2020 3rd IEEE International Conference on Soft Robotics (RoboSoft)
Yale University, USA

Design of Pneumatic Origami Muscle Actuators (POMAs) for A Soft Robotic Hand Orthosis for Grasping Assistance

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***Abstract*— Soft robotics technologies have recently been used in various wearable applications for their high conformability to complex geometries of different parts of a human body. One of most widely explored application areas is rehabilitation by motion and force augmentation. Particularly, assistance of hand motions for stroke patients, using glove-type wearable devices, is actively investigated these days. The glove-type devices can provide additional force for flexion and extension of finger motions, helping grasping tasks of the wearers who do not have enough strength or control of their hand and finger muscles. Many of the glove-type devices are actuated by soft pneumatic muscles composed of elastomer air chambers. In spite of the advantages of flexibility and conformability to three-dimensional body shapes, they require relatively high air pressure enough to overcome the stiffness of the host material as well as complex multi-step molding and casting processes for fabrication. In this paper, we propose pneumatic origami muscle actuators (POMAs) that not only can be fabricated by a simple laser machining process but also consume relatively small pneumatic energy for actuation. Furthermore, the lightweight origami structure of the proposed POMAs provides a high force-to-weight ratio. This paper describes the design and the fabrication of a POMA followed by the characterization results. It also presents a wearable robotic device as an application, which can be used for assisting hand motions for stroke patients, made of multiple POMAs.**

Fig. 1. Soft robotic hand orthosis made of pneumatic origami muscle actuators and demonstration of grasping.

I. INTRODUCTION

One of the most common symptoms after a stroke is partial or entire paralysis of terminal muscles, making the patient incapable of using the hands by intention [1], [2]. Although there exist no treatments to make patients recover completely, it has been clinically proven that rehabilitation can alleviate the symptom more or less. However, one of common drawbacks of conventional rehabilitation methods is an extended period of time for exercises under guidance of a professional therapist or a trainer, along with a continuous financial expenditure from the patient [3], [4]. To address this issue, research and development on robotic wearable devices are actively ongoing these days with clinical tests [5], [6]. For hand rehabilitation particularly, various types of glove-type wearable robots and devices for assisting grasping motions have been proposed [7], [8], [9], [10].

One of the most widely used soft actuators for wearable robotic devices for rehailibtation (Fig. 1) is pneumatic bending muscles made of multiple elastomer air chambers [11], [12], [13]. When the air chambers are filled with compressed air, the chambers expand and pushes each other on one side while the bottom layer, made of a stiffer material, maintains the original length, enabling bending in one direction, which is useful for assisting grasping motions. Since the actuators are operated by fluid in this case, they can create slow, continuous, and smooth motions if the fluid pressure is controlled precisely, making the system suitable for rehabilitation exercises.

Different actuator designs can also be employed for creating similar bending motions. One simple example is to use two materials with different stiffnesses to stretch one side more than the other side for bending [7], [14]. Instead of using two different materials, the stretchable air chamber can be assembled with an inextensible fabric layer [8], [15] or even combined with fibers or particles making an anisotropic composite structure for bending when inflated [16], [17]. Most of soft glove-type wearable devices are made by integration of multiple bending actuators providing either single- or bi-directional motion assistance.

This work was supported in part by the National Research Foundation (NRF) funded by the Korean government (MSIT) under Grant NRF-2016R1A5A1938472 and in part by the Seoul National University Bundang Hospital Research Fund under Grant 14-2017-025.

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978-1-7281-6570-7/20/$31.00 ©2020 IEEE

While the performance of the actuator is important, there are other aspects to be considered for the wearable device to be used for rehabilitation, such as the total weight and size limits [8], [16]. The actuator should be also robust enough to hold high air pressure sometimes to ensure the safety of the user. Moreover, the motion of the actuator should naturally fit the hand shapes and motions of the wearer to provide efficient assistance as well as to be comfortable to wear. At the same time, the specifications of the actuator should meet the required forces and bending angles, response time, and bandwidth [7]. However, pneumatically-powered wearable devices are mostly made of elastomer materials for high stretchability, requiring hermetic sealing, which makes the devices not only heavy but also in need of relatively high air pressure to overcome the stiffness of the host structure.

Therefore, we propose a new type of a soft pneumatic actuator made of a lightweight origami structure, called a pneumatic origami muscle actuator (POMA), which could be used for building an efficient robotic hand orthosis. Origami structures have been widely used in designing soft, lightweight robotic structures, since they are highly flexible and stretchable in certain directions while providing relatively large structural resistance to external forces in the other directions. They can also be made in compact form factors based on designs and applications. Various types of origami structures have been suggested and analyzed mathematically [18], including applications in soft robotics [19], [20], [21]. The idea of our design is to build an air chamber of a pneumatic bending actuator using an origami structure made of a non-stretchable plastic sheet, making the structure flexible. The origami air chamber is then protected by a fabric housing made of a combination of stretchable and non-stretchable fabrics, making the actuator bending in one direction. The proposed POMA not only makes the actuator lightweight but also can be easily manufactured by a simple laser machining process of the origami pattern. Although there have been attempts to incorporate origami patterns with elastomeric air chambers of soft pneumatic actuators [22], [23], they required multi-step assembly or molding and casting processes for fabrication and also did not fully utilize the advantage of foldable structures.

In this paper, we describe the design and fabrication of an individual POMA and then present a soft robotic hand orthosis that can be used for assisting grasping motions of stroke patients by integrating multiple POMAs in a glove. The POMAs were installed to all five fingers. Each POMA was individually characterized first for bending forces and curvatures with respect to varied input air pressure levels. Then, the integrated glove system was tested for grasping motions using different air pressures.

II. Design and Fabrication

A. Origami Air Chamber

A POMA consists of an origami structure as a basic unit. Fig. 2 describes the brief procedure of building a single origami structure for a chamber. The main material used for the chamber is a polyethylene film (thickness: 0.2 mm). The

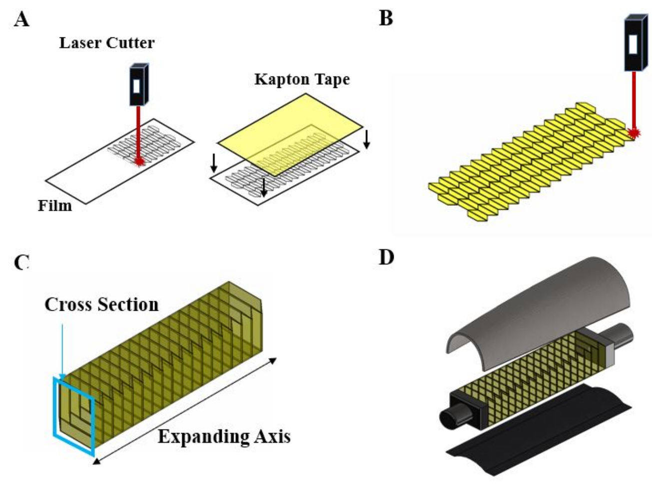

Fig. 2. Fabrication process of a pneumatic origami muscle actuator. A) Laser engraving of origami pattern and sealing with polyimide tape. B) Removal of excessive material. C) Folding of origami pattern and chamber shaping. D) Enclosing actuator with fabric housing.

film is flexible but stiff enough to endure the air pressure up to 100 kPa, which is the maximum pressure in our experiments. The origami structure used in our actuator is a square Yoshimura pattern [22], [24]. The pattern is first designed using computer-aided design software (Solidworks E-drawings, Dassault System Solidworks Corp., USA), and a CO_2 laser cutting machine (Speedy 300 Flexx, Trotec) was used to make the folding lines on the film by engraving (Fig. 2-A). After applying polyimide tape (Kapton, DuPont) on the engraved pattern and removing excessive materials by laser-cutting (Fig. 2-B), a tunnel-shaped origami structure is made by folding the lines back and forth along the axis of the short side and rolling up about the axis of the long side of the film (Fig. 2-C). The actuator is finally enclosed by a fabric housing (Fig. 2-D). The polyimide tape provides air sealing on the folding lines made by laser-engraving while maintaining the flexible structure of the origami pattern. The relatively high tensile and bending resistance of the polyimide tape also makes the actuator robust against repeated actuation.

B. Actuation

The proposed origami air chamber behaves like a soft linear actuator that extends or contracts with pressurization or with vacuum, respectively, along the axis of its length specified in Fig. 2-C. The advantage of the proposed POMs is that the actuation force from the pneumatic energy is fully transmitted only in the direction of actuation, which allows for generation of constant force regardless of the position of the actuator under a constant air or vacuum pressure, unlike typical pneumatic artificial muscles (e.g. McKibben muscles) that show rapid force decrease as they contract.

In order to make bending motions, a POMA is enclosed in a fabric housing made of two fabric layers with different stiffness, non-stretchable canvas fabric and highly stretchable nylon spandex (i.e. polyether-polyurea copolymer) fabric.

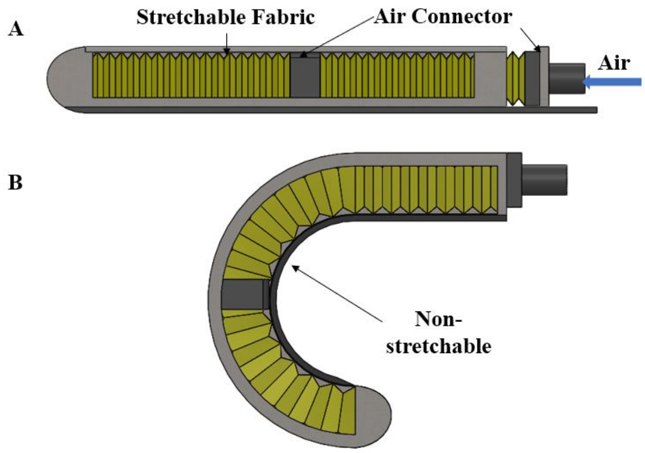

Fig. 3. Actuation behavior. A) Relaxed state without pressurization. B) Bent state actuated with pressurization.

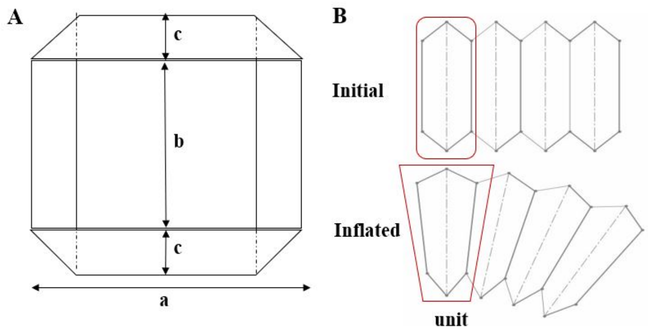

Fig. 4. A) Cross-sectional view of folded origami chamber shown in Fig. 2-C. Three parameters (a,b, and c) that determine the shape of the origami. B) Side view of the origami structure in initial state and bent state with inflation. The red section shows a single unit of one chamber. Several units are connected in series to make one pneumatic actuator. The number of units in each finger is provided in Table I.

When pressurized, the actuator has to elongate its length, but the non-stretchable layer constrains linear extension, resulting in bending. The non-stretchable layer becomes the neutral axis for bending. The spandex layer that can be easily stretched up to 200% of its original length facilitates the bending motion, as shown in Fig. 3. It is essential to hermetically seal the origami chamber completely to ensure the reliable performance of the actuator

C. Actuator Integration with Glove

The main body of the proposed hand orthosis is a fabric glove, and five bending actuators with different lengths were attached to the dorsal sides of the glove fingers. Since the lengths of the five fingers are different, the chamber designs for the fingers should be different to generate similar motions. Fig. 4 shows the parameters of the origami pattern that determine the behavior of the actuator, and they have previously been discussed for analytically modeling the Yoshimura pattern [22]. In this work, we selected different parameter values for each finger based on experimental data.

Fig. 5. Hand orthosis prototype with five POMAs integrated showing extension (left) and flexion (right) motions.

Table I summarizes the selected values for all five fingers. Fig. 5 shows a hand orthosis prototype using a fabric glove integrates with five POMA fingers. With the provided values, we were able to achieve bending motions similar to natural grasping motions. In order to create large bending angles, two origami structures were connected in series for long fingers, such as index and middle fingers.

Since the origami actuator is easily scalable, it is easy to change the size of the orthosis depending on the users. In addition, the pocket design of the finger housing makes it easy to replace or repair the origami actuator if it fails. For a rehabilitation purpose, the entire device should be lightweight so that the weight of the device does not degrade the existing performance of the user. Since we used only lightweight materials, such as transparency films and fabrics, the total weight of the proposed orthosis is approximately 200 grams.

III. EXPERIMENTS

All five finger actuators were experimentally characterized individually for bending forces and angles with varied input pressure levels.

TABLE I

SELECTED PARAMETER VALUES FOR ORIGAMI CHAMBER DESIGN.

Finger	Parameters			
	Length [mm]	a, b, c [mm]	number of units	Weight [g]
Thumb	200	20, 14, 3.0	20	20.6
Index	150,150	18, 13, 2.5	15,15	21.1
Middle	150,170	18, 13, 2.5	15,17	25.2
Ring	150	18, 13, 2.5	13	19.4
Little	130	15, 10, 2.5	10	15.2

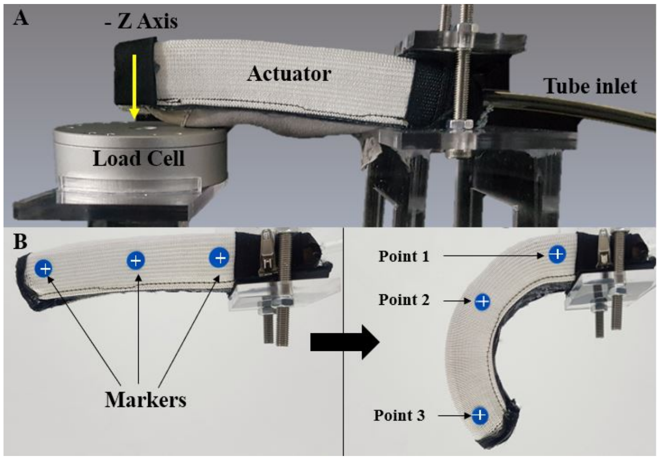

Fig. 6. A) Test setup for measuring bending force using commercial load cell and single pneumatic actuator. All five fingers with actuators were tested identically. B) Finger actuation behavior: before (left) and after (right) pressurization with 0 kPa and 70 kPa, respectively. Three equally spaced markers were attached to the side of the finger for motion tracking.

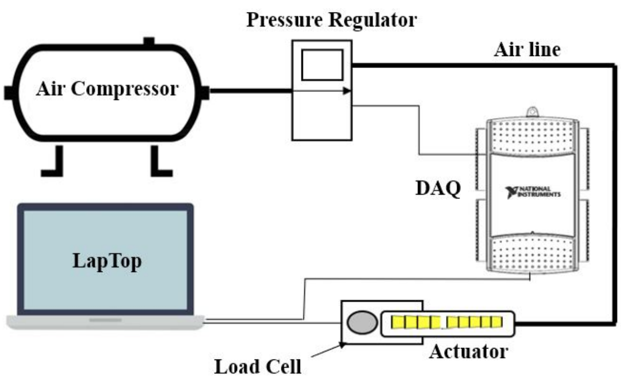

Fig. 7. System overview for experiments and data collection.

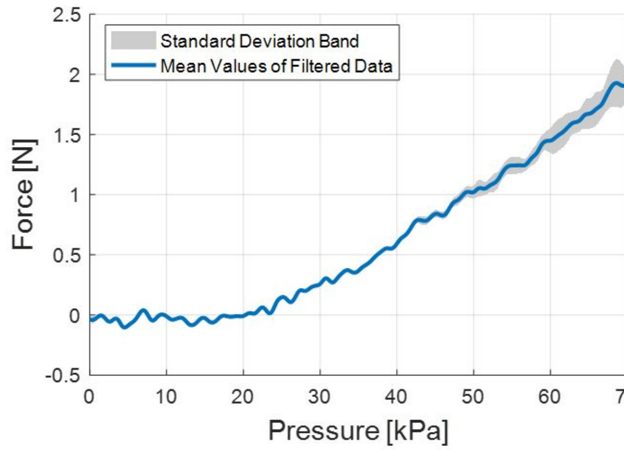

Fig. 8. Force vs. pressure data for index finger actuator. Blue curve shows the mean force values of ten sets of measurements from repeated pressurization-depressurization loops. Shaded band represents the range of standard deviation values. The finger was highly repeatable up to 50 kPa and started showing slight variations afterward. The other four fingers showed similar curves with different sensitivities.

A. Bending Force

In order to measure the bending force of the finger actuator, the base of the actuator was fixed, and the motion of the fingertip was constrained in the vertical direction by a commercial load cell (RFT60-HA01, Robotous), measuring the tip force in the vertical direction (Fig. 6-A) with varied input pressure levels. The pressure was gradually increased and decreased between 0 kPa and 70 kPa during the test using a digital pressure regulator. A total of ten loading-unloading tests were conducted for each finger, and the force was measured by a commercial load cell, and the data was collected through a data acquisition (DAQ) board, as shown in Fig. 7. All five fingers were tested with the same process.

B. Bending Curvature

For testing bending curvature, three equally spaced markers were attached to the side of the finger actuator (Fig. 6-B), and the curvature was measured with varied input pressure levels. The locations of the markers were detected by Image Processing Toolbox provided in MATLAB. We collected the x and y coordinates of the markers in the sagittal plane. The pressure was increased and decreased between 0 kPa and 70 kPa, and ten loading-unloading tests were conducted for each finger in the same way as the force test. Assuming the finger actuator makes part of a perfect circle while bending, we can geometrically calculate the curvature of the finger actuator as long as we know the locations of any three points on the circle.

IV. Results

All five finger actuators were individually tested with a commercial load cell. Fig. 8 shows a force response with varied input pressures for the index finger. The pressure was linearly increased up to 70 kPa for five seconds and decreased back to 0 kPa for another five seconds, and we repeated this loading and unloading loop 10 times. The actuator showed almost no hysteresis during the loading and unloading period. Fig. 8 shows the mean curve with the standard deviation band of the 10 test data sets for the index finger, showing high repeatability in actuation. The relationship between the pressure inside the pneumatic chamber and the force at the fingertip was fitted by a quadratic function above 20 kPa. The minimum air pressure required for actuation was 20 kPa, since the actuator did not generate any force below it. This is due to the stiffness of the chamber-housing structure.

The proposed POMA showed relatively high force outputs with low input pressures, which could be advantageous especially for glove-type rehabilitation devices in which safety is one of critical factors to be considered in design. Furthermore, high grasping force can be easily achieved with relatively low input pressures. Fig. 9 shows the force-pressure curves of the five finger actuators fitted from experimental data using quadratic functions. Due to the different sizes and parameters of the origami designs of the POMAs, the force sensitivities to input pressures are different. The thumb showed the highest bending force due to its larger

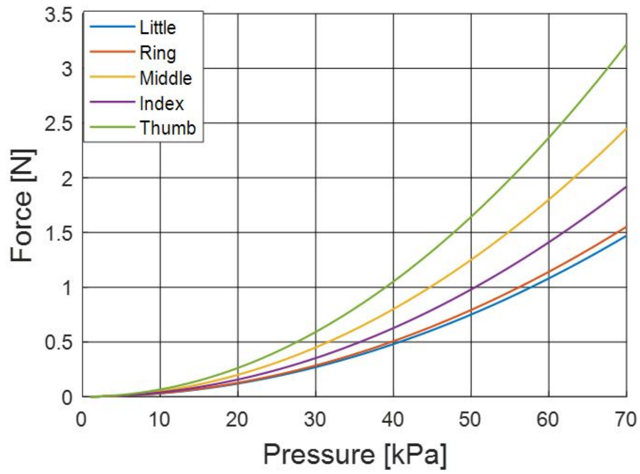

Fig. 9. Fitted curves of experimentally measured force responses of all five finger actuators. All curves were fitted by quadratic functions.

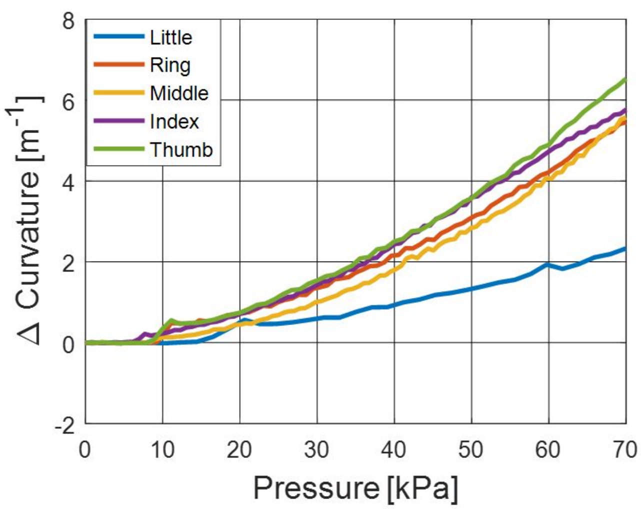

Fig. 10. Curvature changes with varied input pressure levels for all five finger actuators. Four fingers (thumb, index, middle, and ring) showed similar curvature increases, but little finger showed much smaller curvatures with the same input pressures due to the smaller parameter values in origami design.

cross-sectional area. If the cross-sectional areas are the same, the longer finger showed the higher maximum bending force. The little finger showed the lowest force due to the smaller cross-sectional area and length.

Fig. 10 shows the experimental data of curvature-pressure curves for all five fingers. Four finger actuators (thumb, index, middle, and ring) showed similar curvature increases as the origami chamber was gradually inflated with compressed air. The little finger did not bend as easily as the other four fingers with the same input pressures, since it was shorter and weaker than the other fingers.

Table II summarizes the maximum forces and curvatures of all five fingers when approximately 70 kP of input pressure was supplied. In general, the bending force and the bending curvature increased as the cross-sectional area and the length became large.

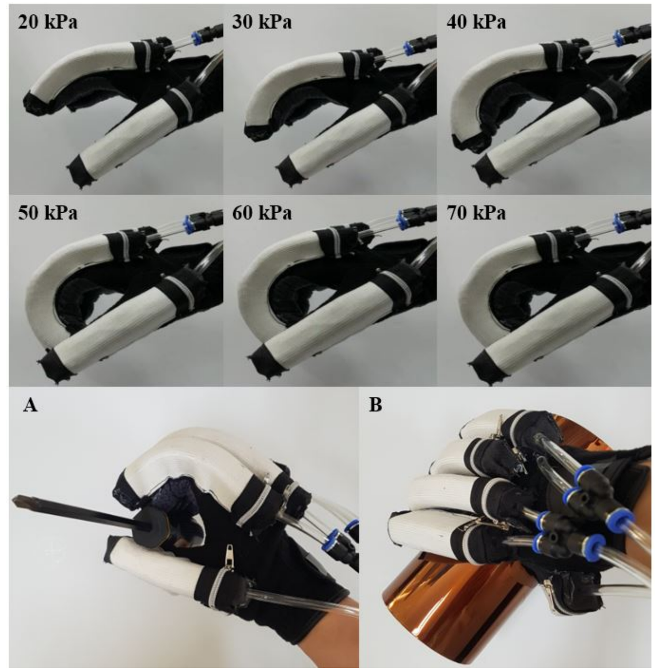

Fig. 11. Bending shape of the glove while raising the air pressure (top). Grasping of small (A) and large (B) objects using different grips. Input pressures are 60 kPa and 50 kPa for A and B, respectively.

V. Application

After characterizing the finger actuators individually, we integrated them with a fabric glove to build a hand orthosis, as shown in Fig. 11. As the input pressure increased, the orthosis was able to make grasping motions with higher bending angles. The orthosis started to close the grip with the thumb at 50 kPa. Since the entire structure of each finger is flexible and deformed with pressurization of the origami chamber, the orthosis is capable of adapting its grip to the shape of the object as, allowing both pinch and power grips, as demonstrated in Figs. 11-A and 11-B, respectively, similar to under-actuated grippers [25], [26], [27].

Although the current actuators and the orthosis presented in this paper were tested with input pressure only up to 70 kPa, it is not the maximum air pressure that the origami chamber can hold. It is rather the minimum air pressure that can demonstrate the feasibility of the device for hand rehabilitation. The next step of this research will be testing the actuator and the orthosis with higher input pressures to determine the full range of performance.

TABLE II

Experiment Results

	Values	
Finger	Maximum Force [N]	Maximum Curvature [m^{-1}]
Thumb	3.2	6.5
Index	1.9	5.8
Middle	2.5	5.6
Ring	1.5	5.5
Little	1.5	2.3

VI. CONCLUSION

A pneumatic bending actuator was designed and fabricated using an origami structure enclosed in a fabric housing. The combination of the stretchable and non-stretchable fabric layers of the housing enabled bending motions of the actuator. The main advantages of the proposed actuator include simple fabrication using laser cutting and engraving, low actuation pressure from the low stiffness origami structure, and lightweightness. The proposed actuator was able to generate over 3 N and 7 m^{-1} of bending force and curvature, respectively, with 70 kPa of input pressure. Furthermore, by integrating multiple actuators in a glove, a soft robotic hand orthosis was developed for use in assisting grasping motions for stroke patients. The prototype showed successful flexion and extension motions of all five fingers. The orthosis prototype was easily wearable and comfortable and also provided the wearer with grasping capability of objects with different sizes and geometries.

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