

A Method to 3D Print a Programmable Continuum Actuator with Single Material Using Internal Constraint

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Abstract

Soft continuum robots require differential control of channel pressure across several modules to trace 3D trajectories at the tip. For current designs of such actuators, sheathing is required to prevent radial expansion when the chambers are pressurized. With the recent development of soft materials additive manufacturing, 3D printing has become a promising fabrication method for soft continuum robots. However, most current designs for continuum actuators are based on molding, which are not designed for 3D printing. This paper proposes an internal constraint-based soft continuum actuator for single material 3D printing, with tunable design parameters to render pre-defined motions. The internal constraint method maximizes the superiority of the rapid prototyping solution in terms of customizing the soft continuum actuators with high fabrication speed and design freedom. The internal constraints come in the form of internal beam elements that not only limit the undesired radial expansion (up to $\sim 14\%$ of conventional design) but also allows the actuator to be pressurized at a higher driving pressure (up to $\sim 160\%$) and higher maximum bending angle (up to $\sim 320\%$) compared to conventional no-beam design. By tuning the design parameter $\mathbf{q}$ (determined by the number of constraint beams n per radial cross-section and the number of such sections k along the axial direction), we can render the actuator to the desired movement under specific driving pressure $\mathbf{p}$. We show numerical simulation and hardware experiment results for a soft actuator to achieve specified bending and twisting motions following this design approach.

Keywords: Soft actuator, 3D printing, Internal constraint

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1. Introduction

Soft robots show advantages in adaptability, safety, and flexibility in the design of actuators and end-effectors compared with their rigid counterparts. Due to the compliance of elastomeric materials, novel soft robots can adapt their morphology to uncertain environments with the emerging cross-disciplinary research of material science, control, and rapid prototyping [1]. Soft robotic approach, therefore, show as a good supplement to the conventional rigid robot for application in Minimally Invasive Surgery [2], human interaction [3], soft and delicate object manipulation [4, 5], and soft sensing [6, 7].

The compliance of soft actuators can be achieved by shape memory alloys (SMA) [8], fluidic elastomeric actuators (FEA) [9], shape morphing polymers (SMP) [10], dielectric-electrically actuated polymers (DEAP) [11], and magnetic or electromagnetic actuators (E/MA) [12]. In particular, fluidic elastomeric actuators based on pneumatic or hydraulic power stand out for their low-cost, high-compliance, and simplicity in control. The internal chamber of the FEA expands when the actuator is pressurized. Due to the isotropy of the elastomeric material, constraints are normally in need to lead the soft actuator to expand to certain directions following the stiffness distribution of the chamber. To achieve desired motions such as bending, elongating/contracting, and twisting, the expansion of the actuator can be constrained through 1) additional fiber reinforcement [13, 14], 2) embedded spine [2], 3) multi-material with different stiffness [15] and 4) structural element design [16, 17].

Direct 3D printed soft pneumatic actuator has become increasingly popular in the field of soft robotics since 3D printing technology with rubber-like material is underlining fast development in recent years [18]. 3D printing soft actuators have many advantages in general. First, the manufacturing accuracy and repeatability are much higher than currently widely used molding solutions, where the latter heavily rely upon external factors, such as temperature, manual skills, and mold accuracy. Secondly, The solution is flexible in dealing with engineering design changes [19]. In general, the mold-based technique needs to go through the design phase, the mold-making phase, the casting phase, the post-processing phase, and the testing phase to evaluate the performance [20]. If the performance is not as ideal as expected or the application task is changed, the designer must go through the entire process again. By contrast, the rapid prototyping solution with 3D printed soft actuators only needs to go through the design, manufacturing, and

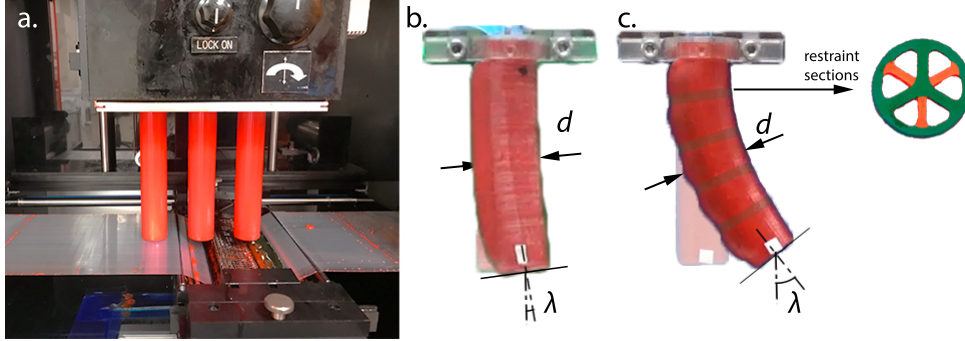


Figure 1: **(b)** Soft actuators with internal constraints printed with a single-material 3D printer. Multiple actuators with different parameters can be fabricated in the same batch. The trial shown in the figure took ~ 2.5 hours. **(b)** Original FMA design with no constraint beam elements pressurized to the maximum 0.06 MPa. Three chambers were used to achieve omnidirectional movement. High radial expansion with a low bending angle is observed. **(c)** Beam-element constraint soft actuator with 4 constraint sections ($k = 4$) and 1 constraint beam in one section ($n = 1$), pressurized to 0.08 MPa. constraint beams are indicated in orange in the cross-section view. d is the radial expansion. λ is the bending angle measured between the bending axial at the tip and the original vertical axis.

testing phases. The time and effort required for each design iteration are much less compared to conventional approaches [18]. Finally, the design flexibility can also be significantly increased with the 3D printing solution. With conventional modeling solutions, the geometry complexity is limited by the manufacturing methods. For instance, soft actuators with complex pneumatic networks need to be molded layer by layer in different curing stages or using complicated investment casting [19]. They also face a great challenge in miniaturizing the design. Although the available soft materials for 3D printing are still limited at the moment, it is reasonable to believe additive manufacturing will play an important role in the next generation of compliant robot design [18].

The fiber reinforcement method is commonly used for uni-directional bending actuators and a few omnidirectional cylindrical actuators by tangling threads to the out layer of the actuator to minimize the radial expansions [13]. Although this threading constraint methodology shows simplicity in design and good results in the performance of casted silicone rubber prototypes, it is challenging to be integrated with 3D printed actuators. In [21], the fiber reinforcement was replaced by printing stiffer material, but a custom-built 4-axis CNC gantry printer was required to complete the fabrication. Embedded spines can also be used to create

uni-directional actuators but less investigated for complex geometry actuators. For example, the soft pneumatic actuator designed by Su et al. demonstrated the use of embedded rigid following chain to achieve in-plane bending motion [22]. External spines were attached to soft actuators in work presented in [2] with Mick-ibben braided sheaths. However, both the internal and external embedded spines may reduce the overall softness of the actuators. The constraints of soft actuators with multi-materials can also be achieved by placing external rings made from stiffer materials to limit the radial expansion [15] or directly fabricating continuous shape of soft robots with multiple materials of different stiffness [23]. The multi-material solution can be promising when adapted with 3D printing technologies. However, it is currently limited by the manufacturing/machine cost and material choices. Alternatively, constraints provided by structural elements design can achieve a similarly restricted motion with only one type of material. It has already shown good performance with soft robots fabricated by molding. Yang et al. designed a single homogeneous material soft pneumatic actuator that buckles to generate motion when negative pressure was applied [17]. Multigait from the Whiteside group is another example of combining the structural elements design with a stiffer material to achieve constraint deformation locally [9]. We believe there is an opportunity to alter the internal structure design instead of the material stiffness to 3D print continuum actuators to achieve pre-defined motions. This direction can further extend the potential of the single material soft 3D printing technologies.

In this paper, we focus on the beam-element based constraint design for soft actuators that can be tuned for a specified motion by changing the design parameter $\mathbf{q}$ and directly 3D printed with a single material, see Fig. 1. Research studies have contributed to optimize the design of soft robots to match specified 2D shapes through tuning physical configurations, such as the threading angle/type of the external reinforcement fiber [24, 25]. Similarly, by changing the density (n , the number of beams in one section) and distribution (k , the number of constrained sections) of the internal structure as the design parameter $\mathbf{q}$, the bending trajectory of our actuator can be programmed accordingly. The beam-element based idea to constrain the soft actuator and design-for-specified motions was tested based on a 3D flexible microactuator (FMA) developed by Suzumori et al. [14, 16]. A conventional fiberless FMA suffers severe radial expansion and high tension on the external wall in the circumferential direction when directly 3D printed with very soft material. The undesired expansion and high tension limit the axial deformation of the actuator, decrease the maximum bending angle, and reduce the strength and durability of such actuators. The significantly increased circumferen-

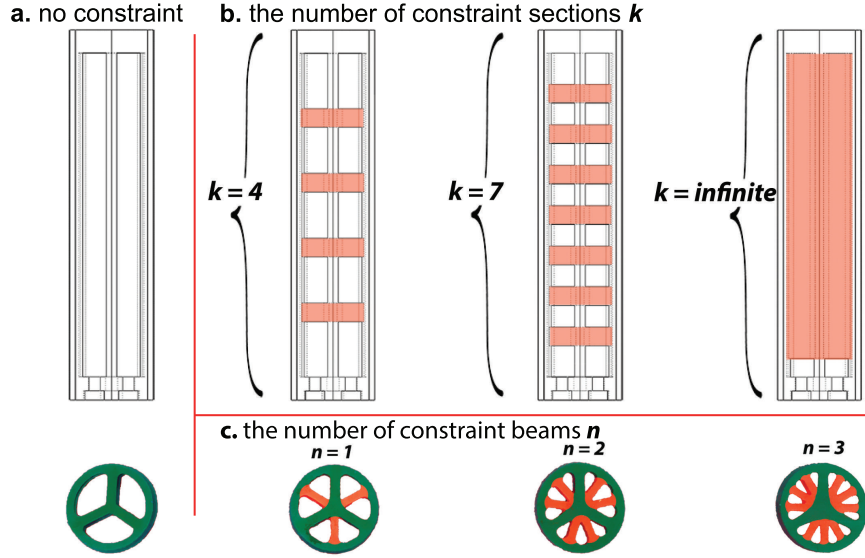


Figure 2: Design parameter $\mathbf{q}$ of the programmable constraint pneumatic soft actuator determined by the number of constraint beams n per radial cross-section and the number of such sections k along the axial direction. **(a)** Original FMA design without beam constraints. **(b)** The number of such sections k along the axial direction. Demonstrated with soft actuators with 4, 7, and infinite (continuous) constraint sections in the axial direction ($k = 4, k = 7$, and $k \rightarrow +\infty$). **(c)** Cross-sections of the actuators produced by slicing the 3D printed actuators. Demonstrated with soft actuators with one, two, and three constraint beams in the cross-section ($n = 1, n = 2$, and $n = 3$).

tial diameter also limits the application of the actuator in a restricted environment. The elastic beam elements applied in the cross-section of the FMA can, therefore, restrain its radial expansion and achieve a higher bending angle. The constraint beam structure also makes the actuator more durable and drivable with a higher pressure. Furthermore, single-material 3D printing requires a less complicated design and manufacturing process compared with multi-material additive manufacturing. Overall, by involving the internal structure in chambers, soft actuators with tunable parameters n and k to achieve specific bending and twisting motions were built in this study with high freedom of design.

The rest of the paper is structured as follows. The conceptual design and kinematics of the soft actuator are described in Section 2. Then, section 3 gives the details of the Finite Element (FE) simulation of soft actuators with different designs of the constraint beam structure. The simulation results show the effect of density (n) and distribution (k) of the constraint beam elements on the bending

angles and radial expansion rate of the actuators. Section 4 shows the experimental setup and results to validate the FE simulation. Section 5 clarifies the method of tuning parameters of constraint beam elements to achieve desired trajectories with three actuators that each consists of two modules. An analytical model with the kinematic model introduced in section 2.3 was used to provide the relationship between the actuator design parameters and deformation as a function of driving pressure. Discussion and conclusion are shown in-depth in section 6.

2. Design and Fabrication of the Constraint Pneumatic Soft Actuator

Internal constraint structure (constraint beam elements) aims to reduce the radial expansion of the soft actuator, increase the durability, and tune kinematics via changing the beam-element design parameters. The single-material 3D printing solution enables the actuator to be fast-fabricated. Fig. 2 a shows a cross-section view of the original design of the soft actuator without any constraint. The shape and size of the design were adapted from our previous optimization work of flexible microactuator (FMA) [14, 26]. The initial diameter d_w and length l_0 of the soft actuator were designed as 18 mm and 80 mm, respectively. The ratio of external wall thickness t_w to the initial diameter d_w was kept at 10%. The ratio of partition wall thickness t_p to the initial diameter d_w was kept at 12.5%. Fig. 2 b and c show the concept with internal constraint beams, which provide additional constraints to limit the radial expansion. The width of the constraint beams t_b was kept at the same as the external wall thickness t_w . Specifications are introduced in Fig. 3 d.

All soft actuators were designed with CAD software (Solidworks 2019) and fabricated with Shore A25 Rebounding resin with a DLP type 3D printer (M3DS-SA5, MITS Electronics corporation, Tokyo, Japan). The rebounding resin has a flexural modulus of 1.0 MPa, Tensile strength of 0.9 MPa, and elongation at break of 290%. For ease of fabrication, fillets of 0.2 mm were added to the connection parts of the constraint beams to the external wall of the chamber. In order to further understand the effect of beam-element constraints in the deformation of the actuators, two specific design parameters were studied: (1) constraint density in the cross-section of the actuators reflected by the number of beams (n), and (2) restrain distribution in the axial direction reflected by the number of constraint sections in the axial direction (k).

2.1. Density: cross-section constraint beam number n

Fig. 2 c shows the cross-section of the actuators. n denotes the number of constraint beams in one single chamber of the actuator. The increasing number of

constraint beams n from 1 to 3 indicates the increase of radial constraint density in each section.

2.2. Distribution: number of constraint sections k

Fig. 2 b shows the open view of the actuators. k denotes the number of constraint sections in the axial direction of the actuator. The thickness of the constraint sections was kept as 4 mm in this study. The constraint sections are always distributed evenly in the axial direction with increasing numbers of the sections. $k \rightarrow +\infty$ were created by making continuous constraint sections.

2.3. Kinematics

The kinematics of the constraint soft actuator were derived with the method introduced in [14] and [27]. The bending motion of the actuator is assumed to be a constant curvature due to its compliance. The kinematics was formulated as a series of substitutions with a modified homogeneous transformation matrix computed via Denavit-Hartenberg (D-H) parameters based on a modular approach. With such an approach, Eq. (1) and (2) are adopted to synthesize the Cartesian workspace coordinates to the actuator inputs (pneumatic driving pressure $\mathbf{p}$) via the continuum robot shape coordinates (Fig. 3 b). The robot shape coordinate is also determined by the design parameter $\mathbf{q}$ that refers to how the actuator is physically designed. In this study, the design parameter $\mathbf{q}$ consists of two tunable parameters n and k , which are the number of constraint beams per radial cross-section and the number of such sections along the axial direction, respectively. The kinematics of a soft actuator with different design parameters of beam elements (n and k) in each module can then be computed by multiplying the transformation matrices (e.g., $A_{13} = A_{12}A_{23}$). For the sake of simplicity, only one chamber pressurization case was introduced in this section. A demonstration of multi-modular soft actuator design was shown in section 5. The kinematics is shown below with the parameters indicated in Fig. 3.

$$\mathbf{x} = \mathbf{f}_{D-H}(\mathbf{f}_1(\mathbf{f}_2(\mathbf{p}, \mathbf{q}))) \quad (1)$$

and

$$\mathbf{x} = \mathbf{A}(\theta, d), [\theta \ d]^T = \mathbf{f}_1(l, \kappa, \phi), (l, \kappa, \phi) = \mathbf{f}_2(\mathbf{p}, \mathbf{q}) \quad (2)$$

where, $\mathbf{x}$ is the tip position and orientation of the actuator, $\mathbf{f}_{D-H}$ is the D-H formulation used to compute rotation and translation parameters θ and d with $\mathbf{A}$ as modified homogeneous transformation matrix found in [27], l is the length of the actuator, κ is determined by the curvature ($\kappa = \frac{1}{r_\phi}$, and r_ϕ is the radius of the

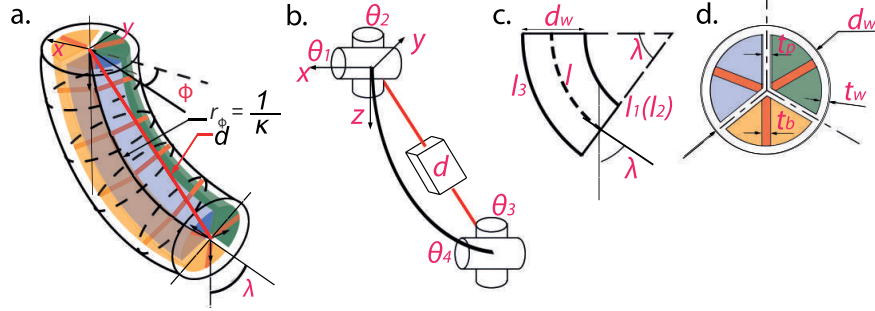


Figure 3: (a) Constraint soft actuator with variables ϕ and λ , where ϕ gives the rotation in the xy plane and λ gives the bending angle. d is the distance from the base origin to the tip of the actuator. (b) The soft actuator is modeled by coupled link/joint arrangement with rotation parameters $\theta_1, \theta_2, \theta_3, \theta_4$, and translation parameter d . (c) Three chambers of length l_1, l_2, l_3 , length of the actuator l . (d) The initial diameter d_w , the external wall thickness t_w , the partition wall thickness t_p , the width of the constraint beams t_b .

curvature), ϕ is the angle of curvature gives the rotation in the xy plane, $\mathbf{f}_1$ is the relation between parameters l, κ , and ϕ and D-H parameters θ_i and d_i . $\mathbf{f}_2$ is the transformation that maps the driving air pressure $\mathbf{p}$ and the design parameters $\mathbf{q}$ of the actuator to the geometric arguments l, κ , and ϕ . The relation of $\mathbf{f}_2$ is determined in section 4.3 by experimental characterization.

In this case, the homogenous transformation matrix A represents the kinematics of a single modular continuum robot with a “virtual” rigid-link [27], see Fig. 3 b.

$$A = \begin{bmatrix} -c_1 s_2 s_3 c_4 + c_1 c_2 c_3 c_4 - s_1 s_4 & c_1 s_2 s_3 s_4 - c_1 c_2 c_3 s_4 - s_1 c_4 & -c_2 s_3 c_1 + s_2 c_3 & c_1 c_2 d \\ -s_1 s_2 s_3 c_4 + s_1 c_2 c_3 c_4 + c_1 s_4 & s_1 s_2 s_3 s_4 - s_1 c_2 c_3 s_4 + c_1 c_4 & -s_1 c_2 s_3 + s_2 c_3 & s_1 c_2 d \\ (c_2 s_3 + s_2 c_3) s_4 & -(c_2 s_3 + s_2 c_3) s_4 & c_2 c_3 - s_2 s_3 & s_2 d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where, c_i denotes $\cos \theta_i$ and s_i denotes $\sin \theta_i$. d is again the distance between the origin and tip of the actuator. Also, $\theta_3 = \theta_2$ and $\theta_4 = \theta_1 + \pi$ since the last two joint variable is aligned to the first two.

Considering only one chamber was inflated (where $\phi = 0$) and assuming the length of actuator l is constant during the actuation:

$$\begin{bmatrix} \theta_1 & \theta_2 & d & \theta_3 & \theta_4 \end{bmatrix}^\top = \mathbf{f}_1(l, \kappa, \phi) = \begin{bmatrix} \tan^{-1}\left(\frac{\cos(\frac{\kappa l}{2})}{-\sin(\frac{\kappa l}{2})}\right) \\ 0 \\ \frac{2l}{\lambda} \sin(\frac{\lambda}{2}) \\ 0 \\ \tan^{-1}\left(\frac{\cos(\frac{\kappa l}{2})}{-\sin(\frac{\kappa l}{2})}\right) + \pi \end{bmatrix} \quad (4)$$

and

$$\kappa = \frac{\lambda}{l} \quad (5)$$

then substituting Eq. (4) and Eq. (5) into Eq. (3) produces:

$$A = \begin{bmatrix} \cos\lambda & 0 & -\sin\lambda & (\cos\lambda - 1)\frac{l}{\lambda} \\ 0 & 1 & 0 & 0 \\ \sin\lambda & 0 & \cos\lambda & \sin\lambda(\frac{l}{\lambda}) \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

where, l is the length of the actuator and λ is the bending angle. The distance from the base origin to the tip of the actuator d (see Fig. 3 a) is determined by l and λ . It needs to be noted that λ can be controlled by changing the driving pressure and tuning the design parameters (n and k), see Eq. 8-10. Thus, the tip position $\mathbf{x}$ of the actuator can be then computed by:

$$\begin{bmatrix} \mathbf{x}_i \\ 1 \end{bmatrix} = A_i R_{i-1} \dots A_2 R_1 A_1 \begin{bmatrix} \mathbf{x}_0 \\ 1 \end{bmatrix} \quad (7)$$

where, R_{i-1} is the rotation matrix determined by the phase shift between the two connected modules (phase shift is created by aligning the two serial connected chambers with a certain degree angular displacement rotated around their common axis), A_i is the transformation matrix of the i th modular, and $\mathbf{x}_0$ is the position of the actuator origin.

3. FEM simulation

Finite Element Method (FEM) has been widely used to assist the design of soft sensors and actuators [28, 29]. The numerical simulation explores the mechanical characteristics of the soft models under different design parameters and loading conditions. In this study, it was used to simulate the soft actuators with different

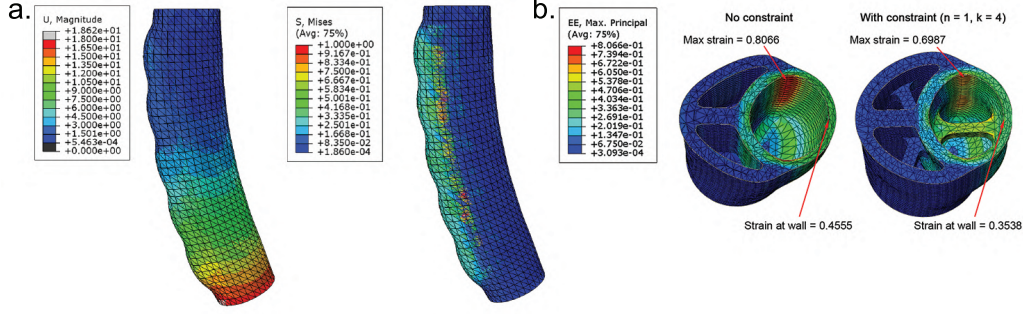


Figure 4: FEA simulation with driving pressure of 0.08 mPa. **(a)** The effect of constraint beam-element on bending angle and radial expansion rate demonstrated by a constraint soft actuator ($n = 1$, $k = 4$) when pressurized at 0.08 MPa. The respective displacement and stress distribution are shown. **(b)** Comparison between soft actuator design without any constrain and soft actuator design with constraint beam-element. A significant reduction of material strain (lead to break) can be observed with the constraint beam-element, from max strain 0.8066 to 0.6987 and strain at the external wall from 0.4565 to 0.3538.

constraint parameters to evaluate the bending angle and radial expansion of the actuators under different input internal pressure. ABAQUS (Abaqus 2018, Dassault Systemes, France) was used to perform the simulation tasks. The material property of the Shore A25 Rebounding resin was obtained through the manufacturer (MITS Electronics corporation, Tokyo, Japan). The neo-Hookean model was used to simulate the hyperelastic performance with coefficients $C_{10} = 0.13$ and $D_1 = 0$. The quadratic tetrahedron hybrid element (element type C3D10H) was assigned to meshes of the model. To simplify the simulation, the inlet of pressurized air and small fillets of the model were not taken into account in the simulation model. Uniform pressure was applied to all internal walls of one single chamber of the actuator from 0 to 0.08 MPa, with steps of 0.02 MPa. Bending angles λ and radial expansion rate $(d - d_0)/d_0$ were measured, as shown in Fig 1 b, c, where d is the thickest part of the actuator after pressurization and d_0 is the initial diameter of the actuator. An illustration of a simulated actuator designed with parameters $n = 1$ and $k = 4$, and driven at 0.08 MPa is shown in Fig.4. The displacement and stress distribution are indicated.

It can be observed that higher strain areas are located on the connecting part between the external wall and the partition wall during inflation. The external wall of the actuator tends to expand in a radial direction if not constrained. Such an undesired radial expansion causes excessive stress/strain on the actuator's ex-

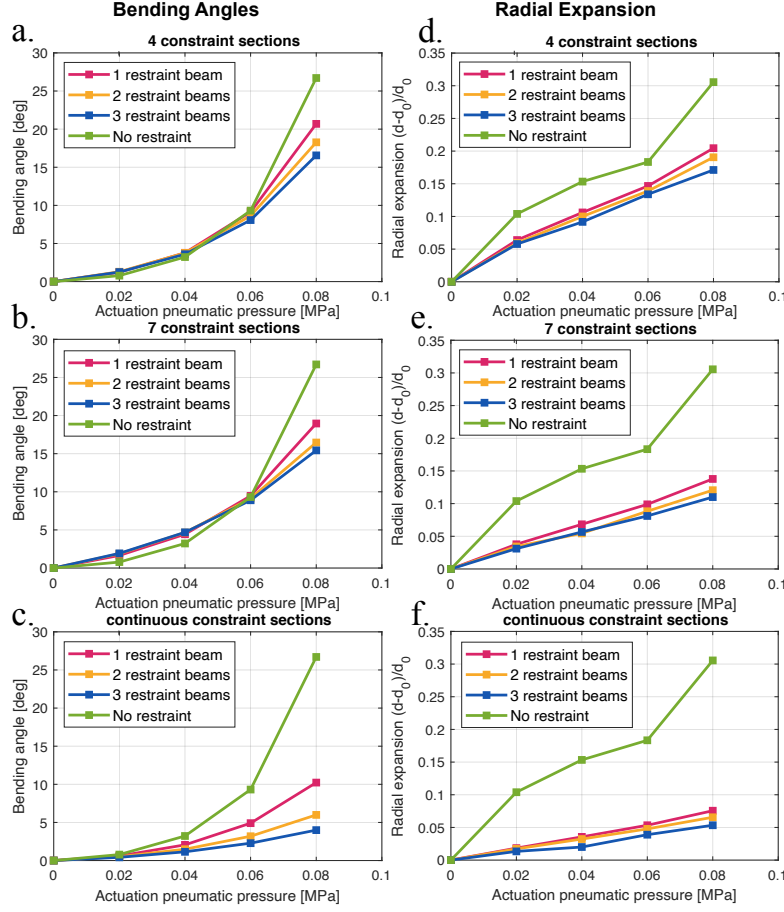


Figure 5: FEM bending angle and radial expansion data

ternal wall. This indicates that the no-beam design is prone to failure compared to the beam-constraint design. In Fig. 4 b, the FEM simulation result shows the material strain of the actuator is reduced with the constraint beam-element, from the maximum strain 0.8066 to 0.6987 ($\sim 13.4\%$ reduced), and the strain at the external wall is also decreased from 0.4565 to 0.3538 ($\sim 22.5\%$ reduced). Thus, the actuator with constraint beam-elements can be driven with a higher pressure.

The simulation result of bending angle is shown in Fig. 5. The simulation data shows that the original no constraint FMA design experienced higher non-linearity compare to the constraint designs, e.g., with $R^2 = 0.78$ of linear fitting compared with $R^2 = 0.88, 0.91$, and 0.94 of models with 1 constraint beam, 2

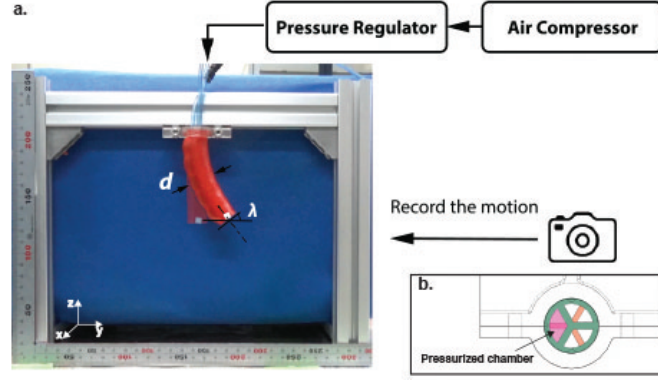


Figure 6: The experiment setup to study the effect of design parameter n and k on bending angle λ and radial expansion rate of the actuators.

restrain beam and 3 constraint beam (all with continuous constraint sections), respectively. Overall, the FEM results show that the constraint beams can reduce the radial expansion significantly. Moreover, the bending angle λ decreases with the increasing density n and section distribution k of the constraint beam elements.

4. Experimental Characterization

4.1. Experimental Setup

Experiments were conducted to validate the FEM. Fig. 6 a. shows the experimental setup while Fig. 6 b. shows how the 3D printed soft actuators were fixed vertically on a metal frame with attached rulers for calibration. Only one chamber was inflated for the given characterization experiments. The actuator was fixed by anchor points to make sure that the opposite partition wall of the inflated chamber is aligned with the x-axis. The pressurized chambers of the actuator were connected to an air compressor (oil-free scroll type, Smart Air SLP-07EED, ANEST IWATA, Yokohama, Japan) with a regulator (RP-1000-8-07, CKD) used in between for pressure control. The kinematics of the actuator was recorded by a camera. Markers are attached to the actuator, while the mounted ruler shows the dimension. The video data were later being processed through MATLAB with the Image Processing Toolbox (Matlab 2019a, The MathWorks, Inc.) to compute the bending angle λ (defined as the angle between the bending axial at the tip and the original vertical axis) and radial expansion rate $(d - d_0)/d_0$. Additionally, break-

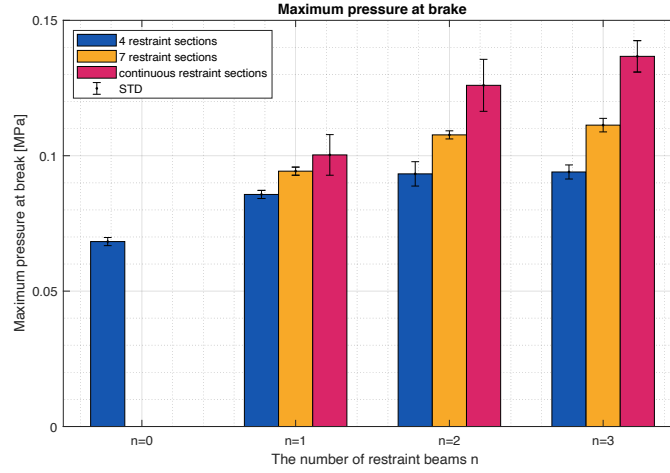


Figure 7: Maximum inflated pressure before rupture for actuators with different design parameters. Mean value and standard deviation were shown with 5 times of repetitions.

ing experiments were also done to test the maximum pressure the actuators can withhold before rupture.

4.2. Pressurized breaking point of the actuators

Fig. 7 shows the maximum driving pressure of the 10 types of actuators before break during continuous and slow inflation. Data were collected with 5 times of repetitions on each type of actuator. Standard deviation error (STD) is shown in Fig. 7.

The original FMA design without constraint beam elements is prone to failure at around 0.07 MPa due to the excessive radial expansion and tension on the external wall created by internal pressure. By contrast, significantly higher maximum driving pressures can be sustained by the actuators with constraint beam elements (up to around $\sim 160\%$ for the design with 3 constraint beams and continuous section). This result aligns with the FEM simulation that the beam reduces the concentrated stress on the external wall. We also examined the actuator after breaking. All of the broken cut happens at the external wall while the beams remain intact. In addition, the data shows that greater driving pressures can be achieved by constraining the soft actuator with a higher density beam elements design, indicating higher stiffness of the soft actuator.

4.3. Bending motion characterization results

Fig. 8 shows the measured bending angle of actuators with different design parameters. Based on the result from the maximum driving pressure test, the actuators were pressurized to only defined safety region (0 to 0.06 MPa for original no beam FMA design; 0 to 0.08 MPa for all 4 constraint sections designs with 1, 2, 3 constraint beams in each section; 0 to 0.08 MPa for 7 constraint sections designs with 1, 2 constraint beams in each section; 0 to 0.09 MPa for 7 constraint sections designs with 3 constraint beams in each section; 0 to 0.09 MPa, 0 to 0.1 MPa, and 0 to 0.13 MPa for continuous constraint section designs with 1, 2, 3 constraint beams in each section, respectively). Fig. 8 shows that the radial expansion was significantly reduced with the constraint beam elements (up to around $\sim 14\%$ for the design with 3 constraint beams and continuous section) compared to the original no-constraint FMA design.

In general, greater bending angles can be achieved with the actuators with constraint beams compared to the actuator without beams (from $\sim 138\%$ to $\sim 320\%$ for different constraint designs). The FMA actuator without constraint also experienced high non-linearity due to the material hyperelasticity. The no constraint design showed minimum bending motion during low driving pressure (less than 0.04 MPa). However, a clear jump can be observed when it approaches 0.06 MPa. This sudden deformation would result in difficulties of the pneumatic control and increase the risk of rupture. It can also be observed in Fig. 8 that the actuator without constraint mainly performed radial expansion during the low driving pressure region (0 to 0.04 MPa) instead of bending. In contrast, the constraint soft actuators show better linearity in bending angles during pressurization. For instance, the actuator with continuous constraint shows better linear fitting ($R^2 = 0.8, 0.81$, and 0.9 of actuators with 1, 2, and 3 constraints, respectively), compared with the actuator without constraint beam ($R^2 = 0.75$). Increased linearity can be achieved by integrating more constraint beams n or constraint sections k . However, under the same driving pressure, bending angles would decrease with more constraints engaged. Although differences in magnitudes can be seen between experimental and simulation results, presumably due to the change of material property during 3D printing, the experimental results align well with the FEM results, revealing a similar trend of pressure response of actuators in terms of bending angles and radial expansion. The experimental data also show small hysteresis for both bending angles and radial expansion rate during inflation and deflation. An example data with a soft constraint actuator ($n = 2, k = 7$) is shown in Fig. 9. Standard deviation error (STD) across the 9 trial experiments is also included.

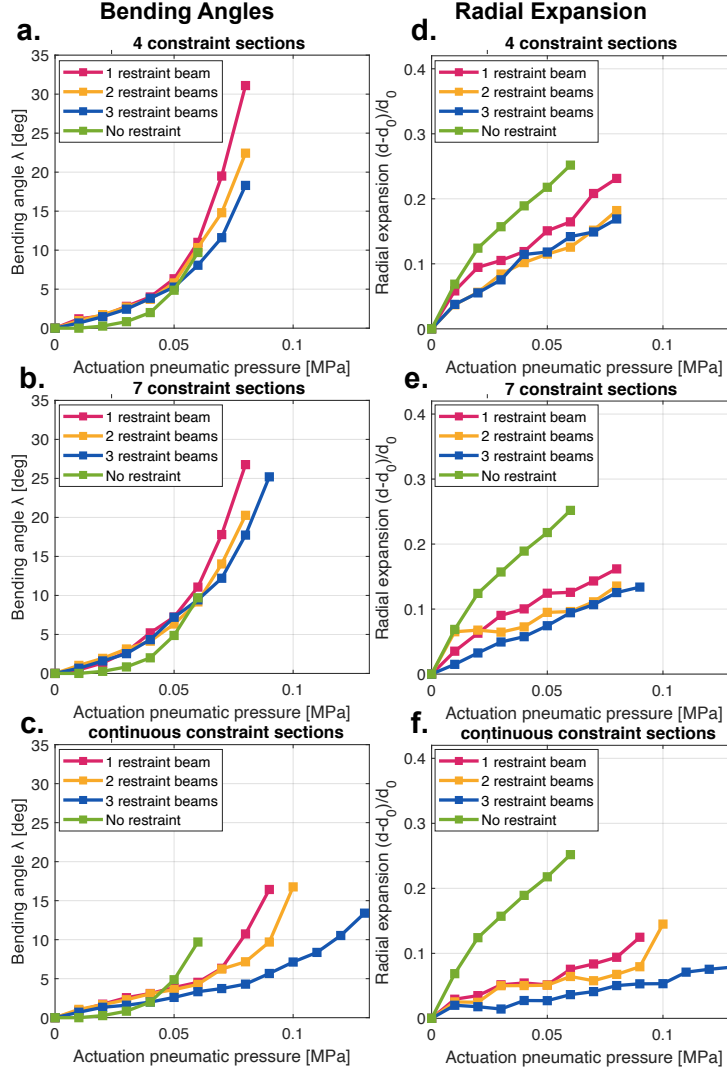


Figure 8: Experimental results. **(a)** Measured bending angle λ with respect to the increasing of driving pressure for $k = 4$ and $n = 1, 2, 3$ designs in comparison with original no beam FMA. **(b)** Measured bending angle λ with respect to the increasing of driving pressure for $k = 7$ and $n = 1, 2, 3$ designs in comparison with original no beam FMA. **(c)** Measured bending angle λ with respect to the increasing of driving pressure for $k \rightarrow +\infty$ and $n = 1, 2, 3$ designs in comparison with original no beam FMA. **(d)** Measured radial expansion rate with respect to the increasing of driving pressure for $k = 4$ and $n = 1, 2, 3$ designs in comparison with original no beam FMA. **(e)** Measured radial expansion rate with respect to the increasing of driving pressure for $k = 7$ and $n = 1, 2, 3$ designs in comparison with original no beam FMA. **(f)** Measured radial expansion rate with respect to the increasing of driving pressure for $k \rightarrow +\infty$ and $n = 1, 2, 3$ designs in comparison with original no beam FMA. All data were reported with the mean value of 9 times of repetition performed on 3 different actuators.

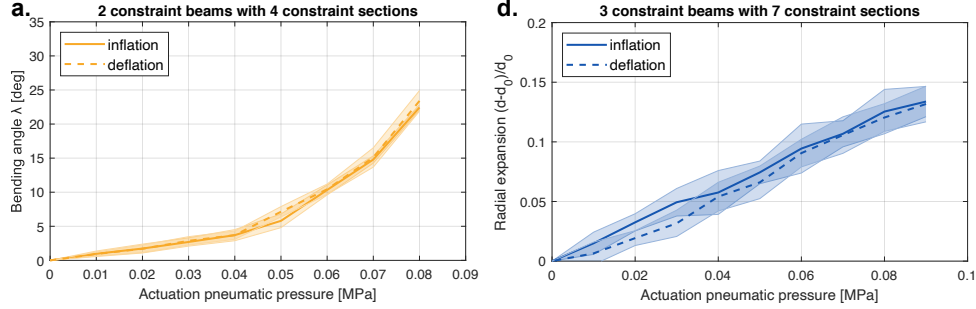


Figure 9: **(a)** The hysteresis and standard deviation error (STD) across 9 trials tests for bending angle measurements. **(b)** The hysteresis and standard deviation error (STD) across 9 trials tests for radial expansion. Example data presented for actuator with the design parameters $n = 2$ and $k = 7$.

The data of empirical bending angles were then characterized to elicit the correlation between design parameters and driving pressures using the third-order polynomial regression to generate the models. Third-order polynomial models are selected in this study based on Akaike's Information Criterion (AIC) [30] (details are included in the Appendix).

$$\lambda = \mathbf{f}_2(\mathbf{p}, \mathbf{q}) \frac{l}{l_0} \quad (8)$$

$$\mathbf{f}_2(\mathbf{p}, \mathbf{q}) = a_1(\mathbf{q})\mathbf{p}^3 + a_2(\mathbf{q})\mathbf{p}^2 + a_3(\mathbf{q})\mathbf{p} \quad (9)$$

and

$$0 \leq \mathbf{p} \leq \mathbf{p}_{max} \quad (10)$$

where, λ is the bending angle of the actuator, $\mathbf{p}$ is the driving pressure, design parameter $\mathbf{q}$ is determined by n and k , n is the number of constraint beams in one section, k is the number constraint sections when the actuator original length is l ($l_0 = 80\text{mm}$ in the given designs), and $\mathbf{p}_{max}$ is the maximum characterized pressure for each type of actuators. The bending angle is considered to be proportional to the characterized value according to the design length of the actuator modular. a_1, a_2 , and a_3 are determined by design parameter $\mathbf{q}$. See Appendix Table 7 for a_1, a_2 , and a_3 as the parameters of the fitted functions $\mathbf{f}_2(\mathbf{p}, \mathbf{q})$ for actuators with different n and k .

The characterized model can then be substituted in the kinematic function show in section 2.3. Based on this principle, actuators can be designed by taking the desired motion as the input and defined by different design parameters $\mathbf{q}$. In

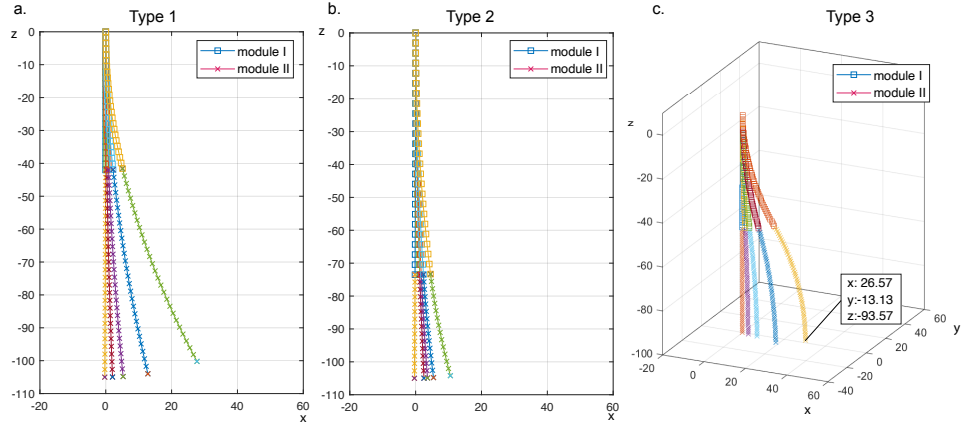


Figure 10: Designed trajectories to meet the desired motions **(a)** The trajectories to achieve higher bending on the top part when pressurized at 0, 0.02, 0.04, 0.06, and 0.08 MPa for the design of type 1 actuator. **(b)** The trajectories to achieve lower bending on the top part when pressurized at 0, 0.02, 0.04, 0.06, and 0.08 MPa for the design of type 2 actuator. **(c)** The trajectories to achieve bending with 120 degree phase shift to enable twisting motion when pressurized at 0, 0.04, 0.06, 0.08, and 0.1 MPa for the design of type 1 actuator.

order to validate the proposed idea, a simple approach was taken by designing actuators with two types of constraints to achieve different bending on the top and bottom parts of the actuator. The designs are shown in section 5.

5. Design for specified motions by tuning the constraint beam elements

In this section, a methodology is demonstrated to achieve specified motions of the actuator by pre-designing the kinematics of two connected modules through tuning the design parameters. Three types of motions were proposed for designing specified restraint soft actuators: 1) higher bending motion of the top part of the actuator while lower bending motion of the bottom part of the actuator; 2) lower bending motion of the top part of the actuator while relative higher bending motion of the bottom part of the actuator; 3) equal bending angle of the top and bottom parts of the actuator but bending in two different planes (with 120 degree phase shift) to create a twisting motion.

The trajectories were then designed based on the previous characterization of bending motion for selected beam elements constraints ($n = 1, 2, 3$ and $k = 4, 7, +\infty$) to match the target motions, as shown in Fig. 10.

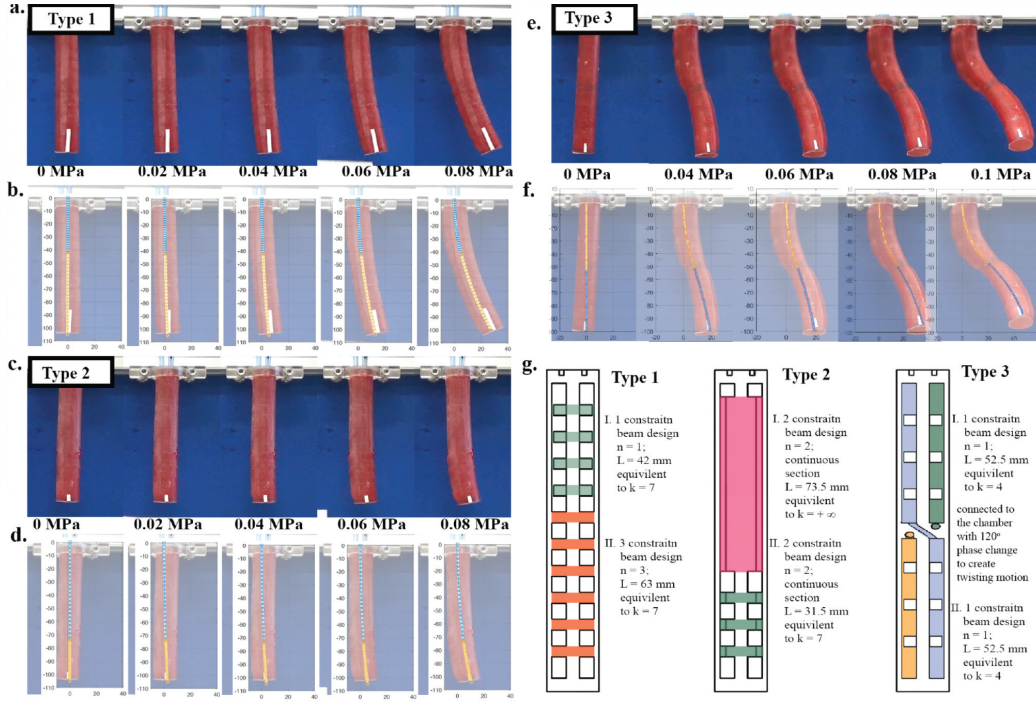


Figure 11: (a) The trajectory of fabricated type 1 actuator when pressurized from 0 to 0.08 MPa. (b) Matching with the designed and computed trajectory. (c) The trajectory of fabricated type 2 actuator when pressurized from 0 to 0.08 MPa. (d) Match with the designed and computed trajectory. (e) The trajectory of fabricated type 3 actuator when pressurized from 0 to 0.1 MPa. (f) Match with the designed and computed trajectory. (g) Design parameters for type 1, type 2, and type 3 actuator.

The single-material 3D printed actuators that follow pre-defined trajectories were then fabricated. The detail design parameters are shown in Fig. 11 g, (1) the 42 mm long top segment of type 1 actuator contains 1 constraint beam ($n = 1$) with sections distributed equivalent to $k = 7$, and the 63 mm long bottom segment has 3 constraint beams ($n = 3$) constructed with the constraint sections distributed equivalent to $k = 7$; (2) type 2 comprises a 73.5 mm top segment with 2 constraint beams ($n = 2$) constructed continuously (equivalent to the case from previous characterization as $k \rightarrow +\infty$) and the 2 constraint beams design distributed in it bottom segment are equivalent to $k = 7$ case with the length of 31.5 mm; (3) type 3 is designed with two same modules (52.5 mm long) with 1 constraint beam ($n = 1$) and constraint sections distributed equivalent to $k = 4$, but connected with 120 degrees of phase shift to create twisting motion. The schematics of each module are shown in Fig. 11 g. Design parameters, including the radius, external wall thickness, constraint beam elements, and material, were the same as actuators described in previous characterization sections. The maximum pressure of 0.08 MPa was applied for type 1 and type 2 actuators and 0.1 MPa for type 3.

All 3D printed actuators were then being pressurized to match the designed trajectories, as shown in Fig. 11 b, d, and f. In Fig. 11, the 3D motion of the actuator was only presented from the front view. The motion of the fabricated actuators matched well with the designed trajectories at different input pressures.

6. Conclusion and Discussion

A beam-element constraint approach to design soft actuators with changeable motions suitable for single material 3D printing is proposed in this paper. The internal structural constraint limits the undesired radial expansion, improves the durability of the actuator by allowing higher driving pressure before rupture, and enables higher maximum bending angles compared to conventional no-beam design. It also allows us to customize actuators with pre-defined motions to simplify differential control of channel pressures across several modules by changing the design parameters. This is particularly useful for repeated movements. The experimental characterization and simulation results validate that soft actuators with diverse kinematics could be achieved by tuning the internal beam elements design, i.e., the number of constraint beams (n) and constraint sections(k).

Compared to other conventional constraint methodologies (fiber-reinforcement, sheaths, and embedded spin), the proposed beam-element method shows the ease and simplicity of being integrated with 3D printing technologies. The requirement of only single material also significantly reduced the manufacturing cost

and made the method easily to be generalized. Post-fabrication processes, e.g., manual threading of the fiber [13], multi-layer casting [31], and additional strain limiting layer [9], are not required for the beam-element based constraint actuators, which enables the actuator to be designed and fabricated for many iterations within a short period of time. This advantage further improves the adaptability of soft actuators applied in an unstructured environment that changes over time since the soft actuator can be quickly modified and re-fabricated based on the need of the current condition. Therefore, the method has the potential to enable a fully autonomous operation cycle from environment exploration, task clarification, design parameter optimization, and rapid fabrication to task performing.

The methodology shows limited forms of actuation since only selected design parameters were experimentally characterized in this study to propose the beam-element constraint approach. However, as part of future study, a large-scale FEM will be conducted to explore the density and distribution of the beam elements, and more 2D profiles of the actuator will be tested and characterized. The available materials and 3D printers to fabricate soft actuators are still limited, but the internal constraint method can be quickly generalized when more soft 3D printing materials are developed in the future. Future work will also focus on developing systematic optimization methods to automate the design procedure.

7. Appendix

n	k	$a_1 (\times 1e5)$	$a_2 (\times 1e5)$	$a_3 (\times 1e5)$	R^2_{3rd}
1	4	1.2868	-0.0808	0.0021	0.9994
1	7	0.7295	0.033	0.0013	0.9982
1	$+\infty$	0.6243	-0.06	0.0022	0.9947
2	4	0.6526	-0.0325	0.0012	0.9987
2	7	0.5884	-0.0338	0.0015	0.9996
2	$+\infty$	0.4331	-0.047	0.002	0.9818
3	4	0.5755	-0.035	0.0014	0.9977
3	7	0.3889	-0.0176	0.0012	0.9966
3	$+\infty$	0.0094	-0.011	0.0008	0.9984

Table 1: characterized parameters of the fitted functions $\mathbf{f}_2(\mathbf{p}, \mathbf{q}) = a_1(\mathbf{q})\mathbf{p}^3 + a_2(\mathbf{q})\mathbf{p}^2 + a_3(\mathbf{q})\mathbf{p}$, where $\mathbf{q}$ is determined by n and k . R^2 of the third order polynomial fitting is reported.

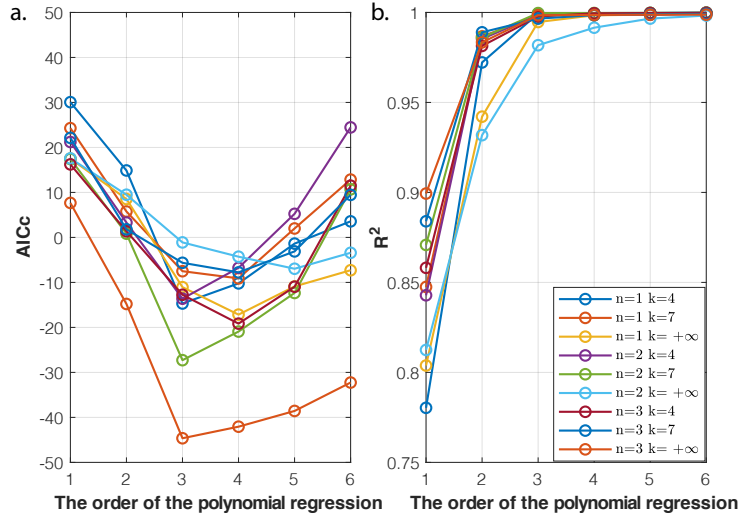


Figure 12: Regression fit of the function for the polynomial order up to 6. (a) The associated AICc test for the evaluation of the regression. (b) The associated R^2 values of the fitted models. Third-order polynomial regression is chosen as most models have the lowest AICc value when the polynomial order is three. The fittings are also accurate enough to describe the experimental data with the minimum R^2 higher than 0.98.

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CRedit Authorship Contribution Statement

Liang He: Conceptualization, Methodology, Software, Data curation, Investigation, Writing- Original draft preparation, Project administration. **Xinyang Tan:** Software, Data curation. **Koichi Suzumori:** Conceptualization, Methodology, Resources, Validation, Investigation. **Thrishantha Nanayakkara:** Validation, Writing- Reviewing and Editing, Supervision.

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