ABSTRACT

Soft actuators are an essential component of soft robots. They are also well suited for human-friendly robots due to their intrinsic safety. The advantages of origami structures have motivated the development of origami-inspired semi-soft actuators. In this paper, a novel rapid, systematic and cost-effective fabrication method for durable origami-inspired semi-soft pneumatic actuators is presented. The proposed method employs heat-shrinkable polymers conforming to reusable molds. It is applicable to a variety of origami patterns, and it produces actuators with consistent performance. Two origami semi-soft pneumatic actuator designs (accordion and Yoshimura patterns) have been fabricated. Each actuator was fabricated in less than 10 minutes (not including the time required to create the molds and plastic components). A nonlinear finite-element model is developed to predict the actuator’s folding behavior and blocked force. The results show that it can predict the blocked force with a maximum error of 5.7% relative to experimental measurements. This model can be used to improve the design of future actuators. Experimental results for isometric, isobaric, isotonic and cyclic fatigue tests for the accordion pattern actuator are included and discussed. The actuator prototype has a maximum stroke of 40 mm (or 36% of its effective length) and a maximum blocked force of 124 N at a vacuum pressure of −80 kPa. It also showed no decrease in performance and no leakage after 1000 cycles with a payload of 0.9 kg, demonstrating its durability compared to previous origami-inspired semi-soft pneumatic actuators. Finally, it has a high force-to-weight ratio as it can lift a load more than 118 times its own weight. Its performance demonstrates that powerful, lightweight and durable actuators can be easily produced by the proposed fabrication method.

INDEX TERMS

Origami pneumatic actuators, soft robots, pneumatic actuators, artificial muscles.

I. INTRODUCTION

Research on soft robots has rapidly grown due to their potential to solve problems that cannot be solved by traditional rigid robots. Soft robots have applications in many areas, including: medicine [1], assistive devices [2]–[4], and exploring unstructured environments [5], [6]. They also provide different ways to perform traditional robot functions, such as grasping [7] or locomotion [8], [9].

Origami is a Japanese art and science that guides the fabrication of 3D paper structures by folding [10]. Origami has many desirable characteristics such as: low material volume and mass; scalability; reduced assembly; ease of miniaturization; and part number reduction [11]. As a result, there are many origami-inspired engineering applications ranging from large-scale deployable aerospace structures [12] to small-scale biomedical devices [13]; mechanical metamaterials [14]; and DNA machines [15]. In the field of soft robots, the integration of origami characteristics results in origami-inspired designs that have “built-in compliance because of the geometry of the folds and the creases in the material, and they are semi-soft, that is, they exhibit the properties of both rigid and soft robots” [16].

Most soft or semi-soft actuators employed in soft robots, and elsewhere, are pneumatically powered as it can provide robust and compact actuators, with low inertia and low stiffness. These actuators may be classified into three main categories according to the source of motion. The first category is fiber-reinforced pneumatic actuators e.g. McKibben muscles [17]. They use an elastic internal bladder and a braided fibre shell to generate contraction when the pressure is increased. The second category is bending actuators, which generate a bending motion when pressurized by constraining one side of the actuator (typically by changing the material thickness or using materials with different properties), e.g. PneuNets [18]. When the bending actuator consists of relatively...
rigid panels connected by compliant hinge joints, it belongs to a third category called origami-inspired actuators [19]. Origami-inspired semi-soft pneumatic actuators (OSPA) possess the advantages of pneumatic actuators combined with the advantages of origami.

Fabrication methods for OSPA are very limited and have not fully matured. Only three distinct fabrication methods have been reported in the literature. The first method, proposed by Martinez et al. [19], employs casting of elastomer coated paper composites. They fabricated several paper-elastomer OSPA prototypes including an extension actuator based on the Yoshimura pattern. The reusable molds were made by 3D printing. Their method has also been adopted by other researchers in [20] and [21]. It is easy to use but is time consuming due to the number of steps involved and the elastomer curing process. As with all pneumatic actuators, the output force of an OSPA is dependent on the operating pressure. The weakness of the paper-elastomer material limited the maximum operating pressures used in [19]–[21] to 30, 20 and 10 kPa, respectively. Furthermore, in [19] only 50 pressurization/depressurization cycles were used to test the actuator for fatigue failure. No fatigue test results were reported in [20] or [21]. The fatigue life of this material is untested beyond 50 cycles.

Additive manufacturing of soft, flexible materials is the second known OSPA fabrication method. For example, Sane et al. [22] fabricated two OSPA based on the Miura-ori pattern; one extension type and one contraction type. They used two different 3D printing methods with two different materials. The extension actuator was made of polyether block amide (PEBA) on a selective laser sintering (SLS) machine, while the contraction actuator was made of thermoplastic polyurethane (TPU) on a fused deposition modeling (FDM) printer. They used a maximum pressure of only 34.5 kPa in their experiments and did not report any fatigue testing results. The limitations of this method include the lengthy printing time, weakness of the printed structure, sealing problems, and in some cases the need for specialized 3D printers.

The third fabrication method for OSPA was presented by Lee et al. in [23]. Their method uses a sheet of polyvinyl chloride that is wrapped around rigid, evenly spaced, transversal reinforcements, and top and bottom endplates. When vacuum pressure is applied the reinforcements control the collapse of the sheet which leads to the actuator contracting. The sheet and other components are held together using tape. They included tests with a vacuum pressure of -83 kPa. This method is limited to one simple origami pattern, and it is likely that the tape would start failing after a small number of cycles. No fatigue tests were included.

In this paper we present a novel OSPA fabrication method that addresses several of the limitations of the existing methods. Our method can fabricate an actuator in minutes using thermal forming. It produces strong actuators with consistent performance and does not require specialized equipment. It uses reusable molds and commonly available heat-shrink tubing. It can also be used to fabricate actuators based on wide range of origami patterns (including actuator designs that cannot be produced by folding). We also present a finite-element model that can be used for studying the effects of different OSPA materials, dimensions and operating conditions on the actuator’s performance.

We begin with a description of the actuator and mold design process in Section II. Heat-shrink material selection is covered in Section III. The fabrication method is presented next (Section IV), followed by the design and fabrication of prototypes for testing (Section V). The actuator modeling is presented in Section VI. Isometric, isobaric, isotonic, and cyclic fatigue test procedures and results are given in Section VII. In Section VIII, the design and fabrication of a soft-ended actuator are presented; followed by conclusions and plans for future research in Section IX.

II. ACTUATOR AND MOLD DESIGN

A. DESIGN OVERVIEW

Two of our designs for OSPA are shown in Fig. 1. Each design consists of top and bottom end caps (shown in blue and orange, respectively), and the flexible origami-inspired section that will be made by thermal forming heat-shrinkable tubing (shown in grey). We chose to fabricate OSPA based on the accordion and Yoshimura patterns since they can produce a larger stroke than other patterns [24] and their ends have constant cross-section so they can be easily attached to the end caps.

After it was discovered that the initial prototypes collapsed when a vacuum pressure of only -15 kPa was applied, we added internal support ribs (not shown in Fig. 1) to strengthen the actuators. Another design approach for preventing the actuator walls from collapsing is to use heat-shrink tubing with thicker walls. We did not pursue this approach since thicker walls will increase the actuator’s longitudinal stiffness. This has the disadvantages of reducing the actuator’s force output (since more of the pneumatic pressure...
B. MOLD DESIGN

Since the actuator’s origami-inspired shape is formed tightly around the mold, to prevent damaging the actuator when removing the mold requires either using a multi-piece mold or destroying the mold. We chose the more difficult option of designing a multi-piece mold since it allows one mold to be reused to fabricate many actuators. This reduces the time spent manufacturing molds and is better for the environment. We also designed the molds to be easily manufactured (e.g. using a common FDM 3D printer).

The main challenges of the mold design process are: the cross-section of each piece of the mold must be smaller than the smallest cross-section of the actuator, the pieces must be designed to stay properly aligned during the thermal forming operation, a viable sequence of removal steps must be developed, and the numbers of pieces should be kept small to avoid complexity. The molds for the actuators based on the accordion and Yoshimura patterns (shown in Fig. 1) will be used to illustrate two designs that meet these requirements. Each mold consists of seven pieces and is designed such that the removal of the center part facilitates the removal of individual side pieces. The mold designs and removal steps for these actuators are shown in Fig. 2 and Fig. 3, respectively. They are shown assembled in their aligned state in part (a) of each figures. The removal steps are shown in parts (b) to (d) of each figure.

C. DESIGN OF END CAPS AND SUPPORT RIBS

The designs for the end caps are shown in Fig. 4. Each features a circumferential groove with a sawtooth pattern that facilitates sealing between the tubing and cap. The bottom end caps include a guide pin that mates with a hole in the mold to ensure alignment of the mold and cap. The top end caps include a section that transitions from the specific origami pattern to the grooved circular section of the cap. This transition section is used to align the top end cap with the lower section of the actuator as will be explained further in the fabrication section (Section IV). The extra support it provides also makes the actuator stronger.

The internal support ribs are used to allow the actuator to operate at higher vacuum pressures. They also have the downside of reducing the contraction due to their thickness. The rib designs for the OSPA based on the accordion and Yoshimora patterns are shown in Fig. 5. They have a radiused edge to reduce stress concentrations at the actuator’s hinges and have a lightweight design. The bottom end rib includes a hole that mates with guide pin on the bottom end cap to provide alignment.

III. HEAT-SHRINK MATERIAL SELECTION

Commercial heat-shrink tubing is the essential element of our fabrication method. The tubing is made from a material that recovers its original smaller surface area when it is heated to its “full recovery temperature”. For OSPA fabrication and performance the most relevant heat-shrink material properties are: tensile strength, ultimate elongation, shrink ratio and full recovery temperature. A higher tensile strength tubing should allow the OSPA to withstand higher pressures and output larger forces without failing. Tubing with larger values for ultimate elongation should be able to conform to the mold better during fabrication and should also provide a greater range of motion when the OSPA is operating. The shrink ratio is the ratio of the original (unshrunk) diameter to the recovered (shrunk) diameter. A larger shrink ratio should make the seals between the tubing and end caps tighter.

Finally, the full recovery temperature influences both the materials chosen for 3D printing the mold and end caps,
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FIGURE 5. Designs for the internal support ribs. (a) For accordion pattern OSPA. (b) For Yoshimura pattern OSPA.

TABLE 1. Commercial heat-shrink tubing candidates for OSPA.

| No. | Heat-shrink brand and part number | Tensile strength (MPa) | Ultimate elongation (%) | Full recovery temperature (°C) | Shrink ratio |
|-----|----------------------------------|------------------------|-------------------------|-------------------------------|-------------|
| 1   | Alpha Wire (F22121N-CL105)       | 10.3                   | > 200                   | 121                           | 2:1         |
| 2   | 3M (FP301-2)                     | 16.5                   | 400                     | 130                           | 2:1         |
| 3   | NTE Electronics (47-21248-BK)    | 13                     | 400                     | > 90                          | 2:1         |
| 4   | TE Connectivity (VERSAFIT-2-0-SP) | 10.3                   | > 200                   | > 90                          | 2:1         |
| 5   | Qualtek (Q2-F4X-2-01-QB48NIN-5)  | >14                    | > 600                   | 100                           | 4:1         |
| 6   | Alpha Wire (FIT-421-2IN)         | 10.3                   | > 200                   | 121                           | 4:1         |

1. Material property values are from manufacturers’ datasheets.

and the process used for heating the tubing. It ranges from 60-350 °C. The most common 3D printing filament is poly-lactic acid (PLA), but it softens at too low a temperature (i.e., its glass transition temperature is around 60 °C) to be used with most heat-shrink materials. Furthermore, preliminary experiments showed that immersing the tubing in boiling liquid produced faster and more homogenous shrinking than other heating methods such as placing the tubing in an oven. Using boiling water is the most convenient choice so heat-shrink tubing with a full recovery temperature of 100 °C (or less) are desirable.

We tested six commercially available brands of heat-shrink tubing with the best combinations of these four properties. The details of these candidates are listed in Table 1. All had a 50.8 mm unshrunk diameter and were tested using the accordion pattern mold whose dimensions are given in Section V. Boiling water was used to shrink candidates 3-5, while boiling ethylene glycol was used with candidates 1-2 and 6. Candidate 1 shrunk well at the mold, but split lengthwise at the bottom end cap. Candidates 2-4 did not fail by splitting. However, they did not fit tightly enough on the end caps to seal well. Candidates 5 and 6 shrunk well to the end caps and sealed well. We believe this is due to their larger values of shrink ratio. Candidate 5 has a greater tensile strength, larger ultimate elongation and is significantly less expensive than candidate 6 ($15.50 vs. $84.28 for a 1.22 m length from Digikey). As a result of this study, we selected the candidate 5 heat-shrink tubing (i.e., Qualtek Q2-F4X) for our OSPA fabrication method.

IV. FABRICATION METHOD

The steps of the proposed fabrication method are illustrated in Fig. 6, and can be summarized as follows:

a) Create the CAD models for the multi-piece mold, end caps and internal support ribs and export them to stl files.

b) Load the stl files and 3D print the mold pieces and end caps out of acrylonitrile butadiene styrene (ABS). ABS is recommended since it is inexpensive, strong, and has a glass transition temperature of around 105 °C so it will not soften during the heat-shrinking steps. The support ribs can be printed out of PLA since they will not be exposed to heat. An inexpensive FDM 3D printer may be used.

c) Assemble the mold and bottom end cap and insert them inside the heat-shrink tubing. Use cellophane tape to temporarily hold the bottom end cap and tubing together.

d) Immerse the assembly gradually into boiling water until the top surface of the mold is level with the top of the water, then wait until the tubing acquires the shape of the mold (typically around 1 min). After the shrinking process is complete, remove the assembly from the boiling water and remove the cellophane tape.

e) Carefully remove the mold pieces from inside the actuator, starting with the middle part, followed by the side parts one at a time (as previously described in Section II). Insert the support ribs, starting with the bottom support rib. The hole in the bottom support rib should be mated with the guide pin on the bottom end cap.

f) Insert the top end cap into the open end of the tubing until it mates with the shape formed in step (d). Next, immerse the assembly in boiling water until the tubing shrinks onto the end cap (requires around 30 sec). If necessary, cable ties can be used to achieve better sealing between the tubing and end caps.

Fig. 6f shows a Yoshimura pattern OSPA that was successfully fabricated using this method. The method has also been used to fabricate the accordion pattern OSPA that is described further in the next section.

V. DESIGN AND FABRICATION OF OSPA PROTOTYPES FOR TESTING

The performance testing will be done on two accordion pattern OSPA prototypes. As shown in Figs. 7a and 7b, the design of the origami portion of the actuator consists of a repeating base unit with a trapezoidal shape. Our design has the following dimensions: \( \alpha = 1.33 \text{ rad.}, \ a = 46.5 \text{ mm}, \ b = 18.5 \text{ mm}, \ c = 20 \text{ mm}, \ d = 20 \text{ mm}, \ D = 50 \text{ mm} \) and \( t = 1 \text{ mm} \). As shown in Fig. 7b, its overall length (including
the end caps) is $L = 140$ mm, and its effective length is $L_{\text{eff}} = 90$ mm. The internal support ribs use the design shown in Fig. 5a and have an edge radius of 1.5 mm.

The two prototypes were fabricated using the method from Section IV. Each prototype used a 175 mm long piece of the heat-shrink tubing selected in Section III (Qualtek, Q2-F4X-2-01-QB48IN-5, 50.8 mm initial diameter). The mold, end caps and ribs were manufactured using an inexpensive FDM 3D printer (Prusa, i3 MK3S). The ribs were made from PLA with 100% infill. The other parts were made from ABS with 50% infill for mass reduction. To improve the sealing reliability, we clamped the heat-shrink tubing to the end caps using TPU flexible cable ties (HellermannTyton, 115-07270). The mass of each fabricated actuator was only 73 g.

VI. MODELING
A. MATERIAL MODELING
A material model is a prerequisite for developing an analytical or numerical model of an OSPA's force output as a function of its displacement and the supply pressure. Since insufficient information on the material properties of polyolefin heat-shrink was available in the literature, or from the manufacturer, we modelled the mechanical behavior of the Qualtek Q2-F4X heat-shrink tubing empirically.

When the tubing takes on the shape of the OSPA during fabrication it is not fully shrunk (i.e., it does not shrink to 1/4 of the unshrunk diameter) so its properties should lie between those of the unshrunk and fully shrunk tubing. With this in mind, tensile tests were performed on ten dumbbell-shaped specimens: five cut from an unshrunk tube and the other five cut from a fully shrunk tube. The tests were conducted according to ASTM Standard D412, as recommended by tubing manufacturer Qualtek. The dumbbell specimens were stretched at a rate of 500 mm/s using an electromechanical universal testing machine (Shimadzu AGS-X Series 50 kN). The collected data exhibited the nonlinear stress-strain behavior that is typical of polymers such as polyolefin. It was effectively modeled by fitting the Mooney-Rivlin two-parameter hyperelastic material model to the
mean of the stress-strain data from the unshrunk and fully shrunk specimens. The fitted parameters are: $C_{10} = -9.24 \times 10^5\text{ Pa}$, $C_{01} = 4.87 \times 10^6\text{ Pa}$ and $D_1 = 0$.

B. FINITE-ELEMENT MODELING

Finite-element analysis (FEA) is the most common approach for modelling soft and semi-soft pneumatic actuators, e.g., [9], [18], [19], and [22]. We have developed a nonlinear FEA model of the accordion pattern OSPA. The model can be used to predict the folding behavior and blocked force when vacuum or positive pressure is applied to the actuator’s internal surface. To reduce the simulation time, the CAD model details which do not affect the actuator’s behavior, such as the sawtooth grooves and holes in the end caps, were removed from the FEA model. The shapes of the internal support ribs were modeled as a flat plate with a middle hole with the same thickness of the real support ribs. Symmetry analysis was also utilized to reduce the size of the problem and simulation time by solving a quarter of the OSPA. The thickness of the polyolefin tube was adjusted to match the measured thickness of the fabricated accordion OSPA, which was 1 mm.

The FEA model was created using the Static Structure module in ANSYS Workbench 2020 R1 with the large deflection option selected. Two element types were used to mesh the model. Tetrahedral elements with ten nodes (SOLID187) were used for the end caps and support ribs. Shell elements (SHELL181) were used for meshing the walls of the OSPA to capture the membrane effect and to avoid the locking phenomena that can occur with FEA of thin-walled structures. After performing a mesh independence study, the number of elements was set to 28,495.

To simulate the isometric and isobaric testing of the OSPA a two-step simulation was developed. The boundary conditions applied in the first step were fixed support of the bottom end cap, and a fixed displacement of the top end cap. To match the experiments, the displacement was varied from 0 to 40 mm in 10 mm increments. In the second simulation step, the displacement of the end caps was kept fixed, and a negative pressure normal to the internal walls of the OSPA was applied, ranging from $-20$ to $-80\text{ kPa}$. Frictional contact pairs were defined between the internal walls of the origami bellow and the internal support ribs because they come into contact when the OSPA folds. Frictional contact pairs were also defined between the external walls that may come into contact during the folding.

Comparisons between FEA and experimental results are presented in Figs. 8 and 9. The partially folded shape of the accordion pattern OSPA predicted by FEA and its actual deformed shape are qualitatively compared in Fig. 8. The predicted and real shapes are visually similar. A quantitative comparison of the predicted and experimental blocked force results for displacements of 0, 20 and 40 mm is shown in Fig. 9. Two trends can be observed from these results. First, the deviations tended to decrease when the displacement increased. Second, the deviations increased.
The measurement setup shown in Fig. 10 was built for performing isometric and isobaric tests of the OSPA prototypes. It uses a stepper motor driven linear actuator (Festo, ESBF-BS-32-200-10P) to change the length of the OSPA. Vacuum pressure is generated using two small vacuum pumps connected in series (AirPO, D2028 12V). The accumulator has a volume of 1 L (Festo, CRVZS-2-160236). Valve V1 is an on/off solenoid valve (MAC, 34B-AAA-GDFB-1BA). Valves V2 and V3 are proportional solenoid valves (Clippard, ET-P-05-25A0). The pressure is measured using an 0-345 kPa absolute pressure sensor with a ±1% accuracy (SSI Technologies, P51-50-A-B-I36-5V-R) and the force gauge has a range of 490 N with an accuracy of ±0.2% (Imada, DPS-110). A linear potentiometer (Novotechnik, T150) is used to measure the actuator’s displacement. After low-pass filtering at 106 Hz the signals are sampled at 1 kHz. The control and data collection are performed using a desktop PC equipped with a data acquisition card (National Instruments, NI-6221).

The test procedure consisted of keeping the OSPA prototype’s displacement constant at a target value while the pressure was slowly decreased through a series of target pressure values. Since the OSPA’s max stroke is around 40 mm, the displacement targets were 0, 10, 20, 30 and 40 mm. The pressure targets were from −10 kPa to −80 kPa in increments of −5 kPa. 100 samples were sampled at 1 kHz at each target point and averaged to reduce noise. Each test was repeated three times and the forces averaged. The average forces from the isometric tests are plotted vs. pressure in Fig. 11a. These forces are also known as “blocked forces”. The results show that the relationship between the blocked force and pressure is close to linear over the OSPA’s stroke. The isobaric force vs. displacement curves are plotted in Fig. 11b. These show that the force decreases as the displacement increases and that the reduction is roughly linear, except at the displacement of 40 mm where a larger decrease can be observed. A maximum force of 124 N was produced at zero displacement with a −80 kPa pressure.

FIGURE 10. Measurement setup built for the isometric and isobaric testing. (a) Schematic (b) CAD model.

FIGURE 11. Experimental results for the accordion pattern OSPA. (a) Isometric plots of force vs. pressure. (b) Isobaric plots of force vs. displacement.
B. ISOTONIC CONTRACTION AND CYCLIC FATIGUE TESTING

A 2nd measurement setup was built to perform isotonic contraction and cyclic fatigue tests of the OSPA prototypes. A CAD image of the mechanical components is shown in Fig. 12. The OSPA moves vertically and constant force loads are generated by attaching different payload masses (up to 8.6 kg). A linear potentiometer (Novotechnik, T100) is used to measure the OSPA's displacement. For safety, the moving components are mounted inside a clear acrylic tube. Custom parts were 3D printed from PLA to attach the OSPA and other components. The vacuum pumps, pressure sensor, valves, data acquisition card and PC used for the isometric testing were also used with this setup.

Payload masses of 2.0, 3.3, 4.0, 5.3, 6.5, 7.7 and 8.6 kg were used. After attaching a payload mass, for each isotonic contraction test the pressure was slowly decreased until it reached −80 kPa while the actuator’s displacement was measured simultaneously. The displacement was then converted to contraction ratio by dividing by the OSPA's length at zero pressure.

The isotonic contraction tests were repeated five times for each payload and the results averaged. Pictures of the contraction tests with payloads of 2.0 and 8.6 kg are shown in Fig. 13a and 13b, respectively. These pictures show that the actuator can lift the 8.6 kg payload but with a reduced displacement compared to the 2.0 kg payload test. The contraction ratio vs. pressure curves for upwards motions with each payload are plotted in Fig. 14a. The curves show that the contraction ratio depends nonlinearly on both the payload and pressure. In particular, with payloads of 5.3 kg or less the contraction ratio can reach about 46%, while at higher payloads the maximum contraction reached
ratio decreases significantly. To demonstrate the actuator’s hysteresis the contraction ratio vs. pressure curves are plotted for upwards and downwards motions in Fig. 14b. Maximum hysteresis values of 18.5%, 12.9% and 7.4% occurred with payloads of 2.0 kg, 5.3 kg and 8.6 kg, respectively.

Since in real applications an actuator must be able to perform its function repeatedly, a lengthy cyclic fatigue test was performed. For this test a 0.9 kg payload was used. A single cycle consisted of the OSPA raising and lowering this payload as the pressure was slowly decreased from $-2$ kPa to $-30$ kPa and then slowly increased back to $-2$ kPa. The test included 1000 of these cycles and lasted for over 9 hours. The OSPA was manually inspected after the test ended, and no defects such as cracks or holes were observed. The pressure vs. time and displacement vs. time plots for the first 10 cycles and the last 10 cycles (i.e. cycles 991 to 1000) are shown in Figs. 15a and 15b, respectively. These plots demonstrate that the OSPA’s performance was consistent over this lengthy experiment, with only small changes occurring when it reached its maximum displacement during the last cycles.

C. COMPARISON WITH TEST RESULTS FROM 2\textsuperscript{ND} OSPA PROTOTYPE

To evaluate the consistency of the fabrication method, the measurement setup and testing procedure presented in Section VII-A was used to test a 2\textsuperscript{nd} accordion pattern prototype. (The two prototypes are shown side by side in Fig. 7c.). The blocked force vs. pressure results obtained for the 2\textsuperscript{nd} prototype are plotted in Fig. 16. Comparing Figs. 11a and 16, the results for the two actuators are very similar except that the 2\textsuperscript{nd} prototype produced slightly less force. The root-mean-square deviation between the force values is 3.3 N and the maximum deviation is 4.8 N.

VIII. SOFT-ENDED ACTUATOR

We have shown designs and prototypes for applications requiring the OSPA to be rigidly attached at both ends. Other applications may require one or both ends to be flexible. To demonstrate that this is possible with our method, we have fabricated an OSPA with one soft end. The body of this soft-ended actuator was fabricated from a 38 mm diameter tube of Qualtek Q2-F4X heat-shrink. To increase its flexibility and range of motion this actuator does not use any internal support ribs. Its non-rigid end cap was manufactured from flexible TPU filament (NinjaTek NinjaFlex) on an inexpensive FDM 3D printer (Creality Ender-3 Pro). The challenge of creating an end cap that has a soft tip, but also seals well, was met by varying the infill percentage during printing. A 100% infill was used with the sawtooth-grooved section, while only a 20% infill was used for the 15 mm radius hemispherical tip.

The prototype is shown in Fig. 17. Positive supply pressure can be used to extend the actuator and press the soft end against the surface of an object. Negative pressure can be used...
to contract the actuator and increase its range of motion. The actuator’s original length is 110 mm. In Fig. 17a, applying a pressure of −55 kPa causes the actuator to reduce its length to 80 mm. In Fig. 17b, changing the pressure to 160 kPa caused it to extend to a length of 135 mm and contact the rigid metal surface. A contact force of only 12 N was produced by the 5 mm deformation of the soft tip. Potential applications for soft-ended actuators similar to this prototype include clamping systems or grippers for holding fragile objects.

IX. CONCLUSION

We have presented a novel fabrication method for OSPA and shown it can be used to rapidly produce strong and durable prototypes using inexpensive equipment and materials. As in our tests, the accordion pattern OSPA prototypes can produce pulling forces using a vacuum (or negative pressure) pump. This has the advantages of safety since bursting will not occur if the material fails. We have also fabricated an actuator with a soft end to show that the end caps do not have to be rigid. The actuator can be extended to press its soft end against an object by using a positive supply pressure. Positive and negative pressures were used to increase its range of motion. In addition to linear force and motion, these actuators can be connected in a variety of ways to produce different motions, e.g., a pair of actuators can be connected by a cable to a pulley in an agonist-antagonist arrangement to produce a bidirectional rotary actuator.

Our FEA model is effective at predicting the folding behavior and blocked force produced by the accordion pattern actuator. It can be used to investigate the effects of different actuator materials and dimensions; and to optimize the actuator’s design for different applications. This will be a topic of our future work.

Our fabrication method currently has several limitations. It cannot be used to create actuators with a diameter less than ~25 mm. This limitation is caused by the design of the reusable mold. Another limitation is the top end cap must include a transition section to align it during fabrication.

This transition section reduces the actuator’s range of motion significantly. A third limitation involves the support ribs. The ribs used in our prototypes allowed them to operate at higher vacuum pressures and produce larger forces, but they also reduced the range of motion. If these ribs can be made thinner, without sacrificing strength, then equally strong OSPA with larger contraction ratios can be produced using our fabrication method. In the future, we will investigate solutions to these limitations; and we plan to fabricate, and test, smaller and larger actuators based on the accordion and Yoshimura patterns, as well as designs based on other origami patterns.

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FIGURE 17. Soft-ended OSPA prototype. (a) Contracted using a pressure of −55 kPa. (b) Extended using a pressure of 160 kPa. The soft end can be seen pressing against the rigid metal surface on the right.
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