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Design of Fully Soft Actuator with Double-Helix Tendon Routing Path for Twisting Motion

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Abstract— **Soft actuators have been widely studied in recent years because of their ability to adapt to diverse environments and safely interact with humans. Their softness broadens their potential range of medical applications since they can provide inherent safety. Among the various motions a soft robot can perform, "torsion" can maximize the efficiency of motion in confined spaces like the human abdominal cavity. This paper presents a fully soft actuator with a double-helix tendon routing path for large-angle torsional motions. The double-helix tendon routing enables the actuator to generate large twisting deformations, while also avoiding buckling generally associated with the torque imbalance in small diameter soft cylinder structures. A sequential casting method was developed for cylindrical structures with internal double-helix pathing. A parametric study of the actuator's twisting angle and the axial contraction with respect to different design parameters was conducted, including the wire tension and path pitch. From the results, when the tendon was pulled with 40 N after the pitch was decreased, the axial contraction of the soft actuator was reduced by half and the torsional angle was doubled up to 600 ° without buckling.**

I. INTRODUCTION

A small-diameter soft manipulator is a promising platform for medical applications passing through the narrow and complex organs due to dexterity based on its compliance. The compliance enables the soft manipulator easily deform (e.g., bending, expansion, contraction, and torsion) using basic control inputs [1-3]. Dexterity of the soft manipulator can be especially enhanced with a twisting actuator that actively rotates the distal tip of the device to dexterously change orientation. For this reason, soft actuators with active rotating capability using torsion of their structure have been widely studied. To create torsion within a soft structure, internal or external torque should be exerted onto it. Previous studies have already applied almost every common actuation mechanism to soft actuators for torsional motion generation. Ionic polymer-metal composite (IPMC) actuators are capable of adaptation to torsional motions [4, 5]. Piezoelectric actuators also have shown their capability to produce combined bending and twisting motions [6-9], and pure-twisting motion [10, 11]. Several actuation mechanisms have been employed to the twisting actuator such as contracting helically embedded shape memory alloy (SMA) wires [12]. They proposed a manipulator that can be actuated by two pairs of antagonistic SMA wire actuators. The manipulator was designed as provided two perpendicular axes of rotation, each with a range up to ±40°. On the other hands, the use of matrices with anisotropic properties was investigated to generate combined bending and torsion deformations. Ahn et al. used anisotropic layers embedded in the matrix to generate a combination of large bending and torsional deformations [13]. The smart soft composite actuator was developed using a pair of SMA wires to generate torsional deformation [14]. It has also been shown that the use of different matrix geometries can increase the stability of an actuator and increase the maximum twisting angle using thinner features. J. Yan et al. made a spiral-type inflatable soft actuator for pure torsion by two spiral chambers twined fibers as a driving mechanism [15]. Pneumatic actuators that can produce large twisting deformations at small [16], medium [17], and large scales [18] have been proposed. All these actuators have generated twisting of less than 100° . To increase the maximum twisting angle of the twisting actuators, F. Connolly et al. proposed a new design for twisting actuators by simply varying the fiber angle of fluidic-powered fiber-reinforced structure. Their actuators achieved an angle of twist up to 180° [19].

Even with technological advances in torsional actuators, some limitations still remain for medical applications. A major drawback of SMA-driven torsional actuators is their response time. This latency may bottleneck their use as a surgical instrument. Another concern is structural complexity; multiple segments and components associated with electricity also increase the complexity of IPMC and the piezoelectric actuators. Increased structural complexity makes complete sterilization of the medical device difficult. Pneumatic actuators are limited by issues with their volumetric deformation in this setting. Most the pneumatically-driven soft actuators are accompanied by undesired expansion/contraction during pressurization, therefore, constraining deformation to a specific direction should be considered in the structural design. This limits the possible range of the actuator sizes. For practical scenarios in clinical practice, the form factor of soft actuators should be strongly considered. One solution to overcome form factor issues in medical applications may be a tendon-driven mechanism that can be combined with a soft manipulator [20-23]. The tendon-driven mechanisms are easy to design and implement into medical devices for bending motions.

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The simplest tendon-driven soft manipulator is generally composed of one backbone and one or two tendons [24-28]. Furthermore, in continuum robots, mechanisms for torsion are used to make extra configurations and enhance their dexterity [29-31]. However, pure torsion is rarely considered as a method of giving active rotational degrees of freedom for continuum robots. If pure torsion is possible in a continuum robot, maneuverability can be substantially enhanced with the use of rotational degrees of freedom. A fully soft structure with large twisting deformations can inevitably increase the dexterity and maneuverability of a robot in a confined space. However, the difficulty of achieving pure torsion in fully soft manipulator is caused by the necessity of multiple rigid constraints in/on the structure to avoid buckling. Basically, buckling is a core working principle in the bending motion of soft structures, on the contrary, pure torsion is not achievable once buckling occurs. Furthermore, rigid sections of the structure limit the softness of the entire structure.

In this paper, we proposed a novel fully soft actuator with a double-helix tendon routing path for the torsional motion (see **Figure 1**). The double-helix path was designed to induce torsional motion and overcome buckling for achieving pure torsion in fully soft structures. The tendon path was fabricated using a sequential casting process. It is a single seamless structure that is completely soft and easy to manufacture. It is capable of producing large twisting deformations (> 600°). This double-helix tendon routing path can avoid the buckling caused by torque imbalances in the soft structure. The detailed design, working principle, manufacturing method, and preliminary testing results are given in Section 2. Section 3 describes the design parameters including wire tension and path pitch through experiments, and Section 4 presents the conclusions and future works.

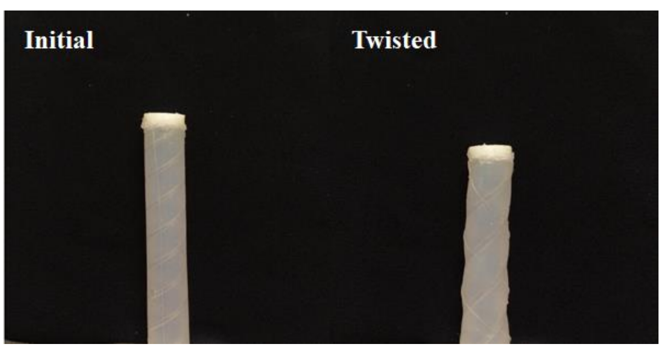

Figure 1. Cylindrical soft actuator with double-helix tendon routing path for torsional motion

II. Design and Manufacturing

Pure torsion in soft structures can be induced by equal and opposite torques at two points on the neutral axis of the structure. Mismatch of the force direction and motion will lead to a reduction in the efficiency of a torsional actuator.

A. Design

To generate torsional motions in a soft structure, torques should be generated at both ends. Pulling a wire that is fixed on the distal tip can generate bending motions, however, the same mechanism cannot be applied to torsional motion. To achieve a torsional motion, a helical wire was designed (see **Figure 2**). A helical path inside a soft structure can function as an actuation path during the motion. The actuation path in this design was created in a form of helix under the basis that the actuation path affects a motion trajectory.

The wire, passed through the inner channel of a soft structure was embedded to directly guide the direction of deformation. A helical path was designed to induce torsional motion using pull-wire actuation. In a helical path, the pitch was considered as a major design variable that strongly relates the twisting performance. The pitch of a helical path can be designed in two ways: constant pitch and variable pitch through the entire section. **Figure 3(a)** shows a path design based on a constant/variable pitch. The structure consists of the torsional layer including outer/inner layers and one core layer (see **Figure 3(b)**). The pitch of each helical path determines the induced motion trajectory as wire tension increases. **Table 1** lays out the various helical path pitch designs of each soft structure.

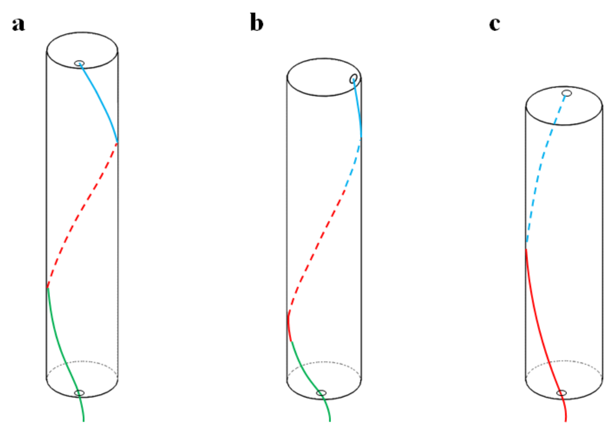

Figure 2. Concept for wire-driven soft manipulator. (a) Initial state with helical path (b) Manipulator deforms into axial and lateral directions simultaneously (c) Path deforms by angle of twist 180 degree

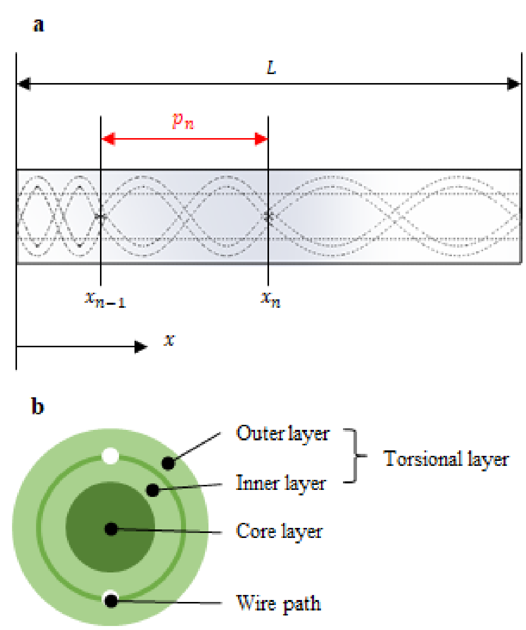

Figure 3. Design of soft torsional actuator. (a) Helical path design based on pitch length. (b) Layer design

When a path pitch p is held constant, the number of turns of the wire can be determined by the total length of the actuator

T. In contrast, when the path pitch p is variable, local pitch length p_n can be defined as follows:

$$p_1 = (0 < x < x_1)$$
$$p_2 = (x_1 < x < x_2)$$
$$p_3 = (x_2 < x < x_3)$$
$$\vdots$$
$$p_n = (x_{n-1} < x < x_n)$$

where $x_n \leq L$. n is determined by the number of turns of the wire. However, when the wire path is a helically shaped, contraction forces occur when the wire is pulled. Since the wire winds around the soft structure, constriction leads to undesired deformation of the soft material in a radial direction. Radial deformation causes a reduction of twisting performance. To resolve this issue and increase the twisting angle, a layer design was proposed. The whole structure is divided into two functional layers, one is a torsional layer that contains a helical wire path, and the other is a core layer. Each layer has different stiffnesses, and a stiffer silicone material is used in the core layer. Even though using a stiffer silicone in the core layer increases the torsional stiffness of the whole structure, restricting radial deformation has a dominant effect on twisting motions in this structure.

B. Manufacturing

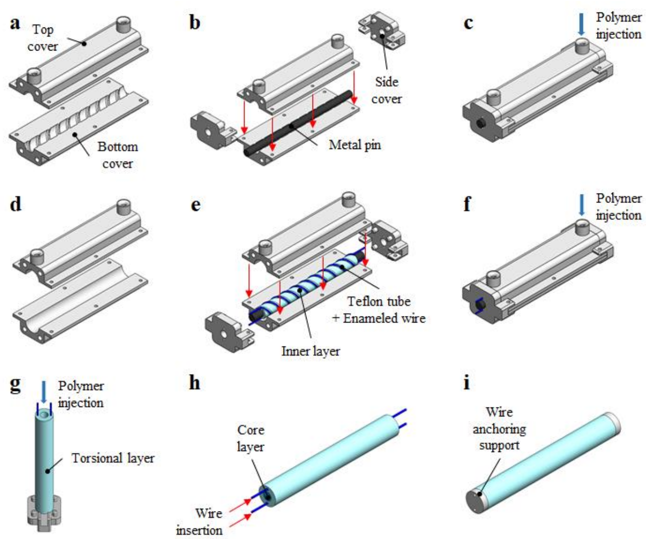

Figure 4. Sequential casting process. (a) Top and bottom covers for inner layer molding (b) Mold assembly for inner layer molding with a metal pin (c) Polymer injection of inner layer molding (d) Top and bottom covers for outer layer molding (e) Mold assembly for outer layer molding with inner layer molding result with enameled wire inserted Teflon tube wound (f) Polymer injection of outer layer molding (g) Polymer injection of core layer molding (h) Wire insertion into Teflon tube after enameled wire removed (i) 3D printed wire anchoring support attached with a silicone adgesive

A sequential casting method for the fabrication of a double-helix path inside a soft cylindrical structure was proposed (see **Figure 4**). Liquid silicone rubber was injected into the mold and cured. The molds used in this process were produced using a high-resolution 3D printer (Objet 260, Stratasys, U.S.) for surface quality reasons. The molding process of a soft torsional actuator requires two major steps: 1) Mold the torsional layer, 2) mold the core layer. For the torsional layers, these two layers were also manufactured in two stages: mold starting with the inner layer, and then the outer layer based on a helical path. The details are described as follows:

(1) Torsional layer: To manufacture the inner layer, the top cover and the bottom cover are first prepared (see **Figure 4(a)**). The side covers are assembled with the top and bottom covers by tightening the bolt and nut. Then, a metal pin is placed through the holes on the side covers (see **Figure 4(b)**). Next, de-gassed liquid silicone rubber (DragonSkin 10, Smooth-On, U.S.) is injected into the assembled mold through a hole in the top of the cover (see **Figure 4(c)**). Finally, the mold assembly is cured in an oven for 30 minutes at 60 degrees Celsius. For the outer layer, the assembly process of the 3D printed molds is replicated (see **Figure 4(d)**), but the inner layer mold is fixed to a metal pin. Teflon tube is wound along the grooves of the inner layer (see **Figure 4(e)**). Enameled wire is inserted into the Teflon tube to fix the Teflon tube in a desired helical shape. For the inner layer, molds are assembled by tightening the bolt and nut, liquid silicone rubber is injected into the mold (see **Figure 4(f)**), and then cured in the oven using the same conditions.

(2) Core layer: The resulting torsional layer from the step 1 is first placed on the side cover, de-gassed liquid silicon rubber is injected into the center of the torsional layer (see **Figure 4(g)**). After curing in the oven has finished, the enameled wire is pulled out and is replaced by a kink-free wire inside the Teflon tube (see **Figure 4(h, i)**). Finally, a 3D printed wire anchoring support is attached using a silicone adhesive (Sil Poxy, Smooth-On, U.S.), and the Teflon tube is pulled out.

The main point of mold design is to cure liquid silicone rubber to a cylindrical shape with an exactly positioned desired helical wire path. The axis of the cylinder body and the axis of the helical path should be the same to prevent buckling while twisting. The metal pin is used in the torsional layer molding process to satisfy this condition. In order to use the metal pin, core layer molding is executed after the torsional layer is molded. Furthermore, to fabricate a helical path with the desired pitch and diameter, the molding process of the torsional layer is divided into two steps. The top and bottom covers of the mold for the inner layer are printed with helical protrusions, allowing them to create a helically grooved inner layer surface. This groove is intended to create the desired helical path, to wind the Teflon tube along the groove to ensure that the Teflon tube is held in the desired position when liquid silicon rubber is injected into the mold. If a single casting method with a rigid helical structure is used, the soft body may be damaged during the demolding process. Even if the helical structure is compliant, the position of the structure is not strongly fixed due to the force caused by the injection of the viscous liquid silicone rubber. Although the sequential casting method is more time consuming than a single casting method, it is a more suitable manufacturing process for helical paths inside soft structures. The sequential casting method was tested as the specifications are shown in **Table I**.

TABLE I. DIMENSIONS OF PROTOTYPED SOFT ACTUATOR WITH HELICAL PATH MADE BY SEQUENTIAL CASTING METHOD

Young's Modulus E (MPa)	Moment of Inertia I (mm^4)	Length L (mm)	Poisson's Ratio ν
1	1,017.9	65	0.49

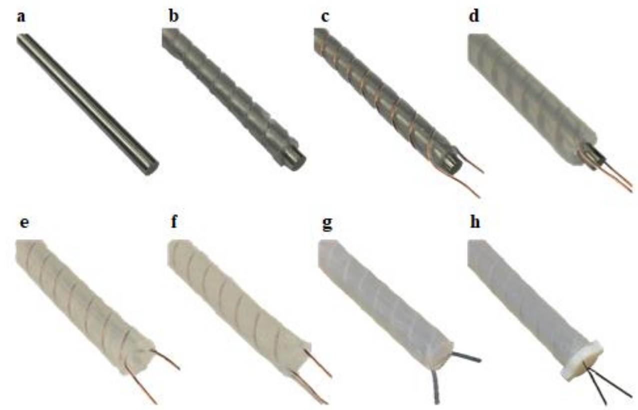

Figure 5. Prototyping of soft actuator with helical path using sequential casting method. (a) Metal pin is prepared. (b) Inner layer molding result. Helical groove is on the surface. (c) Teflon tube with enameled wire inserted is wound around the inner layer. (d) Outer layer molding result. (e) Metal pin is removed. (f) Core layer curing result. (g) Enameled wire is removed. (h) Teflon tube is removed after inserting wire into Teflon tube. Wire anchoring support is attached.

III. EXPERIMENTS

A. Motion Test of Designed Test-pieces

TABLE III shows specifications of various pitch design of test piece. The test pieces are categorized into constant pitch and variable pitch. Totally, 6 types of test-pieces were prototyped by the sequential casting method. The prototyped constant pitch test pieces were tested under the condition that fixed wires at free-end of the soft actuator.

The deformation that is induced by pulling the wires in the soft actuator was investigated. In constant pitch design, the pitch angle decreases as the number of wire turn increases. As shown in **Figure 6(a)**, Side deflection including buckling effect is significant with large pitch angle. On the contrary, almost pure torsion was obtained with smallest pitch angle (see **Figure 6(d)**).

The torsional motion of the prototyped soft actuator with variable pitch were tested. As the pitch angle decreases from the proximal (base) to the distal (end tip), pure torsion appears at the initial stage of the entire motion. After torque is minimalized by phase change in the upper plane, bending motion appears at the last stage (see **Figure 7(a)**). In contrast, as the pitch angle increases from the proximal to the distal, the torsion and bending motion appears simultaneously through the entire motion (see **Figure 7(b)**).

B. Torsional Motion Test

To evaluate the torsional motion performance of the proposed actuator, an experimental setup was designed (see **Figure 8**).

TABLE II. Specifications of various pitch design

Design No.	Pitch type	Pitch (mm)
1	Constant pitch	$p = L$
2		$p = L/2$
3		$p = L/3$
4		$p = L/4$
5	Variable pitch	$p = \begin{cases} \frac{L}{6}\left(0 \le x \le \frac{L}{6}\right) \\ \frac{L}{3}\left(\frac{L}{6} \le x \le \frac{L}{2}\right) \\ \frac{L}{2}\left(\frac{L}{2} \le x \le L\right) \end{cases}$
6		$p = \begin{cases} \frac{L}{2}\left(0 \le x \le \frac{L}{2}\right) \\ \frac{L}{3}\left(\frac{L}{2} \le x \le \frac{5L}{6}\right) \\ \frac{L}{6}\left(\frac{5L}{6} \le x \le L\right) \end{cases}$

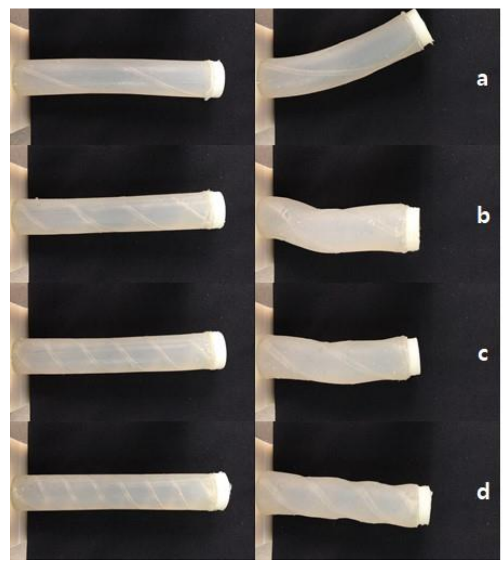

Figure 6. Torsional motion of prototyped soft actuator. (a) Constant pitch ($p = L$) (b) Constant pitch ($p = L/2$) (c) Constant pitch ($p = L/3$) (d) Constant pitch ($p = L/4$)

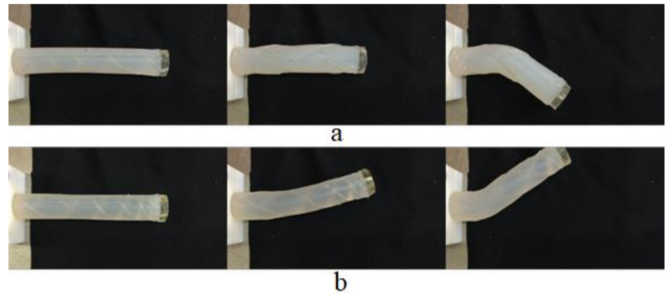

Figure 7. Torsional motion of prototyped soft manipulator. (a) Variable pitch ($p_1 = L/6, p_2 = L/3, p_3 = L/2$) (b) Variable pitch ($p_1 = L/2, p_2 = L/3, p_3 = L/6$)

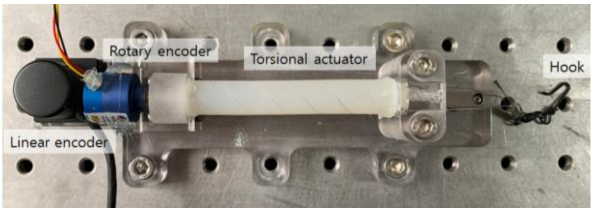

Figure 8. Torsional motion test setup for cylindrical soft actuator

It consisted of a wire type linear encoder (MLS-12-1500, MTL, Japan), a rotary encoder (SME360CP-05, SERA, Korea), a load cell (5kgf, KTOYO, Korea), and a base body that was printed by a commercial 3D printer (Objet 30, Stratasys, U.S.). The wires were tied and fixed to a hook that pulled the load cell. The test was manually conducted over a specified tension range (0 to 40 N). Once the measured tension exceeded 40 N, the load cell unit connected to the hook was slowly released. Viscoelastic effects were negligible because the wire was pulled sufficiently slowly during the experiment.

As a result of the same experiment on six test samples, the angle of twist relative to the tension was the largest in the test sample with the largest pitch angle (test piece #4). Axial contraction was observed along with torsion in all test pieces. Contrary to the twist angle, the vertical contraction decreased as the pitch angle increased. This means that the angle of twist per axial contraction of the actuator was larger than other samples. Since the bending was constrained by the experimental apparatus, the force component that generates bending motions was induced on the component causing torsion, therefore the torsion appeared to be larger. Particularly, the test sample #2 shows a stiff curve along the tension range 30 to 35 N, this is caused by buckling.

Hysteresis was observed in all test samples. This is because the stress-strain relationship of the silicon structure is nonlinear, and the material is anisotropic due to the double-helix tendon path embedded in the structure. The test sample #3, #5, and #6 are all designed with the same number of wire turns. The angle of twist was not significant among these test samples, however, the axial compression and the motion path were different (see **Figure 9(a), (b), (c), (d)**). Using the synchronized angle of twist and axial compression data, the trajectory of the end tip was drawn (see **Figure 9(e), (f), (g), (h)**). The dashed line shows the return path. In the constant with the pitch design, the angle of twist per axial contraction increased proportionally with the pitch angle with the exception of test sample #1. With the same number of wire turns (regardless of the pitch being constant or variable), differences in axial compression rate were dependent on the path pitch design. Compared with the constant pitch test sample #3, with the same number of wire turns, the motion path of the constant pitch design coincides with the pulling and releasing of the wire; in contrast to when the test sample has a variable pitch. It should be noted that the motion path of test sample #5 and #6 are inverted from each other, and the directions of their motion paths are opposite when the wire is released. The results of this test show that the pitch of the tendon path is the key parameter of the soft actuator design. It was experimentally shown that the actuation path and the motion path correspond to each other, and that they can be intuitively designed.

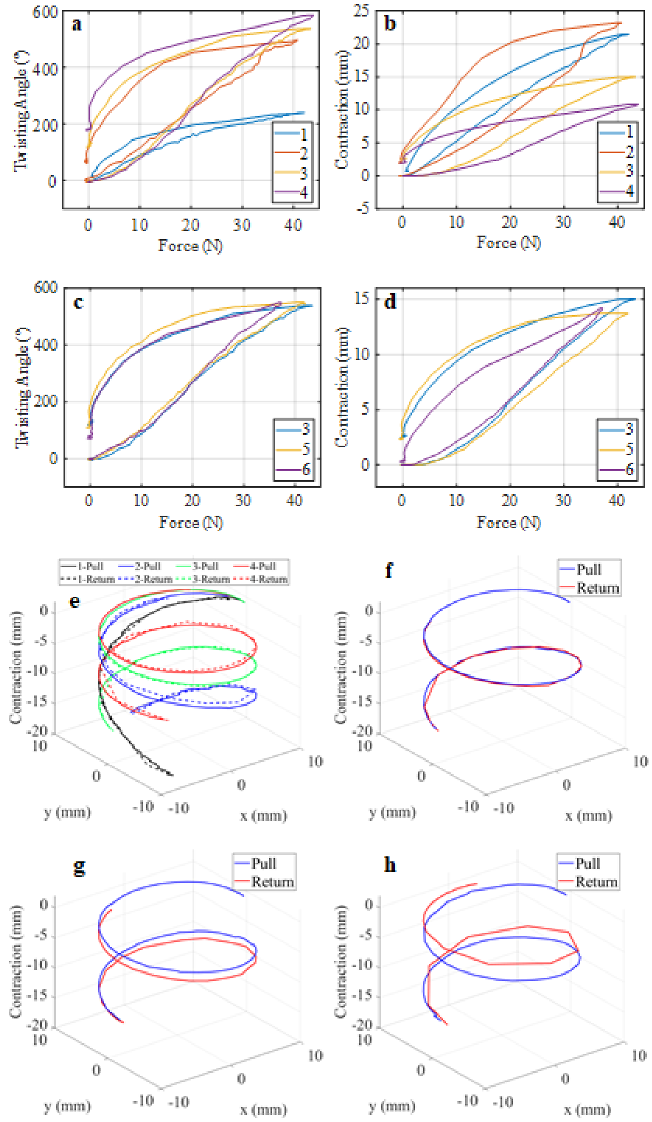

Figure 9. Torsional motion trajectory of soft actuator with various pitch design. (a) Twisting angle by wire tension with various pitch design. (b) End tip contraction by wire tension with various pitch design. (c) Twisting angle comparison between constant pitch and variable pitch. (d) Contraction comparison (e) Torsional motion trajectory with various pitch design. (f) Motion trajectory of the test piece #3. (g) Torsional motion trajectory of the test piece #5. (h) Torsional motion trajectory of the test piece #6.

IV. Conclusion

In this paper, we proposed a novel fully soft actuator with a double-helix tendon routing path for torsional motion. In order to generate pure torsion using a tendon-driven mechanism in a soft structure, an internal double-helix path was designed to induce a pure torsion of the entire structure. Torque imbalance issues associated with buckling were a core consideration of this design. A double-helix tendon routing path can effectively avoid buckling when a proper path pitch design is implemented. For fabrication of a cylindrical structure with a double-helix path inside, a sequential casting method was developed. The sequential casting method allows for the manufacturing of additive layers for a cylinder-shaped structure. To do so, liquid silicone rubber was injected into the mold and cured. The molds used in the whole process were produced by a high-resolution 3D printer to establish high surface quality. The molding process of the soft twisting actuators requires two major steps: 1) mold the torsional layer 2) mold the core layer. For the torsional layers, these two layers were manufactured in two stages again, molded in the order of the inner layer and the outer layer based on a helical path.

It was shown that the design of each layer effects the characteristics of the actuator; with the first mold defining the characteristics related to the wire path and the layer stiffness. This kind of manufacturing method has the potential to further the capabilities of other fully soft actuators, and could be applicable to the fabrication of various types of soft manipulators. From the parametric study using pitch design, when the tendon was pulled with 40 N after the pitch was decreased, the axial contraction of the soft actuator was reduced by half and the torsional angle was doubled up to 600 ° without buckling. The proposed actuator concept opens new doors in the field of soft robotics and further promotes its implementation with inherent safety for medical applications. Future work will focus on further testing of parameters, modeling of actuators, and implementation of this concept in medical applications.

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REFERENCES

[1] M. Cianchetti et al., “Soft robotics technologies to address shortcomings in today's minimally invasive surgery: the STIFF-FLOP approach,” *Soft Robotics*, vol. 1, no. 2, pp. 122-131, 2014.

[2] T. Ranzani, G. Gerboni, M. Cianchetti, and A. Menciassi, “A Bioinspired Soft Manipulator for Minimally Invasive Surgery,” *Bioinspiration & Biomimetics*, vol. 10, no. 3, 2015.

[3] A. Arezzo et al., “Total mesorectal excision using a soft and flexible robotic arm: a feasibility study in cadaver models,” *Surgical endoscopy*, vol. 31, no. 1, pp. 264-273, 2017.

[4] Jeon, J. and Oh, I., “Selective growth of platinum electrodes for MDOF IPMC actuators,” *Thin Solid Films*, 517(17), pp. 5288-5292, 2009.

[5] V. Palmre et al., “An IPMC-enabled bio-inspired bending/twisting fin for underwater applications”, *Smart Materials and Structures*, vol. 22, no. 1, p. 014003, 2012.

[6] N. Hagood and A. Bent, “Development of piezoelectric fiber composites for structural actuation,” *34th Structures, Structural Dynamics and Materials Conference*, 1993. Available: 10.2514/6.1993-1717 [Accessed 30 July 2020].

[7] D. Saravanos, P. Heyliger and D. Hopkins, “Layerwise mechanics and finite element for the dynamic analysis of piezoelectric composite plates,” *International Journal of Solids and Structures*, vol. 34, no. 3, pp. 359-378, 1997.

[8] B. M. Finio and R. J. Wood, “Optimal energy density piezoelectric twisting actuators,” *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, San Francisco, CA, 2011, pp. 384-389.

[9] I. Hotzen Grinberg, N. Maccabi, A. Kassie and D. Elata, “A Piezoelectric Twisting Beam Actuator,” *Journal of Microelectromechanical Systems*, vol. 26, no. 6, pp. 1279-1286, 2017.

[10] O. Rabinovitch and J. Vinson, “On the design of piezoelectric smart fins for flight vehicles,” *Smart Materials and Structures*, vol. 12, no. 5, pp. 686-695, 2003.

[11] A. Bent, N. Hagood and J. Rodgers, “Anisotropic Actuation with Piezoelectric Fiber Composites,” *Journal of Intelligent Material Systems and Structures*, vol. 6, no. 3, pp. 338-349, 1995.

[12] Rodrigue, H., Wei, W., Bhandari, B. and Ahn, S., “Fabrication of wrist-like SMA-based actuator by double smart soft composite casting,” Smart Materials and Structures, 24(12), p.125003, 2015.

[13] H. Kim, S. Song and S. Ahn, “A turtle-like swimming robot using a smart soft composite (SSC) structure,” *Smart Materials and Structures*, vol. 22, no. 1, p. 014007, 2012.

[14] Rodrigue H., Bhandari B., Han M. W. and Ahn S. H., “A shape memory alloy-based soft morphing actuator capable of pure torsional motion,” J. Intell. Mater. Syst. Struct. 26 1071–8, 2015.

[15] J. Yan, X. Zhang, B. Xu and J. Zhao, "A New Spiral-Type Inflatable Pure Torsional Soft Actuator", *Soft Robotics*, vol. 5, no. 5, pp. 527-540, 2018.

[16] B. Gorissen, T. Chishiro, S. Shimomura, D. Reynaerts, M. De Volder and S. Konishi, “Flexible pneumatic twisting actuators and their application to tilting micromirrors,” *Sensors and Actuators A: Physical*, vol. 216, pp. 426-431, 2014.

[17] R. Martinez, C. Fish, X. Chen and G. Whitesides, “Elastomeric Origami: Programmable Paper-Elastomer Composites as Pneumatic Actuators,” *Advanced Functional Materials*, vol. 22, no. 7, pp. 1376-1384, 2012.

[18] S. Sanan, P. Lynn and S. Griffith, “Pneumatic Torsional Actuators for Inflatable Robots,” *Journal of Mechanisms and Robotics*, vol. 6, no. 3, 2014.

[19] F. Connolly, P. Polygerinos, C. Walsh and K. Bertoldi, “Mechanical Programming of Soft Actuators by Varying Fiber Angle,” *Soft Robotics*, vol. 2, no. 1, pp. 26-32, 2015.

[20] M. Cianchetti, A. Licofonte, M. Follador, F. Rogai and C. Laschi, “Bioinspired Soft Actuation System Using Shape Memory Alloys,” *Actuators*, vol. 3, no. 3, pp. 226-244, 2014.

[21] Cianchetti M., “Fundamentals on the Use of Shape Memory Alloys in Soft Robotics,” in *Interdisciplinary Mechatronics: Engineering Science and Research Development*, edited by M. K. Habib and J. Paulo Davim, pp. 227-254, Wiley-ISTE, 2013.

[22] Cianchetti M., Renda F., Licofonte A., and Laschi C., “Sensorization of continuum soft robots for reconstructing their spatial configuration,” in *Conf. Proc. IEEE on Biomedical Robotics and Biomechatronics – BioRob*, pp. 634-639, 2012.

[23] Cianchetti M., Arienti A., Follador M., Mazzolai B., Dario P., and Laschi C., “Design concept and validation of a robotic arm inspired by the octopus,” *Material Science Engineering C*, 31, pp. 1230-1239. 2011.

[24] Khoshnam M., Azizian M., and Patel R.V., “Modeling of a steerable catheter based on beam theory,” in *Robotics and Automation (ICRA), 2012 IEEE International Conference*, pp. 4681–4686, 2012.

[25] Khoshnam M., Skanes A.C., and Patel R.V., Modeling and estimation of tip contact force for steerable ablation catheters,” *IEEE Trans Biomed Eng.* 62, pp. 1404–1415, 2015.

[26] Ganji Y., Janabi-Sharifi F., “Catheter kinematics for intracardiac navigation,” *IEEE Trans Biomed Eng.* 56:621–632, 2009.

[27] Degani A., Choset H., and Wolf A. et al., “Percutaneous intrapericardial interventions using a highly articulated robotic probe,” *The First IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*. pp. 7–12, 2006.

[28] Yoshimitsu, K., Kato, T., Song, S. and Hata, N., “A novel four-wire-driven robotic catheter for radio-frequency ablation treatment,” *International Journal of Computer Assisted Radiology and Surgery*, 9(5), pp. 867-874, 2014.

[29] Gao, G., Ren, H., Xia, Q., Wang, H. and Li, L., “Stretched backboneless continuum manipulator driven by cannula tendons,” *Industrial Robot: An International Journal*, 45(2), pp. 237-243, 2018.

[30] Gerboni, G., Henselmans, P., Arkenbout, E., Furth, W. and Breedveld, P., “HelixFlex : bioinspired maneuverable instrument for skull base surgery,” *Bioinspiration & Biomimetics*, 10(6), p. 066013, 2015.

[31] J. Starke, E. Amanov, M. T. Chikhaoui and J. Burgner-Kahrs, “On the merits of helical tendon routing in continuum robots,” *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Vancouver, BC, pp. 6470-6476, 2017.

[32] Sparks, J., Vavalle, N., Kasting, K., Long, B., Tanaka, M., Sanger, P., Schnell, K. and Conner-Kerr, T., “Use of Silicone Materials to Simulate Tissue Biomechanics as Related to Deep Tissue Injury,” *Advances in Skin & Wound Care*, 28(2), pp. 59-68, 2015.