of the tip-extending structure also increases. In addition, in the proposed mechanism, a membrane is attached to the rigid skeleton to allow entry while pushing through a narrow gap. After the soft membrane-only part at the tip of the eversion mechanism enters the gap before the skeleton, a force is applied in the direction that widens the gap to make space for the skeleton to pass through. This function is suitable for relatively deformable objects such as a human arm. The design of the proposed articulated links and configuration of the membrane combination is explained as follows.

A. Basic Configuration of Articulated Links and Soft Membrane Structure

In this study, the articulated links and the membrane structure are only tied together in one link, not fixed to the whole skeleton, and the joints were bent in the pitch direction at the tip while extending from the tip of the membrane in accordance with the folding (Fig. 3(c)). The articulated links and the membrane structure can be combined using several methods; however, in this study, this configuration was adopted for the following reasons.

First, the articulated links must be moved simultaneously to the membrane and extended while folding back at the tip to ensure that the lifting task can be performed safely. If the articulated links were to move separately from the membrane without folding back at the tip [17], as shown in Fig. 3(a), the extension of the links would have to be controlled based on the measured membrane feed because the extension of the eversion structure is half that of the membrane feed. In addition, the membrane that is in contact with the object may slip against the load-bearing articulated links, and the object may not be held securely.

The folding direction at the tip of the articulated links was assumed to be in the pitch direction (gravitational direction). For a structure intended to fold in the yaw direction (Fig. 3(b)), the rotation axes of the joints should all be in the same direction. However, it is difficult to bend the entire structure using a single bending operation, such as that accomplished using a pulling wire. This is because the generation of torque at each joint for the entire bending process would result in the inner and outer links bending in opposite directions. In addition, for insertion under the human arm, the structure needs to be narrow. Therefore, we decided to use the links with the pitch and yaw joints, and the fold was set along the pitch axis direction (Fig. 3(c)). In this structure, the pitch joint cannot be completely free of rotation because it must support the load in the direction of gravity. This problem was solved by limiting the rotation range. As shown in Fig. 4, it can be rotated upward by a maximum of 90° to enable folding, whereas it does not rotate downward to support the weight. These links can constrain the displacement in only one direction; however, both upward and downward displacements can be constrained by placing the articulated link in a folded position.

In a conventional eversion robot composed of only a single-layer membrane, buckling occurs during the retraction motion and can be prevented by controlling the stiffness of the proposed link mechanism. The tension required for the eversion robot to retract increased in proportion to the pressure. However, even with pressurization, the prevention of buckling is limited, and depending on the length ratio, it can retract[5]. Hence, it is difficult to prevent buckling using only a membrane structure. In contrast, the proposed mechanism can maintain rigidity as it includes articulated links; thus, retraction can be realized with low-pressure retraction tension. The articulated links were designed by geometrically constraining vertical buckling by the angular limit of the links, which prevents buckling. Buckling in the horizontal direction was constrained by the static frictional force between the joints. Although the links are designed to rotate freely, there is enough stiffness in the yaw direction to prevent buckling of the membrane by static friction.

B. Realization of Active Bending and Shape-Fixing

An articulated link structure consisting of links with two rotational joints was devised to realize the bending and shape-

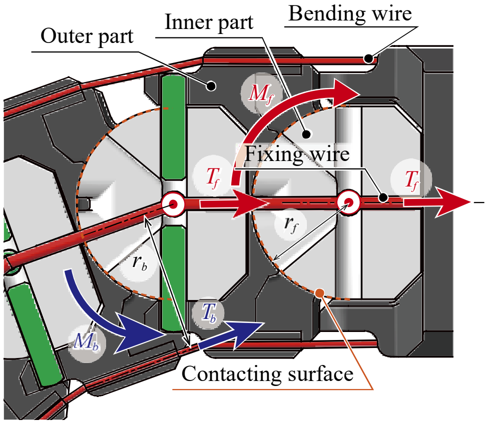


Figure 6. Schematic to illustrate the bending moment caused by the tension of the bending wire and link components

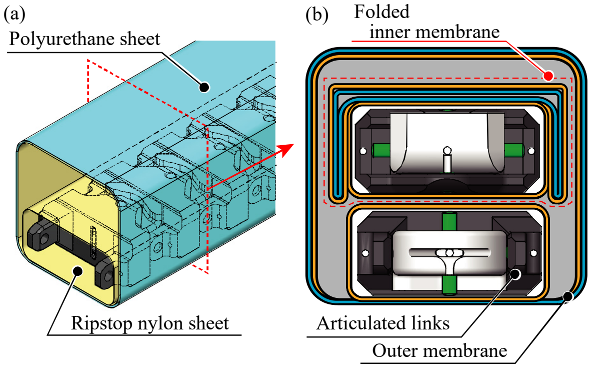


Figure 7. Diagram of the membrane structure
(a) Configuration of layered membrane structure,
(b) Cross-sectional view along the red dashed line in (a)

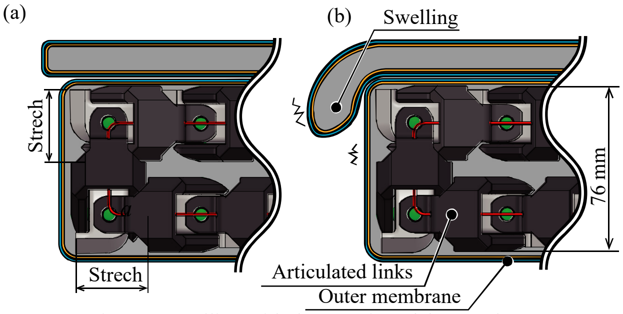


Figure 8 Swelling with the oversize of the membrane

fixing motions (Fig. 4). In this study, we did not use a ball joint; rather, we used a two-axis rotating joint with one degree of freedom, because the range of motion was not wide. Thus, the folded part of the link at the tip is large. In addition, the ball joint had lower rigidity than the rotational link structure with two independent axes; therefore, it was not suitable for the intended application. Therefore, we designed the link based on a universal joint. In addition, only the contact area of the yaw joint was increased to achieve a high holding torque by friction.

The bending action was performed by pulling the wires attached to the left and right sides of the articulated links such that the entire link was curved (Fig. 5). A method involving the attachment of a contracting actuator to the surface of the membrane was proposed as the bending mechanism of a tip-extension structure [18][19]. However, this method limits the curvature of the structure because of its limited contraction rate. In the proposed mechanism, the entire body is curved, owing to the articulated links, to achieve a larger radius of curvature. As shown in Fig. 6, the bending torque M_b is expressed by the distance between the center of the joint and wire r_b and wire tension T_b as follows:

$$M_b = r_b T_b. \tag{1}$$

The shape of this articulated link can be fixed by pulling a wire through the center of each component, and the shape of the link can be fixed by friction [20]. Kiryu et al. [21] and Wang et al. [22] proposed an eversion structure to fix the curved shape by friction between membrane structures; however, to increase the holding torque, it is more effective to apply a strong force to a rigid structure. Therefore, we adopted a shape-fixing function for the articulated links. As shown in Fig. 6, pulling the center wire increased the contact pressure between the parts of the entire link and increased the static friction force at each rotating joint. This constrains the angle of each joint and maintains its shape even after bending. The relationship between the wire tension T_f and the holding torque M_f is expressed as

$$M_f = \mu r_f T_f. \tag{2}$$

Here, μ and r_f are the friction coefficient and the radius of the contact area, respectively. This expression suggests a larger holding torque can be achieved by increasing the contact area radius.

C. Combination with Membrane Structure

In the proposed mechanism, only one set of articulated links, rather than two, was inserted into the membrane structure, and the configuration was vertically asymmetric, as shown in Fig. 3(a) and Fig. 7. Otherwise, the diameter would be extremely large if two frames were inserted in a vertically symmetrical arrangement, and it would not be possible to utilize the advantageous ability of the tip extension structure to extend into narrow spaces.

A membrane that is fully connected to the skeleton is problematic in that it limits movements such as extension and curvature. Therefore, the mechanism proposed in this paper was designed to include a slight amount of slack in relation to the size of the skeleton. Because the rotation axis of the link is at the center, the distance between the membrane and the contact point of the adjacent link is extended or contracted by the folding of the tip during extension, which means that the inflated membrane structure must be axially spacious. In addition, the area in which bending or folding occurs undergoes transition with extension, thus the slacks of the membrane must also move. In addition, in areas where the surface is stretched and contracted owing to folding, as shown in Fig. 8, the slack of the membrane must be able to move as it transitions with the extension. Therefore, the membrane was fixed only at the ends, and not at each link. Similarly, this problem also occurs during curvature. As shown in Fig.5, when curved, the distance between the contact points on the outside of the curvature must be extended to provide the necessary slack for the desired curvature angle. The length of the membrane must be the sum of the length of the skeleton itself with clearance required for the tip to fold, and clearance required for bending. This clearance means that the skeleton

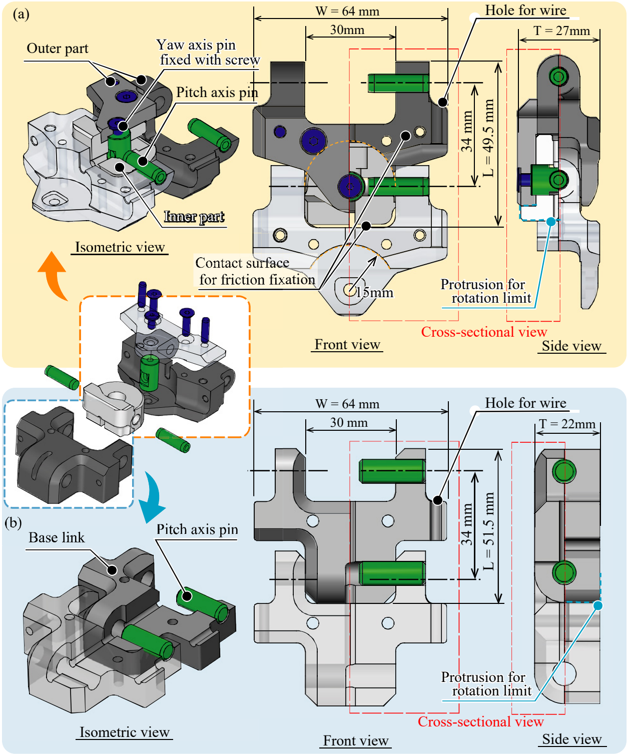


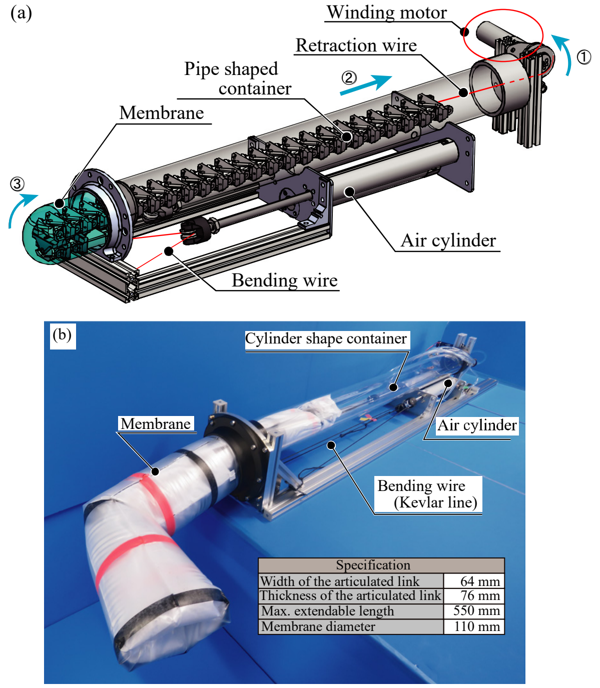
Figure 9. Design of the link: (a) outer and inner part connected with pins and screws; (b) Base link which has only pitch joint

does not extend into the tip of the membrane, which also functions as a cushion; however, because it is not capable of bearing loads, it is necessary to limit the length of this clearance depending on the intended use. If no pressure is applied during retraction, the slack part wrinkles and becomes resistant to retraction. Therefore, sufficient pressure is necessary for successful retraction.

Table1. Specification of three types of links

		Base link	Connected link (outer + inner link)		Entire of skeleton
			Metal	3D print	
Number of link		4	9	21	34
Size(W x L x T) [mm]		64 x 51.5 x 22	64 x 54.5 x 27		L = 1156
Weight [g]		108 / link	120 / set	33 / set	2214 / all links
Material		Aluminium (A7075)	Aluminium (A7075)	Onyx*	
Joint axis		pitch	pitch, yaw		
Rotate angle [deg]	pitch	90	75		
	yaw	0	15		

*Onyx is a material in which carbon fibers are blended into nylon.



Specification	
Width of the articulated link	64 mm
Thickness of the articulated link	76 mm
Max. extendable length	550 mm
Membrane diameter	110 mm

Figure 10. Integration of skeleton and membrane structures and actuators (a) Schematic for prototype, (b) Bent model of prototype

III. MECHANICAL DESIGN

A. Design of Articulated Links

The three parts used as components of the articulated links in this mechanism are shown in Fig. 9. The base link was attached near the base of the eversion mechanism, where the largest amount of torque was applied. This link bends only in the pitch direction and not in the yaw direction because, according to the proposed mechanism, the part passing around the side of the human torso does not need to bend in the yaw direction. The other two links joined to each other constitute the skeleton. The inner and outer links are connected by inserting the inner parts into the inner recesses of the outer parts and by press-fitting pins and screws from the outside. The two parts have a hole in the center to allow the wire to pass through to control the shape. In addition, the outer part has a hole to enable the wire to pass through to bend the structure to the left or right. Finite Element Method was used to design a cantilever beam that would not rupture when a mass of 60 kg was applied to the tip of the beam. Simulations were performed separately for the base links and connected links, which were combined inner and outer links. In both cases, two sets of links and rigid rods were combined; a force of 600 N was applied to the base link at 450 mm from the fixed part of the base side links, and the same force was applied to the connected link at 314 mm which is 450 mm minus the length of the base link. The resulting minimum safety factor was 1.4 for the base link and 1.1 for the connected link. The pitch and yaw axes of the inner part are on the same axis, and the distance between the two axes is 34 mm in the outer part. Other specifications are listed in Table 1. The units of the skeleton are not all composed of the same parts. The first four units have a base link, the next eight units have inner and outer links made of aluminum, and the next eight units comprise 3D-printed inner and outer links. The purpose of this arrangement is to increase the rigidity of only those parts that receive higher loads which located under and base side of the skeleton and reduce the weight of the other parts.

The distance between joints of which the rotation is constrained by friction is variable. Therefore, it is not possible to use bearings that completely constrain the rotation direction. In the proposed mechanism, a larger clearance was provided for the pins of the rotary joint. Thus, when the wire is pulled, the inter-joint distance decreases slightly, and the pins and parts do not contact each other; however, the surfaces of the parts come into contact.

B. Design of Membrane Structure

The membrane structure used in this study consisted of three layers, as shown in Fig. 7. This structure was fabricated using a composite of polyurethane sheets and slippery nylon material, which were thermally welded together to form a bond. The inner pouch is intended for inserting the articulated links, which allows some movement in the axial direction but restricts movement in the diameter direction. The diameter of the membrane was 110% of the circumscribed circle of the cross-sectional quadrangle of the skeleton that passed through the interior of the membrane, and the diameter was defined based thereupon. The length of the membrane is 1302 mm, which is 147 mm longer than the skeleton. It includes 54 mm of slack for tip folding and 93 mm to bend 90°. These parameters were measured in 3D CAD of the skeleton.

C. *Integration of Membrane Structure and Articulated Links*

The membrane structure and articulated links that are actuated using an air cylinder and motor are integrated, as shown in Fig. 10. The membrane and articulated link structures were placed inside a sealed cylindrical container and extended by air pressure (at least 4kPa). This pressure is the value needed to fold back the friction and skeleton in the cylinder. The wire attached to the tip of the articulated links was wound using a motor, and tension was applied to the wire for retraction. An air cylinder was attached to the bottom of the pipe-shaped container to pull the wires threaded on both sides of the articulated links. For bending and fixing wires, 2.6 mm Kevlar lines are used instead of metal wires, considering their slipperiness, bendability, and tensile strength.

IV. EXPERIMENT

A. *Measurement of Holding Torque of Links*

As described in Section II, in the articulated link mechanism, the joint angle in the yaw direction was controlled by pulling the central wire. The holding torque was experimentally measured. We used an experimental setup with a set of inner and outer parts, as shown in Fig. 11. The experimental setup was attached to a tensile testing machine, and the joints were fixed using friction by using an air cylinder to pull a wire. After fixation, the tensile tester was used to generate torque at the joint by pulling wire upward, and the torque that was applied when the joint slid was measured. The wire tension produced by the air cylinder was varied in the range 10–150N, and the holding torque measured. The joint angles were set as 0°, 7.5°, and 15°. To keep the moment arm constant for each angular condition, an arc-shaped pulley centered at the rotational fulcrum of the link is attached to the connected link, as shown in Fig.11. This experiment focused on the holding torque caused by friction; therefore, measurements were performed five times, and the average of the measurements was used for the results.

The measured frictional holding torque in the bending direction is shown in Fig. 12. The relationship between the wire tension and holding torque was linear. The holding torque for a joint angle greater than 0° was less than for a joint angle of 0°. The fitting curve obtained using eq. (2) for a friction coefficient of 0.2 is denoted by the dashed line.

B. *Payload Measurement of Proposed Structure*

The stiffness of the proposed mechanism to support the weight was measured using an experimental machine to determine the tendency of the stiffness to increase with the internal air pressure. The integrated model shown in Fig. 10 was used for the experiment. The amount of deflection was measured using three weights of 500 g, 2000 g, and 3000 g, attached 400 mm from the base, whereupon the displacement was measured by applying a pressure of 0–8 kPa. The measurements were recorded ten times, and the average value was used for the results.

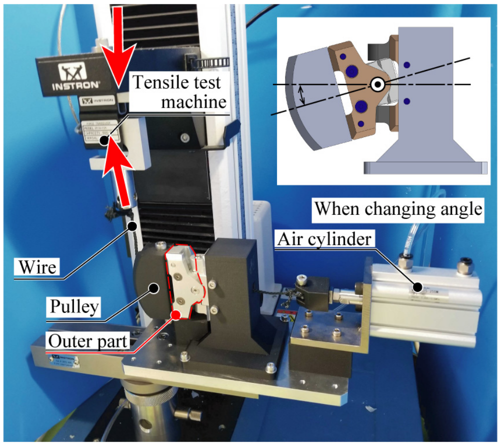


Figure 11. Experimental setup for holding torque by friction

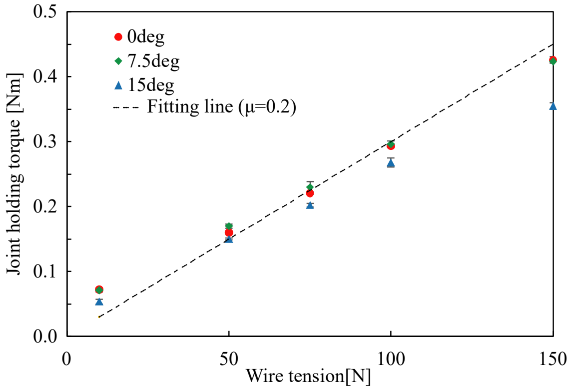


Figure 12. Experimental result for holding torque by friction

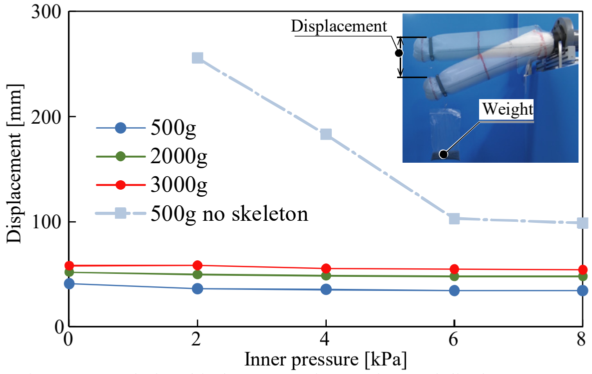


Figure 13. Relationship between wire tension and displacement.
from the straight position

Fig. 13 shows the relationship between the internal air pressure and the measured deflection. In the proposed mechanism, deflection occurs before the weight is attached, owing to the weight of the skeleton. In Fig. 13, the displacement from the straight position (position at which the gravity is zero) is plotted against the pressure and mass of the attached weight. The dashed and full lines show the results of a beam composed only of a membrane, and of a membrane with the skeleton, respectively. In addition, the blue, green,

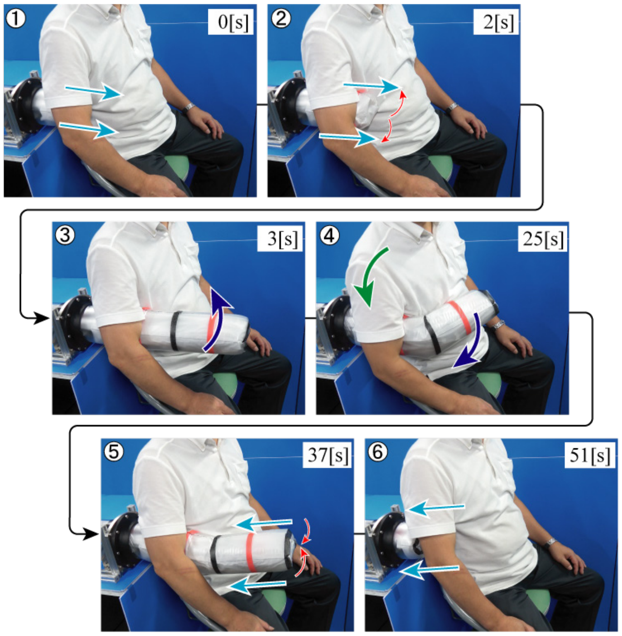


Figure 14. Bending movement to support the human body

and red lines indicate attached weights of 500 g, 2000 g, and 3000 g, respectively. However, the results without the skeleton with a 2000 g and 3000 g weight are not included in the graph because the deflection was too large. (See the supplementary video).

C. *Movement of Prototype*

We additionally conducted an operational test using an integrated model designed to bend according to the shape of the human body and retains its shape to hold the human upper body (Fig. 14). First, the membrane structure was pressurized to inflate and extend it to insert itself between the arm and the torso. Subsequently, the bending wire extending through the articulated links was pulled to bend the structure to take on the contours of the body while maintaining compliance with the pressure. The central wire was then pulled to increase the contact force and securely establish its shape. To retract the membrane to its original state, it was first pressurized and then bent back to straighten its shape using the side wires of the articulated links in the direction opposite to that when it was attached to the human body. Next, the wire was rewound from the end of the articulated links to return the structure to the containment. The motor then rewound the retraction wire attached to the end of the articulated link (see the supplementary video).

V. DISCUSSION

A. *Discussion of Experimental Results*

In this study, the load-carrying capacity of the tip-extension mechanism with an articulated link structure was experimentally measured and evaluated. In this section, we discuss the types of design improvements that are necessary for situations where this mechanism can be applied. First, in the measurement of the holding torque by friction, as described in Section IV A, holding torque of approximately 0.4 Nm can be generated by a maximum wire traction force of 150 N. This means that a force of approximately 0.8 N can be retained when the wire is extended by a maximum length of 500 mm. With this holding force, it is difficult to support a heavy object, such as a human body. For such objects, improvement measures can be considered, such as increasing the radius of the link where friction acts, using a material with higher friction, changing the roughness of the contact surface to improve digging-up friction, or by dividing the contact surface into multiple layers to increase the contact surface [23]. In addition, tension can be added to the bending wires to generate bending torque within a range that does not exceed the holding torque due to friction, thereby further improving the holding torque. In contrast, the bending torque can be decreased for application of the mechanism in situations where it is sufficient to support its own weight, such as in search applications.

The measured deflection in the direction of gravity shown in Fig. 13 indicate that the stiffness can be maintained at low pressure by using the articulated links. The proposed mechanism significantly reduces deflection compared to a membrane-only structure at the low pressure of 8 kPa or less. It can be seen that the change in stiffness due to applied pressure is hardly significant the deflection was reduced by only about 4 mm by applying 8 kPa of pressure to the proposed mechanism without pressure. On the other hand, the inflatable structure without skeleton with an applied load of 2000 g could not hold the object because of the large deflection. It is known that low pressure causes wrinkles near the base side of the Inflatable beam. High pressure is required for the membrane-only structure not only to reduce the deflection but also to prevent the beam from breaking. The difference in deflection when three weights are attached to the proposed mechanism indicates that the deflection due to the skeleton weight has a large effect, because the deflection is does not increase in proportion to the type of weight. Although deflection due to the dead weight was not a problem for the current situation, in future it will be necessary to improve the part of the base link fixed to the containment vessel, as it has the largest moment to support a person, .

B. *Limitation of Proposed Mechanism*

The proposed mechanism, in combination with a rigid link structure, improves the load-bearing capacity and expands the range of adaptable situations; however, it has some limitations. First, the proposed mechanism can only move in the same plane along the Z-axis direction. It is also possible to turn it upward by rotating the entire structure in a torsional direction after curving it; however, in this case, the range of motion is limited. Second, the bending curvature of the entire mechanism is limited due to the different sizes of the membrane structure and the skeleton. The membrane structure will be modified to deform into a smooth curved shape because the membrane is often in a localized bent shape. In addition, the insertion of articulated links limits the narrow space that can be passed through. However, these articulated links can be designed to be smaller depending on the application. Link insertion may interfere with the extending operation of the eversion structure, but this is not a major problem.

VI. CONCLUSION

In this study, an articulated link structure constructed with hard materials was inserted into a tip-extending structure composed of a thin membrane. The combined structure offered both a high load-bearing capacity in the direction of gravity and low frictional insertion, which are the advantages of the tip-extension structure. The proposed mechanism involved using an articulated link with two axes of rotation, the pitch and yaw axes, as the articulated link structure for the tip-extension movement of the membrane. The range of motion was restricted to the pitch axis; therefore, the robot could support its weight. Wires were passed through the articulated links to enable the robot to bend and maintain its shape in the yaw direction.

Since the focus of this paper is on a comparison of stiffness compared to a membrane-only inflatable structure, we did not apply the same level of load as a human being. The requirements of the design set only considered a load of 60 kg, which means safety factor and even heavier humans were not considered. However, as shown in the concept diagram in Fig. 2, multiple sets of the proposed mechanism can be used to support larger loads.

According to the proposed mechanism, the articulated link lies along a straight line, which increases the overall size of the device. This is also far from the concept of Fig. 1. However, we planned to roll up and store the proposed skeleton structure in future works as shown in Fig.15.

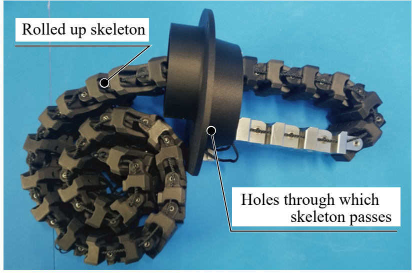


Figure 15. Articulated link in rolled and retracted construction

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REFERENCES

[1] J. Shintake, V. Cacucciolo, D. Floreano, and H. Shea, “Soft Robotic Grippers,” Adv. Mater., vol. 30, no. 29, p. 1707035, Jul. 2018, doi: 10.1002/adma.201707035.

[2] R. Qi, A. Khajepour, W. W. Melek, T. L. Lam and Y. Xu, "Design, Kinematics, and Control of a Multijoint Soft Inflatable Arm for Human-Safe Interaction," in IEEE Transactions on Robotics, vol. 33, no. 3, pp. 594-609, June 2017, doi: 10.1109/TRO.2016.2647231.

[3] E. W. Hawkes, L. H. Blumenschein, J. D. Greer, and A. M. Okamura, "A soft robot that navigates its environment through growth," Sci. Robot., vol. 2, no. 8, p. eaan3028, Jul. 2017.

[4] D. Mishima, T. Aoki, and S. Hirose, "Development of a Pneumatically Controlled Expandable Arm for Rescue Searches in Tight Spaces," The International Journal of Robotics Research, vol. 25, no. 1, pp. 103–110, Jan. 2006.

[5] M. M. Coad, R. P. Thomasson, L. H. Blumenschein, N. S. Usevitch, E. W. Hawkes, and A. M. Okamura, "Retraction of Soft Growing Robots without Buckling," IEEE Robot. Autom. Lett., pp. 1–1, 2020.

[6] D. A. Haggerty, N. Naclerio, and E. W. Hawkes, “Hybrid vine robot with internal Steering-Reeling Mechanism enhances system-level capabilities,” IEEE Robot. Autom. Lett., pp. 1–1, 2021, doi: 10.1109/LRA.2021.3072858.

[7] T. Takahashi, M. Watanabe, K. Tadakuma, M. Konyo, and S. Tadokoro, "Retraction Mechanism of Soft Torus Robot With a Hydrostatic Skeleton," IEEE Robot. Autom. Lett., vol. 5, no. 4, pp. 6900–6907, Oct. 2020,

[8] T. Takahashi, K. Tadakuma, M. Watanabe, E. Takane; N. Hookabe, H. Kajiahara; T. Yamasaki M. Konyo, and S. Tadokoro., “Eversion Robotic Mechanism with Hydraulic Skeleton to Realize Steering Function,” IEEE Robot. Autom. Lett., pp. 1–1, 2021, doi: 10.1109/LRA.2021.3073653.

[9] A. Le van and C. Wielgosz, “Bending and buckling of inflatable beams: Some new theoretical results,” Thin-Walled Structures, vol. 43, no. 8, pp. 1166–1187, Aug. 2005, doi: 10.1016/j.tws.2005.03.005.

[10] A. Hassan, H. Godaba, and K. Althoefer, “Design Analysis of a Fabric Based Lightweight Robotic Gripper,” in Towards Autonomous Robotic Systems, Cham, 2019, pp. 16–27.

[11] T. Abrar, F. Putzu, A. Ataka, H. Godaba, and K. Althoefer, “Highly Manoeuvrable Eversion Robot Based on Fusion of Function with Structure,” in 2021 IEEE International Conference on Robotics and Automation (ICRA), Xi’an, China, May 2021, pp. 12089–12096.

[12] B. H. Do, V. Banashek, and A. M. Okamura, “Dynamically Reconfigurable Discrete Distributed Stiffness for Inflated Beam Robots,” in 2020 IEEE International Conference on Robotics and Automation (ICRA), Paris, France, May 2020, pp. 9050–9056. doi: 10.1109/ICRA40945.2020.9197237.

[13] C. Loh and H. Tsukagoshi, “Pneumatic Big-hand gripper with slip-in tip aimed for the transfer support of the human body,” in 2014 IEEE International Conference on Robotics and Automation (ICRA), Hong Kong, China, May 2014, pp. 475–481. doi: 10.1109/ICRA.2014.6906898.

[14] Tomoyuki Nakamura and Hideyuki Tsukagoshi, “Soft Pneumatic Manipulator Capable of Sliding Under the Human Body and Its Application to Preventing Bedsores,” in 2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), Auckland, Jul. 2018, pp. 956–961. doi: 10.1109/AIM.2018.8452429.

[15] T. Yan, S. Teshigawara and H. H. Asada, "Design of a Growing Robot Inspired by Plant Growth," 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2019, pp. 8006-8011, doi: 10.1109/IROS40897.2019.8968200.

[16] T. Kislassi and D. Zarrouk, “A Minimally Actuated Reconfigurable Continuous Track Robot,” IEEE Robot. Autom. Lett., pp. 1–1, 2019, doi: 10.1109/LRA.2019.2959237.

[17] A. Sadeghi, A. Tonazzini, L. Popova and B. Mazzolai, "Robotic mechanism for soil penetration inspired by plant root," 2013 IEEE International Conference on Robotics and Automation, 2013, pp. 3457-3462, doi: 10.1109/ICRA.2013.6631060.

[18] J. D. Greer, T. K. Morimoto, A. M. Okamura, and E. W. Hawkes, "A Soft, Steerable Continuum Robot That Grows via Tip Extension," Soft Robotics, vol. 6, no. 1, pp. 95–108, Feb. 2019,

[19] A Ataka, T Abrar, F Putzu, H Godaba, K Althoefer, "Model-based Pose Control of Inflatable Eversion robot with Variable Stiffness", IEEE IEEE Robot. Autom. Lett. 5 (2), 3398-3405

[20] R. H. Sturges and S. Laowattana, "A flexible, tendon-controlled device for endoscopy," Proceedings. 1991 IEEE International Conference on Robotics and Automation, 1991, pp. 2582-2591 vol.3, doi: 10.1109/ROBOT.1991.132017.

[21] I. Kiryu, H. Tsukagoshi, and A. Kitagawa, " Grow-Hose-I: A hose type rescue robot passing smoothly through narrow rubble spaces," Proceedings of the JFPS International Symposium on Fluid Power, vol. 2008, no. 7–3, pp. 815–820, 2008.

[22] S. Wang, R. Zhang, D. A. Haggerty, N. D. Naclerio and E. W. Hawkes, "A Dexterous Tip-extending Robot with Variable-length Shape-locking," 2020 IEEE International Conference on Robotics and Automation (ICRA), 2020, pp. 9035-9041, doi: 10.1109/ICRA40945.2020.9197311.

[23] R. Mukaide, M. Watanabe, K. Tadakuma, Y. Ozawa, T. Takahashi, M. Konyo, and S. Tadokoro, "Radial-Layer Jamming Mechanism for String Configuration," in IEEE Robotics and Automation Letters, vol. 5, no. 4, pp. 5221-5228, Oct. 2020, doi: 10.1109/LRA.2020.2983679.