1. Introduction

Designing robots made out of soft elastomeric materials has opened up new possibilities for performing tasks where conventional robots fail, such as for grasping and manipulating delicate or irregular objects,[11–14] complex locomotion and navigation,[15,16] or assisting in complex biological functions, from wearable applications[7–12] to heart muscle contraction.[13] Unlike their rigid counterparts, soft robots can safely interact with humans and require neither environment perception systems nor precise position detection of the objects they interact with. Fluid-driven actuators,[14] e.g., silicone-bodied pneumatic actuators powered by pressurized voids,[15–18] are widely used due to their simple and rapid actuation, easy operation, and scalable implementation. The kinematics of these actuators is directly programmed into their anisotropic structure which stretches differentially under pressure and induces their contraction, expansion, torsion, or flexion. However, these deformation modes that involve large material strains require the use of rubber-like materials (e.g., elastomers). Because of their low stiffness, they generally need thick walls, which results in large unpressurized volumes and limits their designs to small scales (a few centimeters), as larger structures tend to collapse under their own weight.

To use stiffer materials that can be actuated at larger scales, other strategies have been proposed, exploiting the bending deformation of thin structures that remain within the inextensible limit of the material. The actuation process is embedded within networks of cuts or folds to gently grip objects,[19,20] morph,[21,22] or deploy.[23–25] Fabric-based inflatable actuators are particularly attractive because they are generally simple to manufacture, foldable, lightweight, require low operating pressure, can be used at larger scale,[26–30] and develop higher forces[31,32] than their elastomeric counterparts.

In this work, we present a simple strategy for designing a soft gripper based on the deformation of inextensible fabric star-shaped inflatable that contracts radially in a plane under pressure. The gripper consists of a network of flat tubes connected by V-shaped actuators (V-actuator) that act as hinge-like mechanisms. Using experiments, finite element simulations, and theoretical modeling, we rationalize the actuation process and model the mechanical response of a V-actuator as a function of its geometry, applied pressure, and mechanical properties of the fabric. We leverage this quantitative knowledge to program the deformation of the network of tubes and calculate the optimal star shape maximizing the radial contraction and the force applied to the target object. Unlike their rubber counterparts, our inflatable soft grippers can fold flat when not pressurized and have a high stiffness-to-weight ratio, making it easy to extend their design to large scales.

Figure 1 illustrates our approach. Our model consists of two nylon fabric sheets sealed together to form a network of inflatable tubes. The fabric sheet of thickness $t = 300 \mu m$, Young’s modulus $E = 128 \text{ MPa}$, and Poisson ratio $\nu = 0.39$ is characterized by a stretching modulus $Y = E t$ and a bending modulus $B = E t^3 / [12 (1 - \nu^2)]$. The two sheets are heat-sealed along the desired path using a soldering iron mounted on a two-axis translation stage (Experimental Section). A V-actuator consists of two...
rectangular parts connected by an annulus sector forming an angle \( \phi_0 \). Upon inflation, a V-actuator with an initial acute angle of \( \phi_0 = 30^\circ \) in the flat configuration closes completely on itself to a target angle \( \phi_t < 0^\circ \), acting as a hinge-like mechanism (Figure 1a). We take advantage of this closing mechanism to build networks of tubes connected by V-actuators. By concatenating a series of actuators in alternate directions, we build star-shaped closed loops. During inflation, the tube network contracts radially in the plane (Figure 1b). By adding an acrylic frame to provide rigidity to the unpressurized structure, we show that this overcurvature effect can be harnessed to design a soft gripper able to grip objects of different shapes and weights. The actuation process can be easily stacked to increase the gripping force and conform to objects of different geometries, from metal spheres to bottles (Figure 1c,d, and Movie S1, Supporting Information). Friction with the object is increased by coating the inner corners of the star with a silicone-based elastomer (Figure 1e). The prototype achieves remarkably high forces, being able to grip objects weighing several kilograms.

We first model the kinematic and mechanical response of an individual V-actuator before extending our approach to networks.

2. Response of a Single V-Actuator

2.1. Kinematic Response of a V-Actuator

We first proceed to the experimental and numerical characterization of the kinematics of a single V-actuator, consisting of two rectangular arms of width \( W \) and length \( \ell' \) connected by an annulus sector with an inner radius of curvature \( R \). Figure 2a shows the deformed shape of an actuator predicted by finite element methods (Experimental Section, and Finite Element Simulations, Supporting Information). During inflation, the angle between the two arms decreases from the initial angle \( \phi_0 \) in the flat configuration to a target angle \( \phi_t \) which is obtained at high pressures (Movie S2, Supporting Information). The sheet deforms strongly in the vicinity of the edge (see Figure 2a Inset), leading to a geometric localization of the deformation close to the bend reminiscent of the Brazier instability observed in thin-walled cylindrical tubes or the curvature condensation observed in thin elastic sheets.[33–35]

In Figure 2b, we plot the target angle \( \phi_t \) of tubes made with different \( \phi_0 \) and the same width \( W = 2 \) cm, length \( \ell' = 15 \) cm, and radius of curvature \( R = 2 \) mm. Finite elements simulations plotted in red line are in excellent agreement with experimental observations. We observe a linear relationship in which angular contraction is zero at \( \phi_0 = \pi \) and maximum at \( \phi_0 = 0 \). We define the actual coiling factor of the structure \( \lambda(\phi) = (\pi - \phi)/(\pi - \phi_0) \), where \( \phi \) is the actual angle at any stage of inflation.

Figure 2c shows the actual coiling factor \( \lambda \) as a function of the pressure \( p \) measured from both experiments and simulations, showing that \( \lambda \) increases with the operating pressures and saturates at the target coiling factor \( \lambda_t = \lambda(\phi_t) \). The data for different tube widths and membrane thicknesses (Figure 2c) fall on a master curve showing that the coiling process is dominated by the bendability of the membrane \( pW^3/B \). This plot also predicts the operating pressure that must be applied to the actuator to achieve the maximum change in angle which is of the order of \( 10^4 B/W^3 \).

Upon inflation, the system minimizes the total energy \( U_T = U_s - pV \), where \( U_s \) is the strain energy, \( p \) is the fluid pressure, and \( V \) is the total volume enclosed by the system. In the case of an infinitely thin membrane, the total energy is dominated by \( -pV \), whose minimization is equivalent to the
maximization of the volume.\textsuperscript{[36,37]} The typical operating pressure of the order of 10 kPa is too small to induce stretching in the fabric ($p \ll Y/W$) so that the membrane can be considered quasi-inextensible, therefore the resulting shape is a consequence of volume maximization under inextensibility constraints.\textsuperscript{[38,39]} The shape of the curved hinge can be approximated to that of an axisymmetric ring whose cross-sectional profile is obtained by a Lagrangian model maximizing the volume under inextensibility constraints (SI Appendix, Inflation of an annular sector). This optimization problem leads to an optimal coiling factor $\lambda_0(R')$ that only depends on $R' = R/W$. In our case, the optimal coiling $\lambda_0(R' = 0.1) = 1.28$ plotted as a dashed line in Figure 2c captures the asymptotic behavior of the actuator at large pressure for all geometries.

### 2.2. Mechanical Response of a V-Actuator

We now study the mechanical hinge-like response of the V-actuator around its target angle $\phi_0$. The actuator is attached to a universal testing machine with pin-joint conditions (see Experimental Section and inset in Figure 2d), while the pressure imposed in the tube is kept constant. We measure the vertical force $F$ as the V-actuator opens and not or closes and compute the hinge moment defined as $M_h = F \ell \cos(\phi/2)$. We couple this force measurement with the direct observation of the actuator deformation with a camera to compute the moment applied by the structure $M_s$ as a function of the imposed angle $\phi$ (Figure 2d).

We observe that the mechanical response of the hinge presents a small hysteresis and that the moment is highly nonlinear around the target angle. The hysteresis arises from fabric mechanical response and the fact that the closed volume changes as the pressure valve restricts airflow. The hinge mechanism is softer when closed ($\phi > \phi_0$) and stiffer when opened ($\phi < \phi_0$). The experiments are in excellent agreement with numerical simulations plotted as a red line.

To build a fundamental understanding of the mechanical response of the pressurized actuator, we first decompose the moment the sum of the volume variation and the strain energy variation with respect to $\phi$

$$M_T = -\frac{dU_s}{d\phi} + p \frac{dV}{d\phi}$$ (1)

While the variation of the strain energy depends on the localization of the strain energy in the hinge and is difficult to predict analytically, our analytical model allows us to predict the volume...
change as a function of the angle as we show next. We checked numerically that the mechanical response is dominated by the volume variation, as expected in the thin membrane limit.

When the angle of the actuator changes, the main volume variation comes from the hinge and not from the arms. Following the same theoretical framework developed to model the actuator shape at high pressure, we predict the change in volume \( V \) with the imposed angle \( \phi \). Figure 2e shows \(-\nabla(\phi)\) for \( R^* = 0.1 \) and \( \phi_0 = 60^\circ \), where \( \nabla = V/|W^3(\pi - \phi_0)| \) is the dimensionless volume of the hinge section (Inflation of an Annular Sector, Supporting Information). The minimum of the curve corresponds to the target angle \( \phi_t \) obtained when no force is applied to the actuator. The curve has a parabolic-like shape showing a distinctive asymmetry with respect to its minimum. In the membrane limit, this asymmetric potential is directly responsible of the asymmetrical mechanics of the V-actuator, which results in a stiffer response when the V-actuator is open and a softer response when the V-actuator is closed.

More generally, the variation of the volume can be expressed as a function of the coiling factor \( \lambda \) for any given initial angle \( \phi_0 \) as shown on the upper axis of Figure 2e. The target coiling factor, \( \lambda_t \), can be adjusted slightly by changing the slenderness of the actuator as shown in inset. From Equation (1), we deduce the volume-variation contribution to the moment which is plotted as a dashed green line in Figure 2d.

The volume variation with respect to \( \phi \) also gives insights into the mechanical stiffness of the V-actuator defined by \( C = -dM_1/d\phi|_{\phi_0} \). The volume change contribution to the torsional stiffness of the actuators is

\[
C = -\left. pW^3 \frac{d^2V}{d\phi^2}\right|_{\phi_0} = -\frac{pW^3}{(\pi - \phi_0)} \frac{d^2V}{d\phi^2}
\]  

where the term \( d^2V/d\phi^2|_{\phi_0} \) depends only on \( R^* \). From our theoretical model, we numerically compute this term for different values of \( R^* \), finding that it is well-fitted by \( d^2V/d\phi^2|_{\phi_0} = -0.4659R^* + 0.3986 \) (Figure S2C, Supporting Information).

The theoretical prediction of Equation (2) is plotted in Figure 2f for a given \( R^* \) and compared to the stiffness extracted from FEM for three different tube widths. The error bars correspond to the two different ways of computing the moment numerically based on the hinge description \( M_h \) (valid when \( W \ll \ell \)) or the generalized definition \( M_T \) (see Equation (1)). In Inset, we plot the stiffness as function of \( \phi_0 \), which is well captured by Equation (2). The torsional stiffness increases for larger initial angles and diverges at \( \phi_0 = \pi \). In the following, we approximate the mechanical behavior of the actuator around the target angle to a torsional hinge with linear stiffness: \( M(\phi) = -C(\phi - \phi_t) \).

3. Star Soft Gripper

3.1. Kinematics of the Star Gripper

We now take advantage of the actuator closing mechanism to build a soft gripper based on several V-actuators connected in alternating directions in a closed loop. The geometry of our soft gripper is a \( n \)-pointed star that is constructed from a \( n \)-sided regular polygon and isosceles triangles whose bases coincide with the sides of the polygon (Figure 3a). The triangles have arm lengths \( \ell \) and internal angles \( \phi_0 \) at their apex. The external angle between the arms of two adjacent triangles is given by \( \phi_{e0} = \phi_0 + 2\pi/n \). Since the arms of the star always remain straight, we can write

\[
\phi_e = \phi_t + 2\pi/n
\]  

where \( \phi_t \) and \( \phi_e \) refer to the internal and external angles of the star at any stage of inflation.

When the width of the tube is negligible \( (W \ll \ell) \), the actual radius of the circle enclosed by the star is \( R(\phi_t) = \ell \sin(\phi_t)/2) / \sin(\pi/n) \). Notice that in this limit, when \( \phi_t \rightarrow 0 \), the star closes completely.

We model our soft gripper as a set of rigid bars and linear torsional hinges (Figure 3a). The mechanical energy of the system is therefore \( E_{\text{star}} = n/2[C_i(\phi_t - \phi_{i0})^2 + C_e(\phi_e - \phi_{e0})^2] \), where \( \phi_{i0} \) (resp. \( \phi_{e0} \)) are the internal (resp. external) target angles of the star and \( C_i \) and \( C_e \) are the corresponding torsional stiffness. Note that \( \phi_{i0} \) and \( \phi_{e0} \) do not necessarily satisfy Equation (3).

The minimization of the energy with respect to \( \phi_t \) allows us to predict the internal angle of equilibrium

\[
\phi_{t0} = \phi_t + 2\pi/n
\]  

where \( \phi_{t0} \) and \( \phi_{e0} \) do not necessarily satisfy Equation (3).

3.2. Grip Strength of the Soft Gripper

When the gripper catches an object, it applies an inward radial force \( F_i \) if the size of the object is larger than the equilibrium radius of the star \( \rho_{eq} \). To measure the grip strength as a function of the object diameter, we design an experiment where a rigid cone is pushed through the center of the pressurized uncoated star (Figure 3b) while the star is supported on a plate with a hole in its center. The bottom plate is fixed while the cone is attached to the load cell of a universal testing machine. The cone moves downward with a constant imposed velocity so that the star opens radially while the force applied to the cone is measured. Both the cone and the plate are made of glass, which ensures a smooth sliding of the fabric, with a well-defined coefficient of kinetic friction. The hole in the center is large enough to allow the star to open to a few centimeters in diameter before the cone contacts the plate.

Figure 3c shows the cross-section of the corner of the star in contact with the cone and the plate. The forces acting on this cross-section are: the radial contraction force \( F_c \) of the gripper; two normal forces \( N_c \) and \( P \) acting at the contacts with the cone and plate; two friction forces \( F_f \) and \( F_p \) at the contacts with the cone and the plate. A force balance gives the radial force \( F_r \) as a function of the vertical load \( P \) which is measured by the load cell

\[
F_r = \left( \mu + \frac{1 - \mu \tan \gamma}{\mu + \tan \gamma} \right) P
\]  

For small values of \( n \), the interaction between the internal and external torsional stiffnesses restricts the complete closure of the star. This interaction depends on the factor \( C_e/(C_i + C_e) = 1/(2(1 - \pi/(\pi - \phi_0))/n) \), whose value tends asymptotically to 1/2 for large values of \( n \). In the zero-width limit, the equilibrium radius is given by \( \rho_{eq} = \rho(\phi_t)^1 \).
where \( \gamma = 30^\circ \) is half the angle of the cone and \( \mu = 0.1 \) is the kinetic friction coefficient.

The experimental radial force is plotted as a function of the inner radius of the gripper in Figure 3d for different operating pressure. The contact point between the star and the cone depends on the equilibrium radius of the star. We predict the radial contractile force by differentiating the mechanical energy of the system with respect to the radius. At linear order, we find that

\[
F_s = \frac{dE_{\text{star}}}{d\rho} \approx \frac{4n(C_i + C_e)\sin^2(\phi_i/2)}{\rho_0^2\cos^2(\phi_i/2)} \Delta \rho
\]

where \( \Delta \rho = \rho - \rho_{\text{eq}} \) and \( \rho_0 = \rho(\phi_0) \) is the initial inner radius. By deriving the values of \( C_i \) and \( C_e \) from Equation (2), Equation (6) gives us a prediction for the radial stiffness. We observe a slight offset in the force at \( \rho = \rho_{\text{eq}} \) due to the change in volume associated with the local deformation at the cone contact. This additional force should scale with the pressure multiplied by the area of the contact zone, which depends on the geometry of the object. The linear stiffness prediction works best for larger pressures, consistent with the fact that in this limit, the energy term \(-pV\) is dominant over the material’s strain energy.

We define the radial stiffness of the gripper as \( K = F_s/\Delta \rho \). Notice that, for large values of \( n \), this stiffness scales as \( K \approx npW^3/\rho_0^5 \) from Equations (2) and (6). The Equation (6) shows that at fixed \( \rho_0 \) and \( \phi_i \), a larger number of points \( n \) implies a smaller arm length \( \ell \), resulting in greater stiffness.

### 3.3. Optimization of the Shape of the Star

To optimize the actuation of the soft gripper, we seek the optimal shape that maximizes the star contraction \( \rho_{\text{eq}} - \rho_0 \). As a design guideline, we choose internal angles, \( \phi_i = 30^\circ \), that guarantee a complete closure of a single actuator. In the ideal zero-width limit and large \( n \), the inner radius of the star should reduce to zero upon inflation. In fact, finite width effects and interaction between internal and external stiffnesses decrease the maximum contraction of the star. Figure 4a shows the target shape of stars with 3, 4, and 5 points with the same initial inner radius \( \rho_0 = 5 \) cm. In Figure 4b, we numerically compute the target

\[ F_s = \frac{dE_{\text{star}}}{d\rho} \approx \frac{4n(C_i + C_e)\sin^2(\phi_i/2)}{\rho_0^2\cos^2(\phi_i/2)} \Delta \rho \]
shape of the gripper by varying the number of points of the star \((n = 3–8)\) for the same initial inner radius. Notice that \(\ell\) decreases with \(n\), until eventually, it becomes negative for \(n = 9\). The radial contraction is maximal for \(n = 4\) or \(5\) (Figure 4b) reaching 74% of contraction. The final internal radius \(\rho_f\) can also be predicted analytically as a function of \(n\) (blue dots in Figure 4c) by taking into account the finite width of the tubes in good agreement with the numerical calculations (Star Geometry with Finite Width, Supporting Information).

### 3.4. Operating Pressure

We now discuss the effect of the actuator size on the operating pressure and the force developed by the star gripper. The actuation kinematic is independent of the star scale (Figure S5, Supporting Information for a demonstration of a large-scale gripper). If the dimensions of the star are amplified by a factor \(\eta\), \((\rho_0, R, W, \ell) \rightarrow (\eta \rho_0, \eta R, \eta W, \eta \ell)\), but the thickness \(t\) is kept the same, the pressure required to obtain an equivalent contraction scales as \(p \rightarrow p/\eta^3\) and the gripper stiffness as \(K \rightarrow K/\eta^2\). If the thickness of the sheet is also scaled as \(t \rightarrow \eta t\), the operating pressure range does not change and the new stiffness scales as \(K \rightarrow \eta K\).

A limitation of the design is the failure of the gripper observed at very high pressures for which the seal tends to fail at the inner edge of the hinge section. If \(T_{\text{max}}\) is the maximum vertical tension the edge can withstand, then the system fails at a maximum pressure \(p_{\text{max}} \approx T_{\text{max}}/W\). If the dimensions are scaled by \(\eta\), then the maximum supported pressure must be scaled as \(p_{\text{max}} \rightarrow p_{\text{max}}/\eta\), and then \(K \rightarrow K/\eta^2\).

### 4. Performance of the Fabric-Based Star Soft Robotic Gripper

The robustness of the manufacturing process allows us to easily produce multiple stars to further increase grip strength by stacking multiple stars. When \(\rho_0\) is large or the object is too heavy, out-of-plane deformations can be observed while the arms remain straight (see Figure 1d where the inner corners of the star are pushed down). The addition of a rigid frame solves this problem by constraining the arms to the plane. This frame also allows to position the gripper around the object when not pressurized by keeping the flat sheets in the plane.

We increase gripping efficiency by coating the inner corners of the star with a thin silicone-based elastomeric film (Figure 1e, and Coating Process, Supporting Information). We coat the fabric with a polymer solution that forms a thin, almost uniform layer as the film cures to improve friction and object grip.

We test this design for a stack of three stars enclosed in a rigid frame consisting of four acrylic frames connected by stainless steel optical posts (ThorLabs mini-series). We first demonstrate the ability of the gripper to grasp a variety of objects ranging from delicate objects such as a garden mint to complex-shaped objects such as eggs, flat bottles, broccoli heads, and a hand of bananas.
with the same gripper (Figure 5). We then measure the maximum weight the gripper can hold to lift a cylindrical container for an arbitrary pressure $p = 37 \text{kPa}$. While the uncoated fabric can only hold a mass of 2.2 kg, the coated model manages to move masses greater than 8.7 kg. Note that the mass of the three actuators amounts to 60 g, making the lifting ratio (object mass/clamp mass) greater than 100, comparable to the best performance observed for fluid elastomeric actuators and using electro-adhesion.[42] The gripper can lift heavy objects because we take advantage of the high bending stiffness of the inflated tubes. The bending stiffness (per unit width) of a thin-walled inflated cylinder $E W^2 t/(2r)$ is indeed much higher than $B$. [43]

Other advantages of our gripper over other strategies are the simplicity of manufacturing compared to elastomeric gripping methods that require multiple molding steps. The stars can be printed directly in the plane unlike devices that require additional folding or pleating.[32,44,45]
The actuation strategy is scalable due to the predominance of geometry in the tube actuation mechanism. The gripper is also easily transportable and foldable when not under pressure, like other fabric-based designs.

Finally, we consider the limitations of our gripper. First, the size of the object the gripper can grasp is limited by the two diameters of the gripper before and after inflation (smaller than \( \rho_0 \) and larger than \( \rho_1 \)). Although the gripper is very versatile for gripping objects of various geometries, it is not effective for gripping very thin objects such as plates or thin disks.

We envision that our approach of using the actuation of fabric-based inflatable structures, will open new possibilities in developing soft robotic matter on a larger scale capable, of performing complex tasks after the application of a simple stimulus.

5. Experimental Section

Fabrication of Actuators: The inflatables were made by sealing together two thermo-sealable nylon fabric sheets (impregnated with thermoplastic urethane) using a temperature-controlled soldering iron unit (PU81 from Weller) mounted on a CNC machine (Aureus 3X 10 from Euromakers). The fabrications were made by sealing together two thermo-sealable nylon fabric sheets (impregnated with thermoplastic urethane) using a temperature-controlled soldering iron unit (PU81 from Weller) mounted on a CNC machine (Aureus 3X 10 from Euromakers). The gripper is also Weller) mounted on a CNC machine (Zwick Z2.5TH) with XForce HP 10 N load cells. The actuation strategy is scalable due to the predominance of flatable structures, will open new possibilities in developing soft robotic matter on a larger scale capable, of performing complex tasks after the application of a simple stimulus.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

fabric-based actuator, soft actuator, soft gripper

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