Variable Stiffness Soft Actuator using Layer Jamming for Food Handling

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***Abstract*—This study proposes a novel hybrid actuator combining PneuNet with layer jamming actuation to address the problems with conventional soft pneumatic actuators such as stability and lack of integrated locking mechanisms. The introduction of sandpaper-based layer jamming element is made as a solution. A set of experiments were conducted to identify suitable sandpaper grit-level and possible layering arrangement for the jamming section. P220 grit sandpaper showed the best flexural strength change which was suitable for the jamming element. The hybrid actuator was tested to identify the deviation from the typical PneuNet actuator in the performance of bending angle and generated tip force. The novel actuator showed a 25% reduction in bending angle while producing a 30° maximum bending angle at 160 kPa pressure. Tip force of the novel actuator didn't show a significant difference and it produced 2.3 N force at 160 kPa. The integrated jamming element can act as a locking mechanism for the novel actuator. Due to the relaxation of the PneuNet, actuating locking mechanism shows an average 30% bending angle reduction compared to the initial bending angle. A two-finger gripper was produced using the hybrid actuator and it was successfully tested on soft food handling with the integrated locking feature.**

***Index Terms*—soft robotics, layer jamming, PneuNet**

I. Introduction

In the field of robotic actuators, soft actuators are trending due to their increased flexibility, adaptability for different tasks and well-improved safety [1]. Using softer materials similar to those found in living organisms, researchers have developed a variety of actuators that are lightweight, fast-acting and compliant [2].). Soft actuators are highly preferred over rigid actuators for applications such as soft touches, safe interactions with humans, manipulating and grasping fragile objects, agricultural products and food items [3]. Silicones, shape memory alloys, shape memory polymers and hydrogels are commonly used materials in soft actuators.

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Soft Pneumatic Actuators (SPA) are widely used among soft actuators due to their simplicity, low material cost and higher force to weight ratio [4]. Pneumatic Network Actuators (PneuNet) and fiber-reinforced actuators are two popular categories in SPAs [5]. Due to the series of inflatable chambers, PneuNet actuators can produce bending motions with large amplitudes along with a wider force range [6].

The compliant and soft behavior of these actuators, limits their positional accuracy and stability [7] and lack of ability to support large loads and not equipped with an internal locking mechanism have been mentioned as their drawbacks in previous studies [8]. To overcome these drawbacks researchers are focusing on stiffening methods.

A relatively new area of soft robotics has been focused on, achieving variable stiffness using jamming transition. Jamming methods are widely used in soft robotics due to two main reasons, it provides higher stiffness variation with minimal volume change and stiffness variation can be easily adaptive for applications like gripping, locomotion, and shock resistance. Three main types of jamming can be found, such as granular jamming, layer jamming and fiber jamming. These methods use phase transitioning between compliant and rigid structures to achieve variable stiffness [9].

To develop improved actuators, studies have been conducted on hybrid actuators where several actuation methods are used in a single actuator. Park *et al.* [10] and Chen *et al.* [11] and have developed soft actuators integrated with rigid components to improve the performance for SPA actuators. Along with the soft and rigid components Park *et al.* [12] has developed a hybrid actuator with an integrated sensor to evaluate the grasp quality. Using tendon actuation to maneuver pneumatically driven actuators can be found in studies of Stilli *et al.* [13] and Li *et al.* [14].

Variable stiffening using jamming actuation is widely studied in actuator development. Passive jamming is used in Li *et al.* [15] proposed actuator, where increased pressure from pneumatic actuation is passively used for the particle jamming.

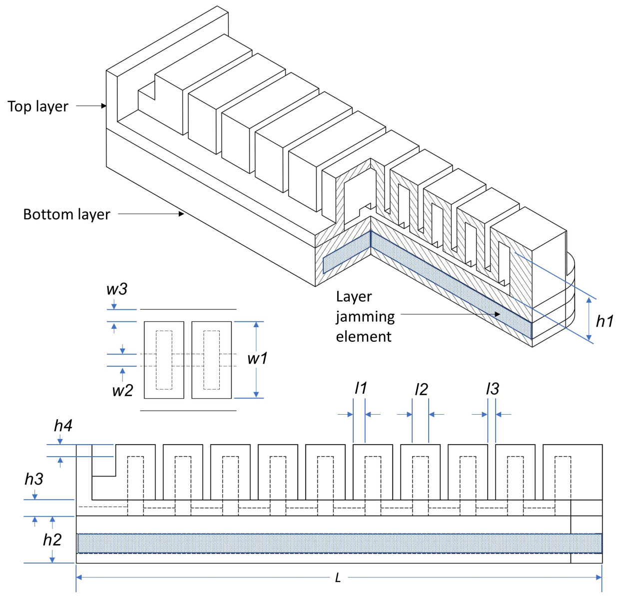

Fig. 1. Main parts of the proposed soft actuator and major parameters.

Tendon driven actuation with jamming transition is used in Mizushima *et al.* [16] proposed actuator and it was used to develop a four-finger gripper.

Collin Mikol and Hai-Jun Su [7] have proposed an actively controlled variable stiffness structure which uses pneumatically actuated muscles with layer jamming actuation. They have discussed the motion and force characteristics of the actuator along with mathematical models. Wall *et al.* [17] has investigated the integration of granular jamming and layer jamming in PneuFlex actuators, a type of soft continuum actuator.

In this study, a novel hybrid actuator combining PneuNet with layer jamming actuation is proposed to address the problems with conventional SPA actuators. The hybrid transformation has increased the load bearing capacity while introducing an integrated locking mechanism. Novel concept of the actuator is described in section II and the fabrication process of the actuator is presented in section III. Section IV explains experiments on layer jamming and hybrid actuation separately. Section V discusses the behavior of the novel actuator.

II. Concept

A typical PneuNet actuator consists of two sections as the top layer and the bottom layer. The top layer contains a series of chambers connected through an internal channel. A non-extensible layer is infused in the bottom section as a strain limiting component. When the pressure is applied to the inner chambers, the chambers will expand causing deformation in the top layer. Due to the strain limiting bottom layer, the deformation in the upper layer will cause a bending motion in the PneuNet actuator.

According to the previous studies, the bending behavior of the PneuNet actuator is highly dependent on the design parameters of the actuator. To select suitable parameters, studies were conducted previously in the lab [18]. PneuNet design with 10 identical chambers was selected for this study of the hybrid actuator with an overall length of 130 mm. A single chamber has dimensions of 25 mm chamber width, 15 mm chamber height, 15 mm chamber length and 3 mm chamber wall thickness (See Fig. 1). Major geometrical parameters of the actuator are shown in Table I.

TABLE I
Geometrical Parameters of the Designed Actuator

Notation	Parameter	Value (mm)
L	Length of the actuator	130
h1	Height of the chamber	15
w1	Width of the chamber	25
l1	Thickness of the chamber wall	3
h2	Height of the bottom layer	12
h3	Height of the intermediate layer	4
h4	Thickness of the chamber top wall	3
w2	Width of the channel	4
w3	Width of the intermediate layer	4
l2	Length of the chamber	4
l3	Length of the chamber gap	2

The strain limiting layer of the PneuNet actuator was replaced by a layer Jamming Element (LJE) to develop the proposed hybrid actuator. LJE was developed by stacking layers of specially selected material inside a closed chamber. By changing the internal pressure of the chamber, friction between each layer can be changed. This leads to a stiffness change in the layer jamming section.

Layered material has a significant effect on the performance of the jamming actuator. Previous studies have been conducted on use of different materials and their performance [19]. Sandpaper was selected as the layered material for the hybrid actuator since it shows higher stiffness change compared to other materials [20].

The proposed hybrid actuator contains a LJE infused in the bottom layer of the PneuNet actuator (See Fig. 2). The bottom layer was modified with an inner slot to insert LJE

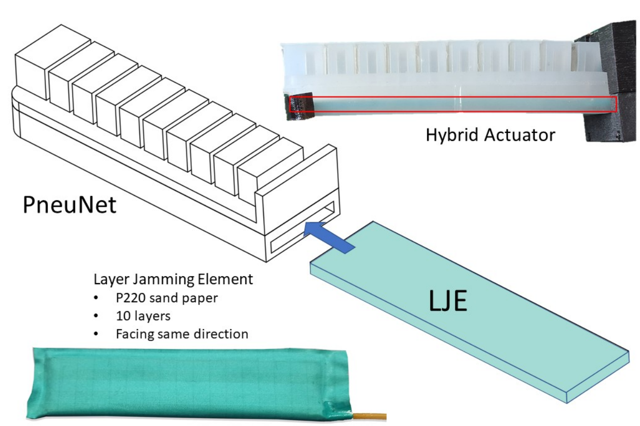

Fig. 2. Hybrid actuator

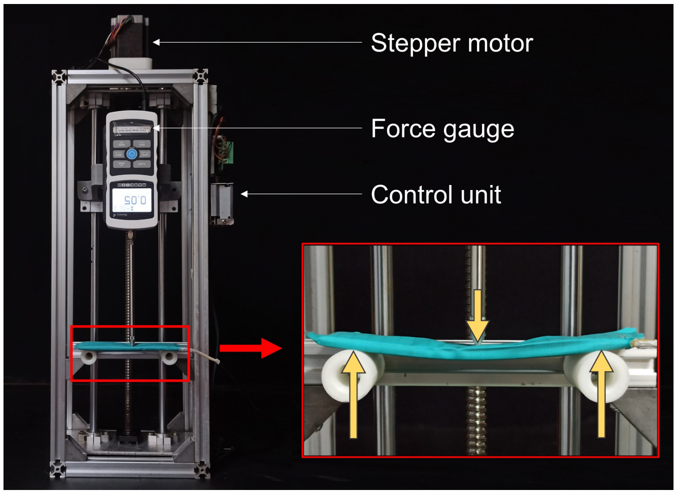

Fig. 3. The test platform used for three-point flexural bending testing

after the fabrication of the PneuNet. The slot is to be accessed easily from the outside so that the LJE can be changed after fabrication to produce different levels of stiffness changes. While the LJE acts as a strain limiting layer to perform bending motion, by combining jamming actuation with PneuNet actuation different combinations of motions can be produced.

III. Fabrication

PneuNet sections and LJE were fabricated separately and combined at the end to perform as a single actuator. A Casting method was used to fabricate the PneuNet part of the actuator. Molds were designed using SolidWorks (Dassault Systems) and 3D printed in separate parts. Two basic molds were assembled for the top layer and bottom layer separately with several 3D printed parts. Smooth-On Sorta Clear 40 was used as the hyperelastic material without any thinning agent. Two parts of materials were mixed in a 10:1 ratio by weight and degassed using a vacuum chamber. Mixed materials were poured into the molds and kept for 8 hours at room temperature to partially cure. Then both parts were separated from the molds and bonded using the same material and kept for 16 hours to fully cure.

In LJE, 30 mm × 120 mm sandpaper strips were used as the layered material. 10 layers of sandpapers were stacked and wrapped from Polyurethane fabric and sealed all the edges using a heat sealer. A flexible tube was inserted into the fabric container and the gap between the tube and the fabric was sealed using superglue. Which makes the flexible tube is the only access point to the sealed chamber. Finally, the LJE is then slid into the slot at the bottom of the PneuNet.

IV. Experiment

A. Identification of Layer Jamming Material

Previous studies show sandpapers can outperform other materials like leather, different gauges of paper and Tyvek in layer jamming operations. To identify the suitable grade of sandpaper and the arrangement of layers, a series of experiments were conducted using different grades of sandpapers. 10 layers of sandpapers were used for a single LJE, and two different arrangements were produced where one element with all the papers faced the same direction (arrangement 1) and one element with pairs of layers facing each other (arrangement 2). Both arrangements were tested for P80, P100, P150 and P220 grit levels in actuated and unactuated scenarios.

TABLE II
Maximum Flexural Strength in Different Stages

Sandpaper Grit Level	**Maximum Flexural Strength (MPa)**		
	Unactuated state	***Actuated state***	***Difference***
220-A1	0.77	11.20	10.50
220-A2	0.39	8.35	7.98
150-A1	1.039	9.50	8.52
150-A2	0.55	8.20	7.65
100-A1	0.98	5.44	4.47
100-A2	1.13	5.11	4.14
80-A1	1.30	4.23	2.94
80-A2	1.01	4.23	3.30

A custom test rig was used to perform the three-point flexural bending test (See Fig. 3). The test rig was equipped with a Mark-10 Series 4 force gauge and linear guide system driven by Nema 23 stepper motor. System control and data logging were done using LabVIEW software. Logged data was filtered with Savitsky Golay filter to reduce noise perturbation. By defining acting load (force) as F, length of the support span as L, width as b and thickness as d, flexural strength (σ) for a rectangular sample under a load in three-point bending setup can be calculated as follows (1):

$$\sigma = 3FL/2bd^2 \tag{1}$$

Test result for each sample of layer jamming section in unactuated and actuated states are shown in Fig. 4 (a) and Fig. 4 (b). The flexural strength difference between actuated and unactuated states were calculated and shown in Fig. 4 (c). Table II shows the maximum flexural strength in each stage for different sandpaper grit levels and arrangement.

The arrangement where all sandpapers are facing the same direction shows the highest deviation in flexural strength compared to the other arrangement. To select a suitable sandpaper gauge following requirements were considered. First one is the higher difference in flexural strength between actuated and unactuated states and the second one is lower flexural strength in unactuated state. The purpose of lower flexural strength is to easily manipulate the actuator with minimum resistance when LJE is in unactuated state. Higher flexural difference provides the higher stiffness change for the hybrid actuator. Since, P220 shows the highest difference, according to the Fig. 4 (c) and the lowest flexural strength in Fig. 4 (a), it was selected as the layered material to be used as the LJE in the hybrid actuator.

B. Hybrid Actuator Experiment

An experimental platform was developed to evaluate the behavior of the hybrid actuator. Actuator was attached to a

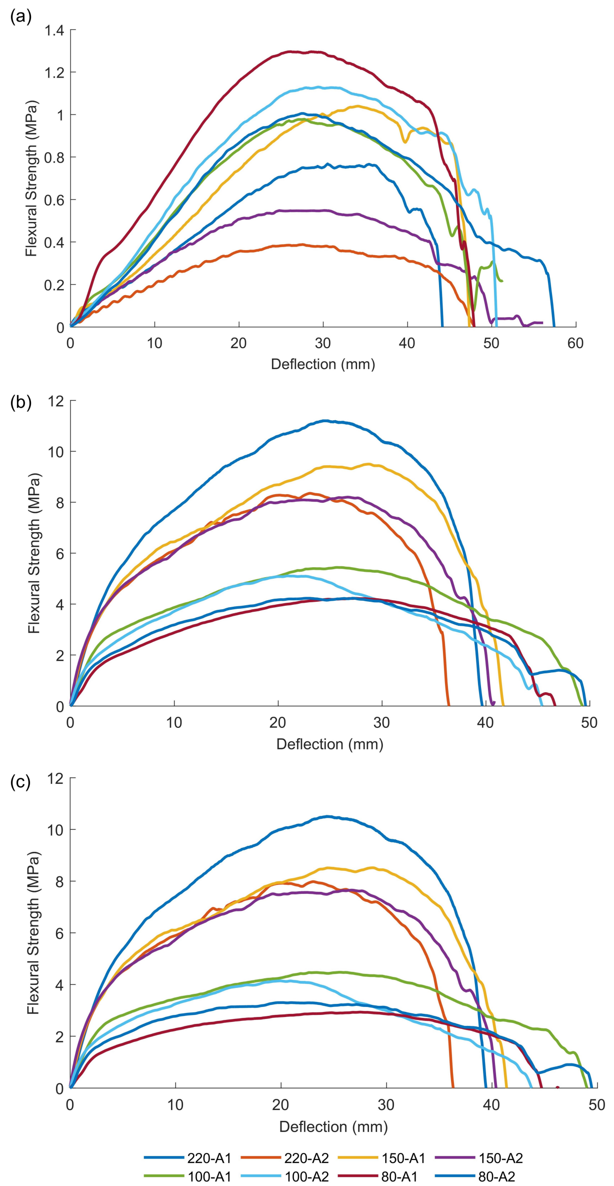

Fig. 4. Flexural strength analysis (a) Flexural strength at unactuated state (b) Flexural strength at actuated state (c) Flexural strength diference between actuated and unactuated states

fixture and placed in front of a 1 cm × 1 cm grid horizontally to eliminate the effect of gravity. A pressure regulator (SMC-ITV2030-212S) was used to control the pressure supplied through an air compressor (Displacement type, 24L). Negative pressure was supplied from a separate vacuum pump and a vacuum chamber. The vacuum supply was controlled through a manual valve (FCV 1) and a separate bypass valve (FCV 2) was added to supply air to the LJE from the atmosphere (See Fig. 5). The pressure regulator was controlled through a microcontroller board (Arduino Mega).

To identify the deviation in the behavior of the proposed actuator compared to a typical PneuNet, the actuator was tested in two arrangements. In the first arrangement, LJE was removed from the actuator and the higher thickness bottom layer was allowed to act as its own strain limiting layer. In the second arrangement, LJE was inserted and kept without actuating. In each arrangement, the motion of the actuator was observed as shown in Fig 6. Actuator was subjected to a pressure range between 0 kPa to 160 kPa. Image-J image processing software was used to track the black marker at the tip to calculate the bending angle of the actuator. To measure tip force in both arrangements, Mark-10 Series 4 force gauge is used as shown in Fig 7.

V. Discussion

Comparison between arrangement 1 and arrangement 2 bending angles are shown in Fig. 8 (a). In both scenarios, it shows a linear behavior between bending angle and the supply pressure. Inserting a LJE has reduced the bending angle compared to a typical PneuNet (arrangement 1). Maximum average bending angle achieved by the actuator in arrangement 1 is 40° at 160 kPa. However, in arrangement 2 maximum average bending angle is only 30° in identical pressure. It shows an average 25% reduction in bending angle compared to arrangement 1. However, forces generated at the tip of the actuator do not show any significant difference when LJE was added. Arrangement 1 and 2 shows similar tip force values as shown in the Fig. 8 (b). Both arrangements produce an average 2.3 N force at the tip of the actuator at 160 kPa.

Evaluation of the locking feature of the actuator was carried out at different pressure levels. In each pressure level, positive pressure was supplied first to the PneuNet actuator, then LJE was actuated by supplying negative pressure. After releasing the positive pressure, actuator holds its position by the jamming force. Due to the relaxation of chambers and straightening force from the PneuNet, actuator changes its position as shown in the Fig. 9. Straightening force is defined as the force created by the actuator while attempting to return to its neutral position. Fig. 10 (a) shows the reduction in bending angle which is calculated by the tip position change. With the increment of initial pressure, a higher bending angle can be observed in the PneuNet. A higher bending angle generates a higher straightening force of the PneuNet. When the locking mechanism is actuated LJE is resisting

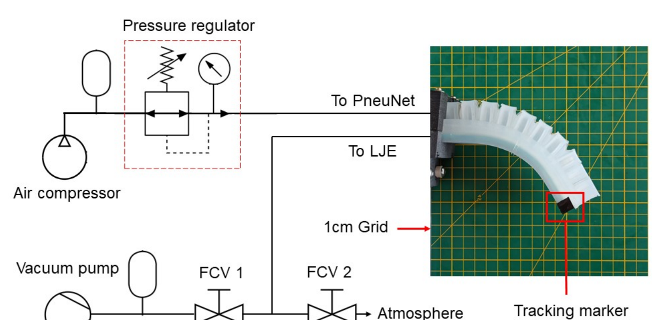

Fig. 5. Experimental platform

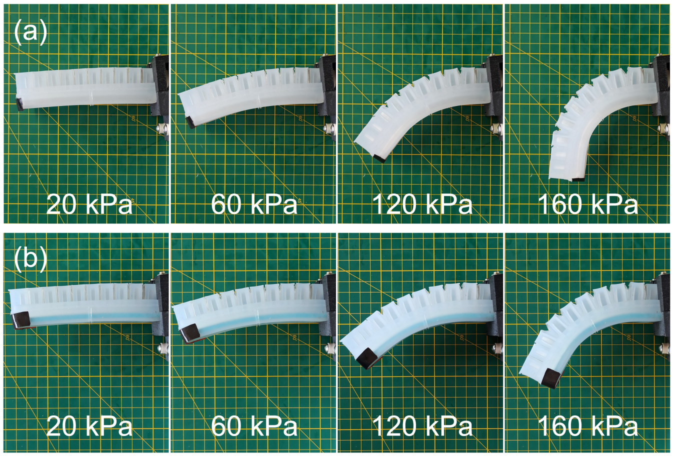

Fig. 6. Motion of the actuator in different pressure levels (a) Motion of the actuator without LJE (Arrangement 1) (b) Motion of the actuator with LJE (Arrangement 2)

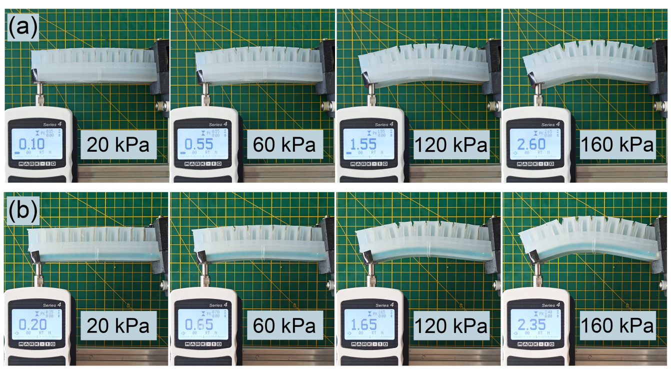

Fig. 7. Actuator tip force for different pressure levels (a) Actuator tip force in arrangement 1 (b) Actuator tip force in arrangement 2

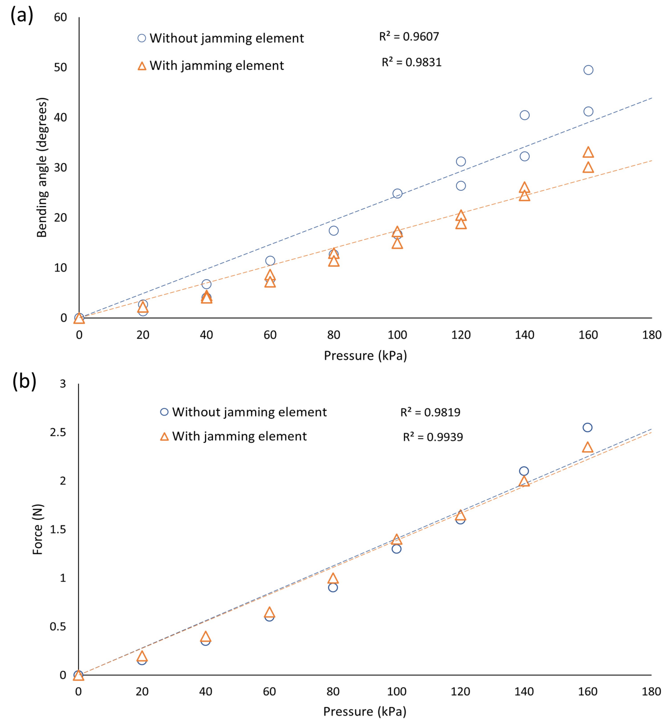

Fig. 8. Behavior of the actuator with and without the LJE (a) Bending angle vs pressure (b) Blocked force vs pressure

the straightening force generated in the PneuNet. Therefore it shows a linear increment in bending angle reduction along with initial pressure increment.

Bending angle reduction due to relaxation is compared with the initial bending angle as a percentage value as shown in Fig. 10 (b). The average reduction in bending angle of the hybrid actuator is 30% for the pressure range from 0 kPa to 160 kPa.

Using the proposed novel hybrid actuator, a soft gripper was developed. A two-finger gripper is introduced using the actuator as fingers. The soft gripper was used to manipulate soft food items which need critical gripping forces. The locking mechanism was successfully evaluated in food handling with the gripper. Fig. 11 shows the gripper used on a tomato with the locking feature. Initially, a tomato (92 g) was gripped using only positive pressure to activate the PneuNet. After successful gripping, LJE was actuated with the negative pressure and PneuNet was released. The actuator is successful in holding the tomato even though the release of positive pressure created a reduction in bending angle.

VI. Conclusion

This paper presents a novel soft actuator which uses a hybrid actuation method combining a PneuNet with a layer jamming element (LJE). This novel hybrid actuation is proposed to overcome the problems typical SPA actuators face. By embedding LJEs to the PneuNet, it acts as a strain limiting layer and also provides an additional locking feature to the actuator. To select the proper material and layering method for the layer jamming section, a series of three-point flexural bending tests was performed and P220 sandpaper was selected as the suitable material. By testing the actuator with and without the LJE the deviation between typical PneuNet and novel actuator was observed. The proposed actuator shows around 25% reduction in bending angle compared to the typical

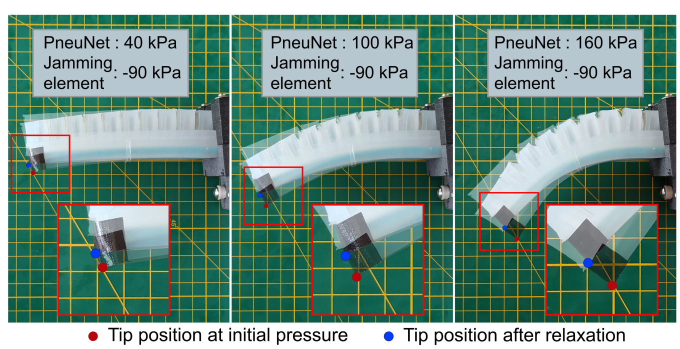

Fig. 9. Variation in bending angle reduction due relaxation of PneuNet

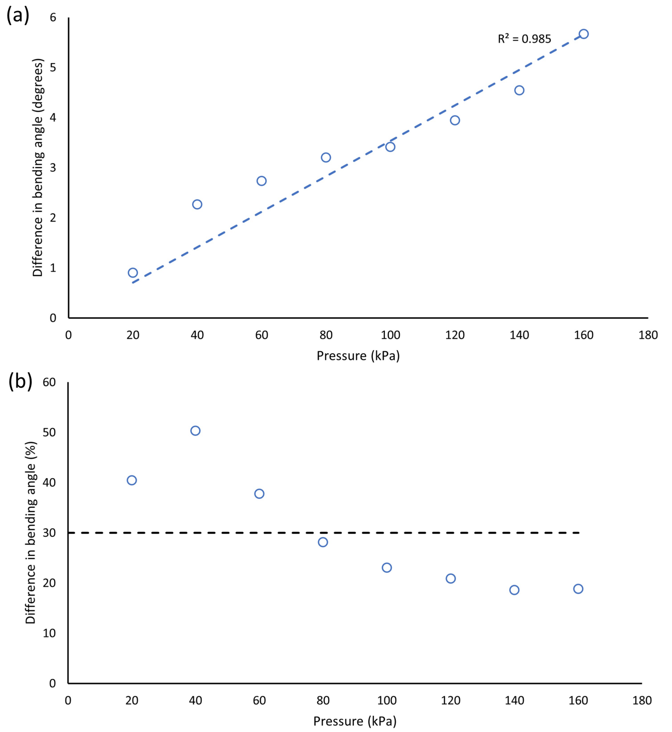

Fig. 10. The reduction in bending angle analysis when PneuNet shape only maintained by LJE (a) Bending angle reduction vs pressure (b) Percentile reduction in bending angle vs pressure

PneuNet while producing 30° of maximum bending angle at 160 kPA. No significant deviation in tip force compared to the typical PneuNet was observed in the proposed actuator and it produced 2.3 N force at 160 kPa. Analysis of the locking mechanism by LJE showed a reduction in bending angle while activating the mechanism. With the increment of the pressure value, the reduction of the bending angle also increased. An average 30% reduction in bending angle was observed compared to the initial bending angle in the presence of the locking mechanism. Using the novel hybrid actuator, a two-finger gripper was introduced and it was successfully tested on soft food items including the integrated locking mechanism.

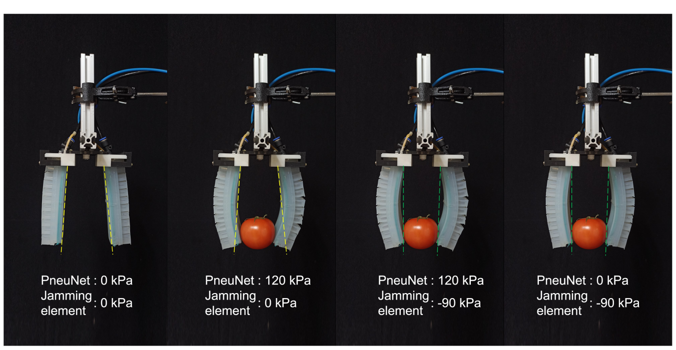

Fig. 11. Soft gripper evaluation

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