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3D PRINTING OF FIBER REINFORCED SOFT ROBOTICS

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ABSTRACT: Soft robotics is a rapidly growing new field of robotics whereby the robots are fundamentally soft and elastically deformable. Many of the soft robotics are inspired by soft bodied animals, are made of intrinsically soft, extensible and highly compliant materials. In this paper, 3D inkjet-printed fiber reinforced soft composites were used to develop a pneumatic actuated soft robotics. The fiber reinforced soft composites are able to remain flexible yet strong due to the thin inextensible fibers embedded within the matrix. Then it is being adopted into designing a soft robotic which can perform controlled motion such as extension with varying air pressure. The potential and challenges of current 3D printed soft robotics will also be discussed.

KEYWORDS: 3D printing, additive manufacturing, 3D printed composites, multi-material inkjet printing, soft robotics

INTRODUCTION

Conventional robotic systems are mostly made of rigid mechanical components such as links and joints so that they can perform extremely fast, precise, powerful and repetitive position control tasks efficiently. Robots have applications in various industries for instance, manufacturing and industrial automated assembly line, and into healthcare, space exploration, military surveillance and cooperative human assistance (Kim, Laschi, & Trimmer, 2013; Majidi, 2014). However, the robotic systems have to be less rigid and more flexible to have the capabilities to perform more adaptive and flexible interactions with complex unpredictable environments, and to become more lifelike and compatible for human interaction (Iida & Laschi, 2011; Lipson, 2014).

Therefore, with inspiration from the nature, soft robotics is currently a rapidly growing new field of robotics whereby the robots are fundamentally soft and elastically deformable and adapt their shape to external constraints and obstacles. Many of the existing soft robotics are inspired from the biomechanical features of soft bodied animals, and are made of intrinsically soft, extensible and highly compliant materials (e.g. rubbers and silicone) that can deform and absorb energy during a collision (Rus & Tolley, 2015).

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Soft components allow the animals to conform to various surfaces, and to lower the impact force or stress concentration by distributing the stress over a larger contact area. This is especially important for soft robotics interacting with soft materials such as tissues and organs and encountering deformable surfaces such as mud and soft soil as stress concentrations may cause physical injury with humans or robot immobility, respectively (Majidi, 2014).

There are currently three common actuation techniques for soft robotics: shape memory alloys (SMA), dielectric elastomeric actuators (DEA) and pneumatic actuation. Pneumatic or hydraulic powered soft actuators are very popular because of the ease of fabrication, lightweight, high power-to-weight ratio and low material cost (Galloway, Polygerinos, Walsh, & Wood, 2013; Polygerinos et al., 2015; Tolley et al., 2014). Pneumatic actuators use compressed air and pressurized fluids to produce forces and displacements for soft materials. This technique has been used in the McKibben pneumatic artificial muscle which consists of an internal bladder surrounded by a braided mesh shell in the 1950's (Ching-Ping & Hannaford, 1996; Roche et al., 2014). Although this method can produce relatively large force and displacement, it requires extensive pressure infrastructure. A soft robotic that uses pneumatic actuators has recently been developed. Compressed fluid is used to inflate chambers in a network of pneumatic channels in the elastomer, while the asymmetry in the design or the intrinsic property of the constituent materials like fibers, causes the component to actuate or move in a controlled manner (Shepherd et al., 2011; Tolley et al., 2014).

The design of soft robotics are mostly inspired by the biomechanics of the soft-bodied animals, for instance, annelids (earthworms and leeches), molluscs (squid and octopus) (Calisti et al., 2011; Laschi, Mazzolai, Mattoli, Cianchetti, & Dario, 2009) and insect larvae (caterpillars) (Huai-Ti, Gary, & Barry, 2011). Contraction of the worms' longitudinal muscles shortens the body and expands its diameter while contraction of the circumferential muscles can achieve the opposite motion. Unlike worms, larvae do not have circumferential muscles, they contract the longitudinal and oblique muscles to crawl and climb (Kim et al., 2013). The octopus arms are composed of densely packed transverse, longitudinal and oblique muscle fibers and they articulate the shape by shortening, elongation, bending, or torsion (Laschi et al., 2012; Laschi et al., 2009). These fiber reinforced actuators can be achieved through spatial arrangement of the inextensible fiber elements such as nylon and Kevlar, in a soft matrix such as silicone. However, the multi-step moulding and curing of fiber reinforced silicone is time-consuming and labour-intensive, and may take several days to complete the fabrication process.

Additive manufacturing has the capability to handle soft materials and even multi-materials and graded material for various novel applications such as flexible sensors and impact absorbing honeycomb structures (Agarwala et al., 2017; Dikshit et al., 2018; Dikshit et al., 2017). It can significantly broaden the design freedom, design space and accuracy for soft robots as the material can be controlled and deposited precisely using the 3D printer and software (Yap et al., 2016; Yap et al., 2017). It is also possible to shorten the fabrication process and simplify the manufacturing as moulds are no longer required in this case (Yang et al., 2017). Several direct additive manufactured soft robotics have been demonstrated using multi-material 3D printing technique, for instance, the SMA actuated robot with materials with two different friction coefficients (Umedachi, Vikas, & Trimmer, 2013), functionally graded combustion-powered soft robot (Bartlett et al., 2015) and quadruped robot with 3D printed soft legs (Drotman, Jadhav, Karimi, deZonia, & Tolley, 2017) and a motor-tendon actuated soft-bodied robots (Cohen, Vikas, Trimmer, & McCarthy, 2015).

In this paper, 3D multi-material inkjet-printed fiber reinforced soft composites were used to develop a pneumatic actuated soft robotics. The fiber reinforced soft composites are able to remain flexible yet strong due to the thin inextensible fibers embedded within the matrix. Then it is being adopted into designing a soft robotic which can perform controlled motion such as extension with varying air pressure. The potential and challenges of current 3D printed soft robotics will also be discussed.

MATERIALS AND METHODS

The design consists of an elastic body wrapped by rigid and inextensible fibers in varying angles. The actuator would elongate and twist under pressure depending on the helical fiber. The fiber reinforced soft composites were produced using the multi-material inkjet printer Connex 3 Objet 500 from Stratasys (MN, USA). Different photopolymers can be selectively jetted onto the platform through the print head nozzles and are cured simultaneously by UV light. The elastomer material used was the Agilus30 Black FLX985 while the fiber was printed using the VeroWhiteplus RGD835. The 3D printed soft actuator is shown in Figure 1.

Helical fibers with 1.5 mm diameter were embedded in a hollow tubular shape with 70.0 mm length and 2.0 mm thickness. Three different actuator designs were created to study the effects of the fiber angle as well as the fiber winding.

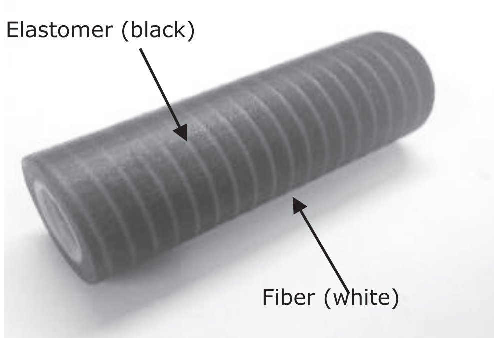

Figure 1. Fiber reinforced soft composites: fiber (white) winding around the elastomer material (black)

Table 1. Three design configurations of the 3D printed fiber reinforced actuators

Model	Fiber Angle/°	Fiber type
A	10.0	Double helix
B	7.5	Single helix
C	5.0	Single helix

The actuation was performed using a pressurized air source, i.e. the bicycle pump. A pressure gauge and a check valve were connected in the actuation system to measure the internal gauge pressure and to prevent backflow of the air.

RESULTS AND DISCUSSION

The extension ratio, β, of the 3D printed fiber reinforced actuators were calculated using the equation in Eq. (1).

$$\beta = \frac{Resultant\ Length}{Initial\ Length} \tag{1}$$

Initial length is the original length of the actuator which is fixed at 70.0 mm. The resultant length was measured using a Vernier caliper after the actuator was pressurized to varying gauge pressure of 20 kPa, 40 kPa, 60 kPa, 80 kPa and 100 kPa. The readings were averaged from two measurements.

Figure 2 shows the extension of the three different configurations of actuators under different gauge pressures. Model B with single helix and 7.5° fiber angle demonstrated the highest extension ratio while model A and C have similar extension rate under different gauge pressures. This trend can be attributed to the number of fiber revolution within the elastomer. Model B has the least fiber revolution of 12 while both model A and C have similar and higher revolutions of 18 within the actuator. Hence, the extension of the 3D printed fiber reinforced actuator is affected by the fiber angle placement and number of revolutions, instead of the helix type.

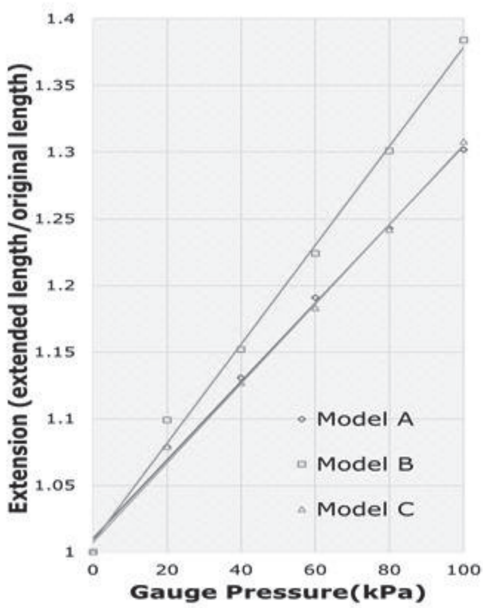

Figure 2. The extension of the actuator at different gauge pressure for three design actuator configurations.

CONCLUSION

3D printed fiber reinforced actuator was produced and we investigated how the fiber angle and fiber types within the elastomer would affect the extensibility of such actuator. The amount of deformation as a function of pressure can be controlled and optimized by exploring different design space of fiber reinforced actuators. Though current work only demonstrating the ability to perform extension using the fiber reinforced actuator, other motions such as bending and twisting, can also be explored by varying the spatial arrangement of the fiber and elastomer materials. 3D printing of soft actuators is much more time-saving and the achieved extension ratios of fiber reinforced soft actuators are comparable to those fabricated by conventional molding methods. Nevertheless, current 3D printed multi-materials are still weak against fatigue. The 3D printed elastomer still has relatively low strength as compared to silicone and hence the actuator could not withstand pressure higher than 100 kPa.

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REFERENCES

Agarwala, S., Goh, G. L., Yap, Y. L., Goh, G. D., Yu, H., Yeong, W. Y., et al. (2017). "Development of bendable strain sensor with embedded microchannels using 3D printing", *Sensors and Actuators A: Physical, 263*, 593-599.

Bartlett, N. W., Tolley, M. T., Overvelde, J. T. B., Weaver, J. C., Mosadegh, B., Bertoldi, K., et al. (2015). "A 3D-printed, functionally graded soft robot powered by combustion", *Science, 349*(6244), 161.

Calisti, M., Giorelli, M., Levy, G., Mazzolai, B., Hochner, B., Laschi, C., et al. (2011). "An octopus-bioinspired solution to movement and manipulation for soft robots", *Bioinspiration & Biomimetics, 6*(3), 036002.

Ching-Ping, C., & Hannaford, B. (1996). "Measurement and modeling of McKibben pneumatic artificial muscles", *IEEE Transactions on Robotics and Automation, 12*(1), 90-102.

Cohen, E., Vikas, V., Trimmer, B., & McCarthy, S. (2015). "Design Methodologies for Soft-Material Robots Through Additive Manufacturing, From Prototyping to Locomotion", (57137), V05BT08A015.

Dikshit, V., Nagalingam, A. P., Yap, Y. L., Sing, S. L., Yeong, W. Y., & Wei, J. (2018). "Crack monitoring and failure investigation on inkjet printed sandwich structures under quasi-static indentation test", *Materials & Design, 137*, 140-151.

Dikshit, V., Nagalingam, P. A., Yap, L. Y., Sing, L. S., Yeong, Y. W., & Wei, J. (2017). "Investigation of Quasi-Static Indentation Response of Inkjet Printed Sandwich Structures under Various Indenter Geometries", *Materials, 10*(3).

Drotman, D., Jadhav, S., Karimi, M., deZonia, P., & Tolley, M. T. (2017, May 29 2017-June 3 2017). *3D printed soft actuators for a legged robot capable of navigating unstructured terrain.* Paper presented at the 2017 IEEE International Conference on Robotics and Automation (ICRA).

Galloway, K. C., Polygerinos, P., Walsh, C. J., & Wood, R. J. (2013, 25-29 Nov. 2013). *Mechanically programmable bend radius for fiber-reinforced soft actuators.* Paper presented at the 2013 16th International Conference on Advanced Robotics (ICAR).

Huai-Ti, L., Gary, G. L., & Barry, T. (2011). "GoQBot: a caterpillar-inspired soft-bodied rolling robot", *Bioinspiration & Biomimetics, 6*(2), 026007.

Iida, F., & Laschi, C. (2011). "Soft Robotics: Challenges and Perspectives", *Procedia Computer Science, 7*(Supplement C), 99-102.

Kim, S., Laschi, C., & Trimmer, B. (2013). "Soft robotics: a bioinspired evolution in robotics", *Trends in Biotechnology, 31*(5), 287-294.

Laschi, C., Cianchetti, M., Mazzolai, B., Margheri, L., Follador, M., & Dario, P. (2012). "Soft Robot Arm Inspired by the Octopus", *Advanced Robotics, 26*(7), 709-727.

Laschi, C., Mazzolai, B., Mattoli, V., Cianchetti, M., & Dario, P. (2009). "Design of a biomimetic robotic octopus arm", *Bioinspiration & Biomimetics, 4*(1), 015006.

Lipson, H. (2014). "Challenges and opportunities for design, simulation, and fabrication of soft robots", *Soft Robotics, 1*(1), 21-27.

Majidi, C. (2014). "Soft robotics: a perspective—current trends and prospects for the future", *Soft Robotics, 1*(1), 5-11.

Polygerinos, P., Wang, Z., Overvelde, J. T. B., Galloway, K. C., Wood, R. J., Bertoldi, K., et al. (2015). "Modeling of Soft Fiber-Reinforced Bending Actuators", *IEEE Transactions on Robotics, 31*(3), 778-789.

Roche, E. T., Wohlfarth, R., Overvelde, J. T. B., Vasilyev, N. V., Pigula, F. A., Mooney, D. J., et al. (2014). "A Bioinspired Soft Actuated Material", *Advanced Materials, 26*(8), 1200-1206.

Rus, D., & Tolley, M. T. (2015). "Design, fabrication and control of soft robots", *Nature, 521*, 467.

Shepherd, R. F., Ilievski, F., Choi, W., Morin, S. A., Stokes, A. A., Mazzeo, A. D., et al. (2011). "Multigait soft robot", *Proceedings of the National Academy of Sciences, 108*(51), 20400-20403.

Tolley, M. T., Shepherd, R. F., Mosadegh, B., Galloway, K. C., Wehner, M., Karpelson, M., et al. (2014). "A resilient, untethered soft robot", *Soft Robotics, 1*(3), 213-223.

Umedachi, T., Vikas, V., & Trimmer, B. A. (2013, 3-7 Nov. 2013). *Highly deformable 3-D printed soft robot generating inching and crawling locomotions with variable friction legs.* Paper presented at the 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems.

Yang, H. Y., Lim, J. C., Liu, Y. C., Qi, X. Y., Yap, Y. L., Dikshit, V., et al. (2017). "Performance evaluation of ProJet multi-material jetting 3D printer", *Virtual and Physical Prototyping, 12*(1), 95-103.

Yap, Y. L., Dikshit, V., Lionar, S. P., Yang, H., Lim, J. C., Qi, X., et al. (2016). *Investigation of fiber reinforced composite using multi-material 3d printing.* Paper presented at the 2016 Annual International Solid Freeform Fabrication Symposium, Austin, TX, USA.

Yap, Y. L., Wang, C., Sing, S. L., Dikshit, V., Yeong, W. Y., & Wei, J. (2017). "Material jetting additive manufacturing: An experimental study using designed metrological benchmarks", *Precision Engineering, 50*, 275-285.