Compliant Actuators for Hand Exoskeletons

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***Abstract*— Compliant pneumatic actuators have a number of desirable characteristics for wearable robotic systems. The actuators can be lightweight, quiet, integrated with clothing, and tolerant of uncontrolled degrees-of-freedom. The components can be soft, minimizing safety concerns about contact with the user. These attributes are especially desirable for actuated exoskeletons for the hand. With the hand exoskeletons, especially, there is a need for the highly compliant actuators. We present the characterization of a novel actuation design in which pneumatic chambers traverse the palmar side of the hand to provide the extension assistance needed by many individuals with hand impairment, such as stroke survivors, while minimally impeding active finger flexion. The impact of chamber cross-sectional shape, dimension, and wall thickness on extension force creation and flexion impedance was examined in computational and physical models. A finite element model was created in SolidWorks to estimate the impact of bending of the finger joints on chamber performance. Experiments were subsequently performed on physical chambers molded out of Dragon Skin 20. We found that a rectangular chamber shape created significant extension force (6.3 N at 68.9 kPa of air pressure) and gave low passive bending resistance of only 1.47 N at 30° flexion. Experimental data showed that thinner chamber walls allowed for higher flexion forces to develop at low pressures while decreasing passive bending resistance. These chambers can be quickly and easily created using 3D printed ABS molds which enables customization for each individual.**

Keywords*— *soft pneumatic actuators, high compliance, palmar, hand exoskeleton

I. INTRODUCTION

Soft actuators are valuable additions to the fields of robotics and healthcare. Their ability to conform to irregular shapes gives them an advantage over traditional actuators in terms of fit, comfort and customization when it comes to wearable robotics, such as exoskeletons. Soft actuators are especially valuable when used to actuate fingers, as traditional actuators may be too heavy, bulky, or rigid for use with the hand. Past pneumatic exoskeletons for the hand have generally placed actuators on the dorsal side of the hand [1]–[3]. These devices tend to focus on production of finger flexion. Stroke survivors, however, typically maintain the ability to voluntarily flex the fingers but may need substantial assistance with finger extension [4]. By placing the actuators on the palmar surface of the hand, extension force can be provided without creating undue joint contact forces in the fingers and while maintaining a low profile to encourage use while reaching into a purse of pocket. The goal of the work presented here is to characterize the performance of pneumatic actuators intended for the palmar side of the hand. Specifically, we wanted to improve upon a previous design employing air chambers made from RF-welded polyurethane [5]. The extension force and flow properties of different chambers were modeled using SolidWorks (Dassault Systèmes, France). Physical chambers were then made out of Dragon Skin 20 with varied characteristics (shape, size, wall thickness, ribbing) and were tested at multiple finger postures and air pressures.

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II. SOLIDWORKS SIMULATION

SolidWorks simulations were performed for tubes with various cross-sectional shapes (circular, semi-circular, triangular, and rectangular), made of either Dragon Skin 20 (Smooth-On Inc, USA) or polyurethane (to compare against the previous air chamber material). Chambers included either no ribbing, solid ribbing, or hollow ribbing. Rib features were intended to prevent excessive narrowing, or kinking, of the tube during extreme flexion.

A total of 24 tube designs were simulated. Each design was deflected to an angle of up to 30° and the minimum channel diameter and flowrate of the deformed tubes were measured to evaluate their behavior when flexed and their ability to quickly pressurize (**Fig. 1**). The force required to deform the tubes was measured to determine their compliance. The deformed tubes were then pressurized in the simulation, and their extension force was measured.

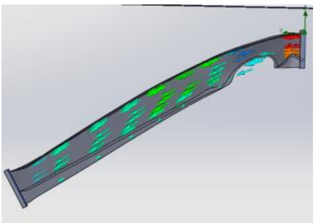

Figure 1: Chamber with triangular cross-section after deflection. Flow Trajectories visible.

The simulations showed that, across the various shape designs and joint angles, both the solid and hollow ribbing increased the minimum channel diameter of the tube compared to the tube designs with no ribbing. Hollow ribbing was the most successful feature at preventing kinking; however, hollow ribbing also reduced flowrate by almost 50% in most tube shapes due to increased turbulence in the air flow. For the rectangular chamber, solid ribbing was found to increase passive bending force by an average of 19.3% while hollow ribbing was found to reduce passive bending force by 21.4%; similar trends were seen for all other cross-sectional shapes. The semi-circular design had the lowest passive bending resistance (0.49 N at 30°) and the second highest extension force, and the rectangular design had the highest extension force (10.65 N at 30°) and second lowest passive bending force (1.47 N at 30°).

Based on these results, additional simulations were performed with the rectangular design to determine the effect of actuator depth and wall thickness on passive and pressurized bending force. Decreasing the depth of the actuator reduced passive bending resistance by 69% but only decreased pressurized extension force by 9.1%. Extension force was simulated for wall thicknesses of 0.5, 1.27 and 2.54 mm. The 1.27 mm wall design generated 12% and 68% more extension force than the 2.54 and 0.5 mm wall designs, respectively.

III. FABRICATION AND TESTING

ABS molds were 3D printed and used with Dragon Skin 20 to fabricate the rectangular actuators, which were found to produce the optimal results in the simulations. A rectangular insert was pressed into the filled cavity to create the internal dimensions of the tube. The insert had sprue slots at the end for removing excess material. The insert was press-fit seated inside of the cavity to ensure the proper depth and positioning. The cavity mold was disassembled into two pieces (for easier de-molding) and then the insert was removed. The end of the tube was sealed with a molded Dragon Skin cap. Actuators were tested by sewing them to a jointed testing platform and measuring extension force over a range of pressures (0-68.9 kPa) and joint angles (0-75°).

The chambers with 1.8 and 2.54 mm wall thicknesses were able to withstand the full 68.9 kPa, while the chamber with the 1.27 mm wall thickness developed a pinhole at 68.9 kPa and the chamber with 0.76 mm wall thickness developed a pinhole at 20.7 kPa. Passive bending forces were high for the 1.8 and 2.54 mm walled actuators, somewhat lower the for the 1.27 mm actuator and negligible for the 0.76 mm actuator (**Fig. 2**). Extension forces were pressure and joint angle dependent. Each actuator had a region where extension force was not significantly higher than the unpressurized bending force when pressure was low and the bending angle was small. Thicker actuator walls required higher pressures to significantly exceed passive bending forces. The 1.27 mm actuator began to exceed passive bending forces at 6.9 kPa and at 48.3 kPa the 1.27 mm actuator was able to generate 4-5 N of extension force (**Fig. 2**). The 1.27 mm chamber performed best in extension force production and bending resistance minimization.

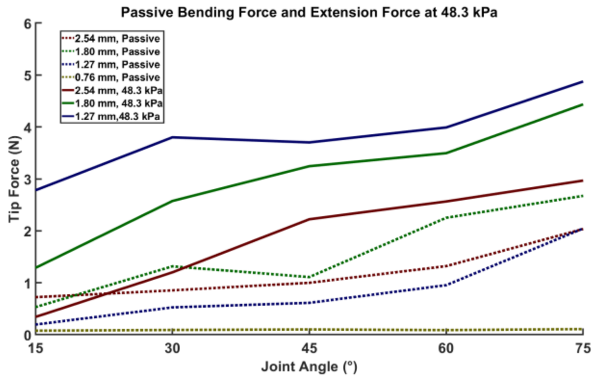

Figure 2: Passive bending force (dotted lines) and extension force at 48.3 kPa of (solid lines) rectangular actuators over a range of bending angles.

IV. Discussion

The mold design formed a blind tube using an insert which was free floating at one end that allowed for uneven wall thicknesses to develop in the tubes. This design relied on the insert "seating" within the cavity mold but the imprecision of 3D printed parts meant that if the insert was not perfectly straight or the seating was imperfect then the insert would drift toward one side of the cavity and cause the thickness of the walls to change along the length of the tube. Inconsistency in wall thicknesses contributed to actuators failing at low pressures.

Unfortunately, as a vacuum chamber was not used for degassing the mixture, bubbles were present within the actuator tubes. The molded tube caps did not have bubbles present because their molds expose a much larger surface area to the atmosphere which allowed more degassing to occur during curing. These trapped bubbles did not cause failures for the actuators with thicker walls (2.54, and 1.8 mm) but thin walled actuators (0.76 and 1.27 mm) developed pinholes at low pressures due to the bubbles. Future efforts will use a vacuum chamber during fabrication. Because of the need for high compliance, design features such as torque compensating layers, discrete fluid chambers, and fiber wrapping would not be suitable. Additionally, fiber wrapping would not be appropriate due to the potential to hyper-extend the finger joints [3].

Future designs should seek to keep wall thickness at 1.27 mm or less because thinner chamber walls maximize extension force and minimize passive bending force. If necessary, Dragon Skin 30 can be used to develop actuators with very thin walls to minimize passive bending resistance. SolidWorks simulations showed that hollow ribbing can decrease passive bending force and this feature may be incorporated into future designs if necessary to further minimize passive bending resistance. When actuators were bent to an angle of approximately 45° they collapsed at the bending point and formed a kink. Also, at a bending angle of 45° we see a general decrease or maintenance of passive bending resistance. It is possible that formation of the kink reduces passive bending resistance. Future design iterations include a mold design which secures both ends of the insert to ensure that wall thicknesses are consistent (**Fig. 3**), testing of both rectangular and semi-circular actuators, and the use of a pressure chamber for degassing. Degassing the elastomer mixture to eliminate bubbles which will allow for the creation of extremely compliant and thin walled actuators. These additional fabrication and design improvements will lead to the creation of better highly compliant actuators.

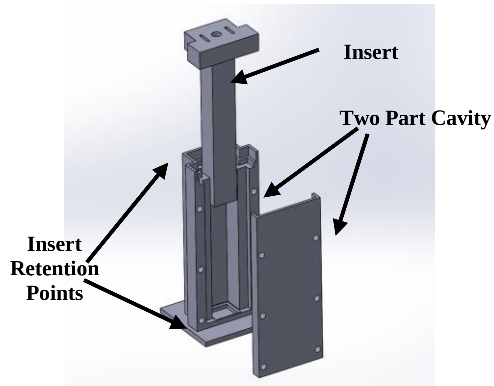

Figure 3: Revised Mold design for open rectangular tube with insert retention at both ends.

V. References

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