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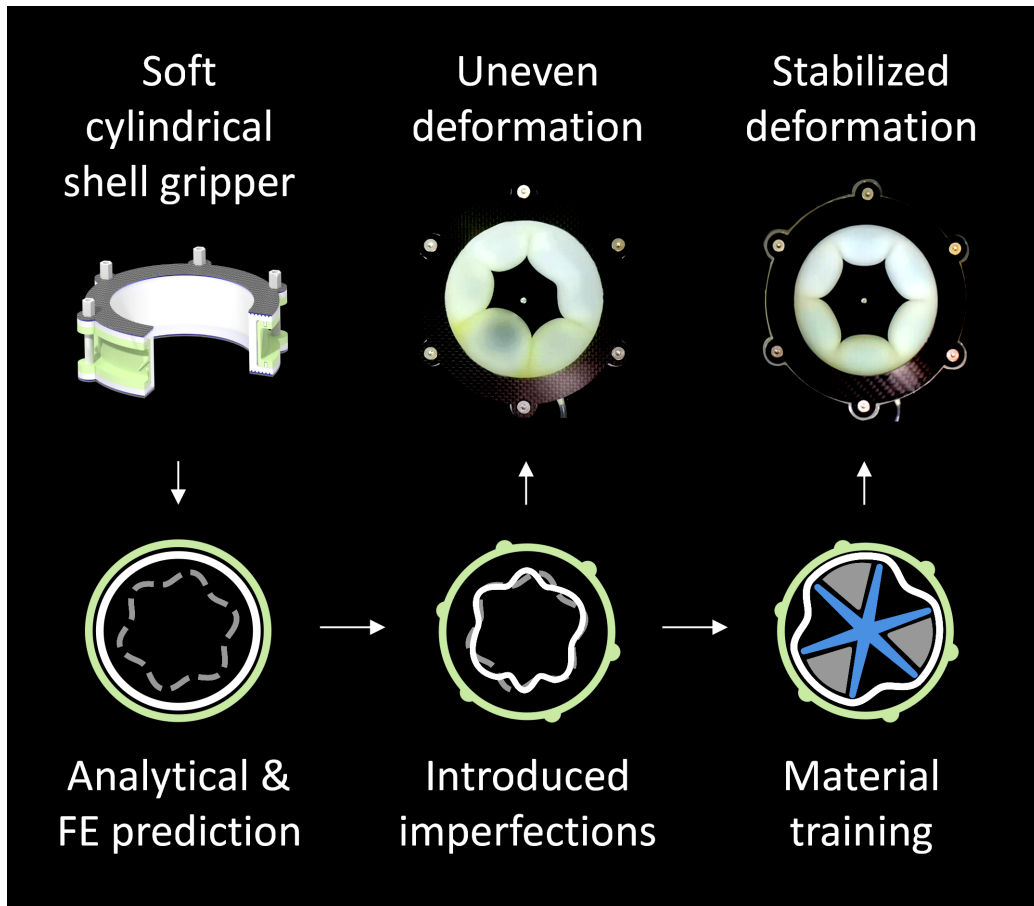
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Graphical Abstract

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Highlights

Stabilizing the buckling instabilities of soft cylindrical shell grippers

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- We investigate the buckling instabilities of soft cylindrical shell grippers and propose methods to stabilize their instability patterns.
- Analytical and numerical models predict the theoretical mode number of buckling instabilities based on geometric parameters.
- Imperfections are introduced intentionally to achieve tunable instability patterns.
- A material *training* process utilizing the Mullins effect enhances the uniformity and stability of the deformation.
- Stabilized grippers exhibit increased contact area, enhanced self-centering, and improved repeatability.

Stabilizing the buckling instabilities of soft cylindrical shell grippers

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Abstract

Soft cylindrical shell grippers consist of a rigid outer shell and a soft inner layer that inflates inward under internal pressure. This inflatable ring actuator mechanism enables the gripper to conform to and stably grasp objects, offering unique advantages in handling irregular shapes and compliant materials, and making these grippers promising candidates for soft robotic manipulation. However, upon inflation, their soft inner walls often undergo a sequence of buckling instabilities—from wrinkling to creasing and more complex post-buckling behaviors. Due to the stochastic nature of these buckling instabilities, the resulting deformation patterns—such as the number, positions, and deflections of creases—vary unpredictably, leading to inconsistencies in gripper performance. This study investigates the factors governing the buckling instabilities of soft cylindrical shell grippers and proposes strategies for their stabilization. Through theoretical analysis and finite element (FE) simulations, we establish the relationship between geometric parameters and the predicted buckling instabilities. To control the instability morphology, we introduce evenly distributed geometric imperfections and implement a material *training* process to mitigate non-uniform deformation by leveraging the Mullins effect. We demonstrate that these combined strategies significantly improve grasping performance, including increased contact area, enhanced self-centering, and improved repeatability. Finally, we validate the gripper’s effectiveness in real-world scenarios through on-arm pick-and-place experiments. This work provides a framework for designing soft cylindrical shell

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grippers with greater reliability, while maintaining simplicity in fabrication.

Keywords: gripper, soft robot, cylindrical shell, instability, buckling

1. Introduction

Soft shells, often in a cylindrical form, are ubiquitous in both nature and the field of engineering, from biological tissue like intestines [1], to storage tanks and vessels [2, 3]. Soft shells are prone to buckling instabilities [4, 5] such as wrinkling [6, 7], folding [8, 9], creasing [10], ridging [11], and crumpling [12], under external loads due to their low thickness and stiffness [13]. The morphology of these buckling instabilities largely depends on the imperfections of the soft shells [14, 15, 16], and are thus random and hard to control. Although the mechanics of buckling instabilities have been widely studied, comparatively less is known about how to control and stabilize these instability patterns.

Soft robots, compared to traditional rigid robots, offer greater flexibility, safety, and environmental adaptability by virtue of their ability to conform to objects and the surrounding environment [17, 18, 19]. As one of the major contributions of soft robotics, soft robotic grippers have opened up many new applications [20, 21]. They are capable of handling objects with complex geometries, require less precise control, exert larger driving forces, and ensure safe interactions with humans [22, 23].

Soft cylindrical shell grippers stand out with their simplicity in design and grasping capability, the latter of which arises from their enveloping grasping mechanism [24, 25, 26]. These grippers typically consist of a rigid outer shell that forms the main body and an inner soft layer that inflates or deflates according to internal pressure (Figure 1A). Upon inflation, the inner layer expands, reducing the gripper’s inner diameter and generating an enveloping force to grasp objects.

A major challenge with soft cylindrical shell grippers is the emergence of unpredictable buckling instabilities, which are largely induced by imperfections introduced during fabrication, such as uneven material distribution, cracks, and geometric irregularities. The buckling instabilities typically evolve from wrinkling to creasing—the dominant instability in grasping—and eventually to more complex post-buckling morphologies as pressure increases (Figure 4D). The randomness of imperfections introduces uneven instability

patterns and directly compromises the predictability and consistency of grippers.

A common approach to mitigate these buckling instabilities is to divide the uniform air chamber into multiple smaller chambers [27, 28, 29]. While this reduces creasing behavior by decoupling circumferential deformation, it also decreases contact area and grasping force, especially for objects with larger *grasping diameters*, i.e. the diameter of the minimum circumscribed circle encompassing the object’s contour. Additionally, introducing more air chambers complicates the pneumatic circuit and control system while amplifying fabrication and assembly challenges, leading to higher probability of defects. Therefore, an effective approach should maintain the integrity of a uniform air chamber while addressing the instability issue.

In this paper, we investigate the factors that influence the buckling instabilities of soft cylindrical shell grippers and propose strategies to achieve a controlled buckling pattern while preserving a uniform air chamber. We characterize the buckling pattern based on three parameters: the number of “creases” (i.e., meridional lines corresponding to local minima of radial deflection that may potentially evolve into true creases at higher pressures. Throughout this work, we use the term *crease* in this generalized sense unless otherwise specified.), the relative position of creases, and the maximum deflection of each *petal* between adjacent creases. First, we analyze how geometric parameters influence the theoretical mode number (i.e., the theoretical number of creases) m_{th} through analytical and FE methods. Subsequently, we examine how the number of intentionally-introduced evenly-distributed geometric imperfections N affects the actual mode number m_{a} and the positioning of the creases, allowing for rational tuning of these instability parameters. Finally, we implement a material *training* process to stabilize the maximum deflection of each *petal* and compare the performance of stabilized and unstabilized grippers. Our results demonstrate that by rationally introducing geometric imperfections and applying material *training*, the buckling instabilities of soft cylindrical shell grippers can be stabilized—yielding tunable buckling patterns, increased contact area, and improved self-centering compared to untreated grippers.

2. Theoretical instability patterns

In this section, we present a theoretical study of the buckling instabilities of untreated soft cylindrical shell grippers, conducted through both analytical

and FE simulations. We can determine how the theoretical mode number m_{th} varies with changes in the geometric parameters of the grippers. These results establish a baseline for the following intentional introduction of imperfections to the grippers.

2.1. Analytical solutions

We model the soft inner wall of the soft cylindrical shell gripper as a cylindrical shell of height h , wall thickness w , and radius R , which is simply supported at both ends and subjected to uniform external pressure p (Figure 1A). The critical pressure p_{cr} is defined as the lowest pressure at which the axisymmetric form loses its stability (Figure 1D). We first assume that the cylindrical shell is thin-walled, made of homogeneous, incompressible, linear elastic material that obeys Hooke's law and has a Poisson's ratio of $\nu = 0.5$. We also assume that the shell has perfect cylindrical surfaces and is loaded concentrically at every cross-section. We define the origin of the coordinates in the middle surface of the shell, with the X , Y , Z axes along the longitudinal, circumferential, and radial directions, respectively. u , v , and s represent the shell displacements in X , Y , and Z axes respectively (Figure 1B, C).

With the bending in the X and Y directions neglected, the equilibrium equation in the X and Y directions can be simplified as [30]:

$$\frac{\partial N_x}{\partial x} + \frac{\partial N_{yx}}{\partial y} = 0 \quad (1)$$

$$\frac{\partial N_y}{\partial y} + \frac{\partial N_{xy}}{\partial x} = 0 \quad (2)$$

In Equation 1 and 2, N_x and N_y are the in-plane normal forces in unit shell element, while N_{xy} and N_{yx} are the in-plane shear forces in unit shell element (Figure 1B). While equilibrium in the Z direction takes the form of:

$$\frac{N_y}{R} + \left(N_x \frac{\partial^2 s}{\partial x^2} + N_y \frac{\partial^2 s}{\partial y^2} + 2N_{xy} \frac{\partial^2 s}{\partial x \partial y} \right) + \left(\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} \right) + p = 0 \quad (3)$$

where N_y/R represents the projection of N_y in the Z direction due to the initial curvature R of the cylindrical shell. $\left(N_x \frac{\partial^2 s}{\partial x^2} + N_y \frac{\partial^2 s}{\partial y^2} + 2N_{xy} \frac{\partial^2 s}{\partial x \partial y} \right)$ represents the projection of in-plane forces in the Z direction induced by

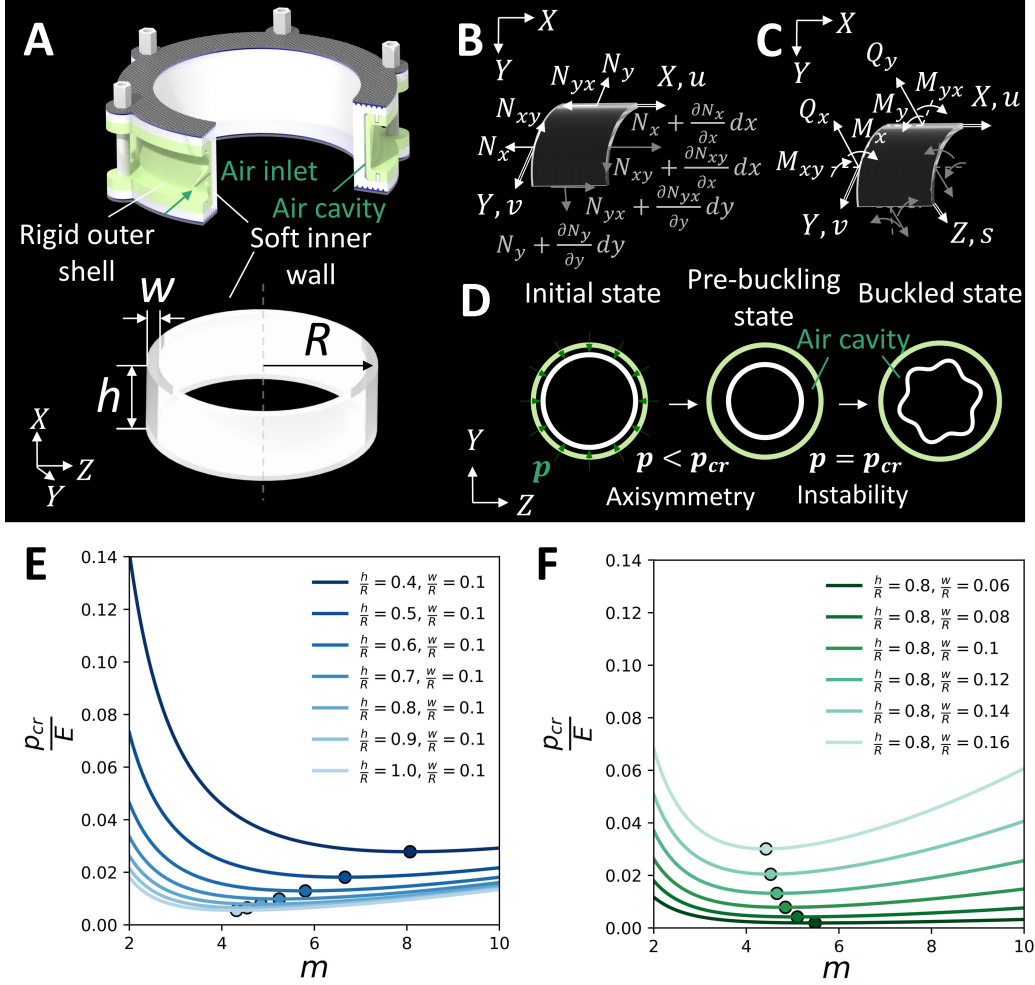


Figure 1: **Modeling and theoretical analysis of buckling instabilities in soft cylindrical shell grippers.** (A) Schematics of a typical soft cylindrical shell gripper and modeling of soft inner wall of the gripper. (B) In-plane forces in a unit cylindrical shell element. (C) Transverse shears, bending moments, and twisting moments in a unit cylindrical shell element. (D) Evolution of morphology of the cylindrical shell gripper during pressurization. i) the initial state before applying pressure, ii) the pre-buckling state after applying pressure, and iii) the buckled state when applied pressure reaches its critical value. (E, F) Variation of normalized critical pressure p_{cr}/E with respect to circumferential mode number m with different geometric parameters. The solid dot represents the lowest point of the curve, corresponding to m_{th} .

the Z -direction deflection of the pressurized shell. p , Q_x , and Q_y , are the applied pressure and transverse shear forces in Z direction and in the surfaces perpendicular to the X and Y axis respectively (Figure 1D).

The moment equilibrium equations in the X and Y directions are given by [30]:

$$\frac{\partial^2 M_{xy}}{\partial x \partial y} - \frac{\partial^2 M_y}{\partial y^2} + \frac{\partial Q_y}{\partial y} = 0 \quad (4)$$

$$\frac{\partial^2 M_{yx}}{\partial x \partial y} + \frac{\partial^2 M_x}{\partial x^2} - \frac{\partial Q_x}{\partial x} = 0 \quad (5)$$

Here, M_x and M_y are the bending moments per unit length acting on the lateral sides of the element parallel to the Y and X axes respectively, while M_{xy} and M_{yx} are the twisting moments per unit length on the lateral sides of the moments (Figure 1C).

By introducing the *flexural rigidity* $D = \frac{Ew^3}{12(1-\nu^2)}$, the moment-curvature relations the X and Y directions can be expressed as:

$$M_x = -D \left(\frac{\partial^2 s}{\partial x^2} + \nu \frac{\partial^2 s}{\partial y^2} \right) \quad (6)$$

$$M_y = -D \left(\frac{\partial^2 s}{\partial y^2} + \nu \frac{\partial^2 s}{\partial x^2} \right) \quad (7)$$

$$M_{xy} = -M_{yx} = D(1 - \nu) \frac{\partial^2 s}{\partial x \partial y} \quad (8)$$

By substituting Equation 4, 5, and 8 into Equation 3, we will get the relation between the derivatives of s , internal forces N , and exerted pressure p :

$$D \left(\frac{\partial^4 s}{\partial x^4} + 2 \frac{\partial^4 s}{\partial x^2 \partial y^2} + \frac{\partial^4 s}{\partial y^4} \right) - N_x \frac{\partial^2 s}{\partial x^2} - 2N_{xy} \frac{\partial^2 s}{\partial x \partial y} - N_y \left(\frac{\partial^2 s}{\partial y^2} + \frac{1}{R} \right) - p = 0 \quad (9)$$

According to the *adjacent equilibrium criterion* [30], the total displacements and strains at any point in the cylindrical shell when buckling occurs can be divided into two parts: the axisymmetric middle surface pre-buckling part with subscript 0 and the bifurcation part with subscript b (Figure 1D).

$$u = u_0 + u_b \quad (10)$$

$$\varepsilon_x = \varepsilon_{x0} + \varepsilon_{xb} \quad (11)$$

Similar to displacements and strains, other physical quantities before and after the transient moment of buckling, including stresses, forces, and moments, are adjacent equilibrium configurations with no increment in the applied pressure p (see Supplementary Materials for details).

By substituting constitutive and kinematic relations, and neglecting the pre-buckling rotations $\partial s_0/\partial x$ and $\partial s_0/\partial y$, we can decouple (u_b, v_b, s_b) and have:

$$D\nabla^8 s_b + \frac{Ew}{R^2} \frac{\partial^4 s_b}{\partial x^4} + pR\nabla^4 \frac{\partial^2 s_b}{\partial y^2} = 0 \quad (12)$$

the boundary conditions at the ends of the cylindrical shell (at $x = 0$ and $x = L$) can be represented as:

$$s_b = 0, \frac{\partial^2 s_b}{\partial x^2} = 0 \quad (13)$$

When the cylindrical shell loses stability, the radial displacement field s_b is postulated as a harmonic function spanning both axial (x) and circumferential (y) directions. Such a kinematic ansatz inherently satisfies the governing equations and prescribed boundary constraints. At the very moment when the cylindrical shell loses stability, the pressure exerted on the shell stays the same at p_{cr} while the axisymmetric radial displacement s_b collapses into the form of:

$$s_b = A \sin\left(\frac{m\pi y}{\pi R}\right) \sin\left(\frac{n\pi x}{h}\right) \quad (14)$$

where m and n represent the mode number along radial and axial directions respectively, and A represents the amplitude (Figure 1D). According to Brush and Almroth [31], in order to minimize the external critical pressure p_{cr} , the secondary equilibrium path will have one half sine wave in the axial direction, i.e. $n = 1$. By substituting the derivatives of s for x and y , we obtain:

$$\frac{p_{cr}}{E} = \left(\frac{w}{R}\right)^3 \cdot \frac{\left(\pi^2 + \left(\frac{h}{R}\right)^2 m^2\right)^2}{12(1 - \nu^2) \left(\frac{h}{R}\right)^4 m^2} + \left(\frac{w}{R}\right) \cdot \frac{\pi^4}{n^2 \left(\pi^2 + \left(\frac{h}{R}\right)^2 m^2\right)^2} \quad (15)$$

To determine the theoretical mode number m_{th} of a given set of geometric parameters $(h/R, w/R)$, we must identify the mode number m that minimizes the critical pressure p_{cr} . As air is pumped into the cylindrical shell gripper, the pressure exerted on the inner wall gradually increases. When the pressure reaches the minimum critical pressure, $(p_{cr})_{min}$, the cylindrical

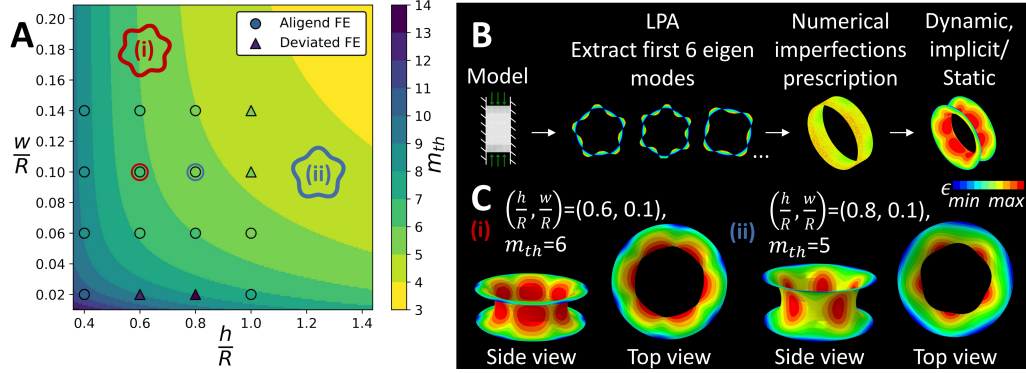


Figure 2: **Simulation of theoretical mode number m_{th} .** (A) Comparison of simulated theoretical mode numbers m_{th} with predictions from the analytical model. The simulated results are represented as scattered points overlaid on the analytical heatmap, where the color bar indicates the rounded theoretical mode number. (B) Overview of the numerical simulation methodology. (C) FE snapshots of two cylindrical shell geometries. Color bar represents the maximum in-plane principal strain.

shell loses stability and collapses into a buckling mode m_{th} corresponding to $(p_{cr})_{min}$ (Figure 1D). Since the material properties are assumed invariant with geometry and applied pressure, minimizing p_{cr}/E (i.e. the normalized critical pressure) is equivalent to minimizing p_{cr} . Using Equation 15, we calculated p_{cr}/E as a function of m for various $(h/R, w/R)$, as shown in Figure 1D, E. The minima of these curves correspond to the theoretical mode number m_{th} for the respective geometric parameters. Consistent with classical findings [2] and empirical conclusions [32] (see Supplementary Materials for details), m_{th} decreases considerably with h/R and marginally with w/R . The complete mapping of m_{th} as a function of $(h/R, w/R)$ is presented in Figure 2A, where theoretical mode numbers m_{th} are rounded to the nearest integer.

2.2. FE simulations

Simultaneously, to investigate the influence of gripper geometry on mode numbers, we simulate the buckling instabilities of cylindrical shell grippers by performing FEM in the commercial software Abaqus 6.13 (SIMULIA, Providence, RI). In the simulations, the grippers are simplified as hyperelastic cylindrical shells fixed at the top and bottom surfaces and subjected to uniform pressure applied to the outer cylindrical surface (Figure 2B). Considering that all grippers in this study are fabricated from silicone elastomer (Smooth-On Ecoflex 00-30), we adopt an incompressible neo-Hookean ma-

terial model based on experimental data. The geometry is discretized using tetrahedral (TET) shell elements, and a linear perturbation analysis (LPA) is performed to obtain the eigenvalues (critical pressure p_{cr}) and eigenmodes (buckling modes corresponding to the respective p_{cr}). To ensure numerical stability, the first six eigenmodes are extracted and imposed as numerical imperfections on the cylindrical shell before applying pressure. It is important to note that these imperfections are artificial constructs introduced to stabilize the numerical process rather than physical imperfections observed in experiments. They do not directly correspond to the theoretical mode number m_{th} derived from analytical analysis. Without these imposed imperfections, the numerical algorithm may yield unrealistic results due to inherent limitations in the computation process. Subsequently, nonlinear static or dynamic implicit simulations are carried out to simulate the inflation process under uniform pressure (Figure 2B).

In Figure 2C, we present FE snapshots of two shells during inflation. The results demonstrate strong qualitative agreement between analytical predictions and simulations, with both shells buckling into the theoretical mode predicted by the analytical model. To further validate this approach, we simulated additional geometries ($h/R, w/R$) and compared the theoretical mode m_{th} obtained from simulations with the analytical predictions (see Supplementary Materials for details). As shown in Figure 2A, 3/4 of the simulated mode numbers align perfectly with the analytical predictions, and 7/8 of simulated values deviate by at most one mode number from the analytical results. This level of agreement is particularly noteworthy, as the analytical model is primarily designed for slender cylindrical shells with a *non-dimensional Batdorf parameter* ζ typically on the order of 10^2 to 10^4 , whereas the shells in our study have ζ ranging from 1 to 50 [33]. Despite the discrepancy, the simulation results confirm that the analytical model can provide a rapid and reasonably accurate estimation of the theoretical mode number. This approximation is sufficient for use as guideline in the design and application of soft cylindrical shell grippers in our study.

3. Tunable buckling patterns through imperfections

In the previous section, the theoretical mode number m_{th} of soft cylindrical shell grippers without imperfections was explored. However, imperfections can significantly impact the buckling pattern [14], and numerous imperfections are inevitably introduced during the synthesis of elastomers

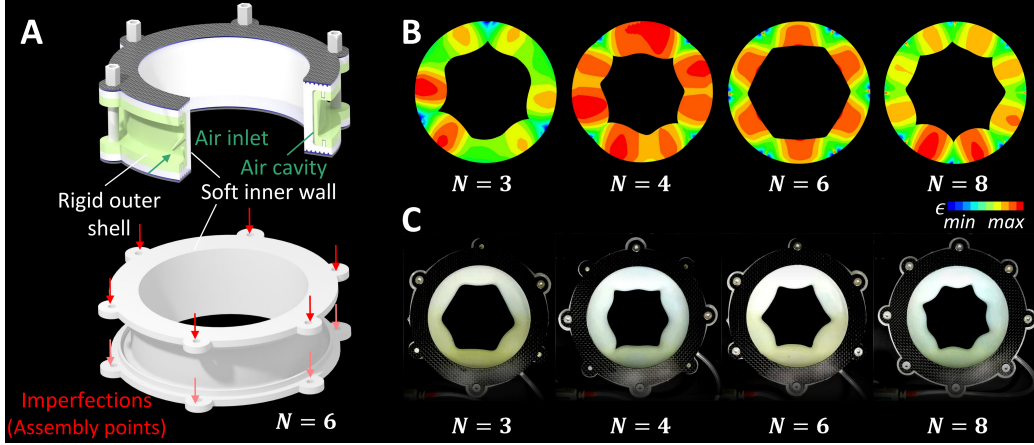


Figure 3: **Buckling instabilities in soft cylindrical shell grippers with imperfections.** (A) Schematics of a typical soft cylindrical shell gripper and its soft inner wall with imperfections. (B,C) FE and experimental snapshots of grippers with $N = 3, 4, 6, 8$ imperfections. Scale bar, 2 cm.

and the assembly of the soft-rigid-hybrid grippers. Among all the assembling methods to fix the soft inner wall and rigid outer wall, the use of mounting screws is the simplest. Therefore, in this section, we primarily investigate the impact of geometric imperfections introduced by the assembly points of the mounting screws on the buckling pattern of the grippers (Figure 3A). By understanding how geometric imperfections affect the buckling pattern, it becomes possible to intentionally introduce controlled imperfections to achieve tunable mode numbers and precise positioning of creases.

3.1. FE simulations

We first perform FE simulations to study the impact of introduced imperfections on the buckling pattern and understand the underlying physics. We characterize imperfections by the number of assembly points N , and the actual buckling pattern of the gripper by the actual mode number m_a . Geometric imperfections were represented by prescribing displacements at the assembly points to simulate the loading of the mounting screws. The inflating process was simulated similarly to the simulation of m_{th} by applying uniform pressure to the wall of the cylindrical shell.

To ensure the accuracy of the analytical model's prediction for m_{th} , we considered a gripper geometry with $(h/R, w/R) = (0.6, 0.1)$ ($\zeta = 3.1$), for which the analytical and FE predictions both yield $m_{th} = 6$.

3.2. Experimental results

Grippers with this geometry were fabricated to experimentally investigate the effects of imperfections on their buckling behaviors. Silicone elastomer Ecoflex 00-30 is molded into a soft cylindrical-shell-shaped inner wall, and mounted through screws with a 3D-printed rigid outer wall, two carbon fiber plates, two layers of holdings spikes, and pneumatic circuits (Figure 1A). The dimensions of the grippers are taken as $R = 100$ mm, $w = 5$ mm, $h = 30$ mm, resulting in a normalized geometry of $(h/R, w/R) = (0.6, 0.1)$. Quasi-static loading was applied by slowly inflating the grippers through an air pump, and a camera was used to capture the buckling behavior during the inflation process.

Figure 3 B,C present snapshots from FE simulations and experiments of soft cylindrical shell grippers with $N = 3, 4, 6, 8$ assembly points. We observed good agreement between simulations and experiments, with all four cases showing similar buckling morphologies. For $N = 3, 4, 6, 8$, the actual mode numbers were $m_a = 6, 4, 6, 8$, indicating that the actual mode number, m_a , is influenced by both m_{th} and N . Our results suggest that when N is close to m_{th} , N dominates and precisely controls m_a , enabling highly tunable instability morphologies. Conversely, when there is a larger disparity between N and m_{th} , the influence of N diminishes, and m_{th} becomes the dominant factor, which is exemplified in the $N = 3$ case.

4. Stabilization of maximum deflection

While the number of creases can be reinforced through the addition of imperfections as described above, the size of each *petal* may not always be evenly distributed. This is due to the irregular formation of polymer chains during the manufacturing process as the silicone is cured, resulting in some regions of the soft material being stiffer than others. This phenomenon also causes certain areas of the soft layer to inflate and stretch more than others (Figure 4A). This is compounded by *Mullins effect*, where increased loading results in the stress softening of rubbers [34]. The instantaneous and irreversible softening of the material occurs whenever the load increases beyond its prior all-time maximum value [35, 36, 37]. This was observed in the inflation tests of the soft grippers, where the *petals* which are ‘bigger’ (undergo larger strain) grow increasingly large with further inflation while the other un-stretched *petals* do not inflate to the same degree. This uneven-ness in deformation is undesirable as it leads to asymmetry of the gripper and might

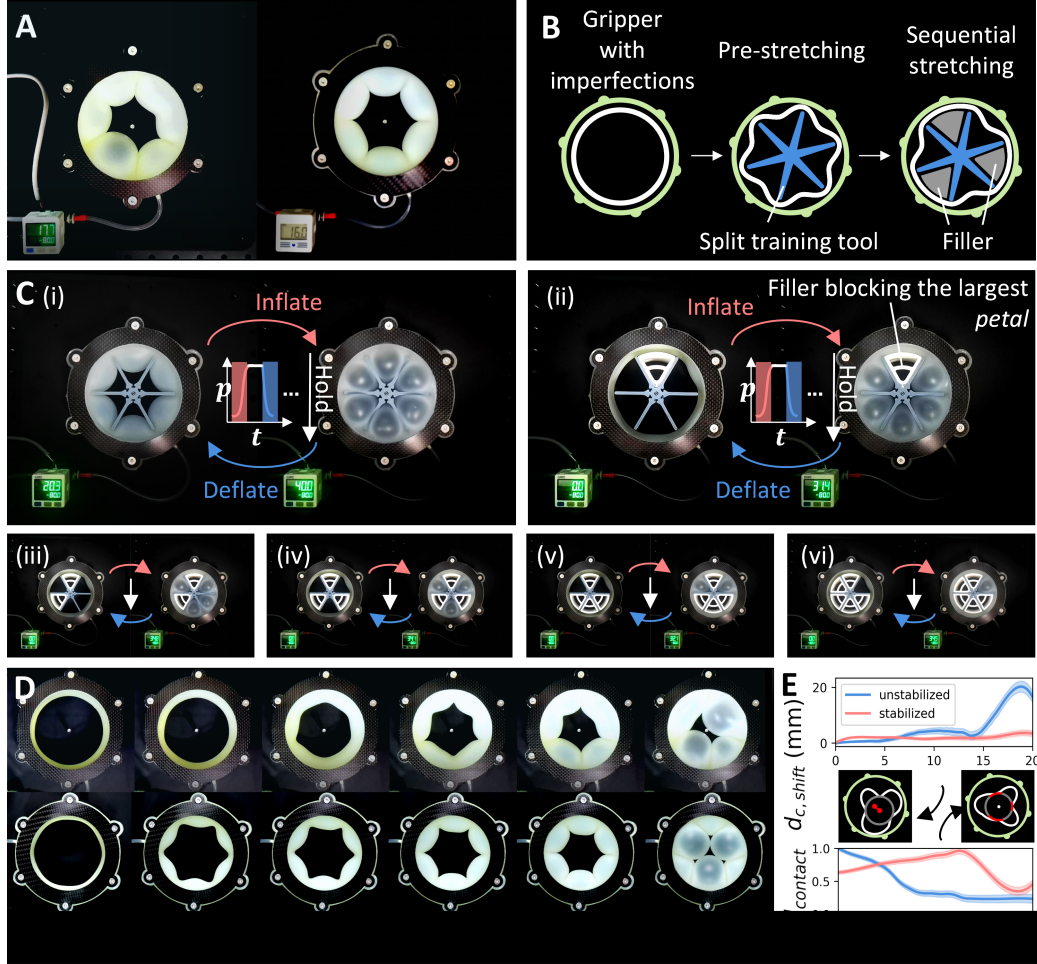


Figure 4: **Stabilization of maximum deflection.** (A) Experimental snapshots comparing grippers without and with maximum deflection stabilization. Scale bar, 2 cm. (B) Schematics of the stabilization process. (C) Experimental snapshots of stabilization procedure: (i) pre-stretching of the gripper, followed by (ii)–(vi) sequential stretching of individual *petals* to equalize their maximum deflection. Scale bars, 2 cm. (D) Deformation of an unstabilized and a stabilized soft gripper during the inflation process. Scale bar, 2 cm. (E) Grasping-center shift and contact-area percentage of unstabilized and stabilized grippers during inflation. The middle schematics illustrate how these quantities are computed. The red line segment on the left connects the inner and outer grasping centers, C_{inner} and C_{outer} (shown as magnified red dots). The red arc on the right represents the portion of the inscribed circle that is in contact with the soft inner wall, which is used to quantify the contact-area percentage.

result in a poorer grasping position as the contact area between the payload and gripper is not maximized or may result in the payload being carried in an off-center position. As such, it is a challenge to create a gripper where the buckling is even and symmetric in a consistent manner.

In order to overcome this problem, we propose a pre-stretching procedure to *train* the gripper so that it creases and inflates evenly and consistently. This is done using a 3D-printed split training tool that divides the internal gripper area evenly into six segments as shown in Figure 4B. When attached to a fixed mount at the center of the gripper, the six points of the split training tool enforce minimum deformation points on the gripper. Removable filler pieces were also created as shown in Figure 4B to block out segments as needed.

The pre-stretching process was first performed to a newly manufactured virgin gripper using the split training tool placed on a fixed mount in the center of the gripper without filler pieces as shown in Figure 4C (i). The gripper was then put through an inflation, hold, deflation cycle repeatedly with the split training tool in place. This ensures that the minimum deflection point on the gripper is *trained* into the material as the points which never undergo large strains will remain stiffer than the other parts of the gripper. Through this process, the position and circumferential size of each segment can be made consistent.

However, the rate at which each segment inflates, i.e., the stiffness of the material at the maximum deformation point of each segment, is still not guaranteed to be the same for each segment. The next step is then to stretch the maximum deformation point of each segment so that every point undergoes the same maximum loading in the pre-stretching phase. This is achieved by using the filler pieces to block out segments which are softer and hence have the tendency to undergo larger strain, forcing the other segments to be stretched to the same degree. This process is shown in Figure 4 (ii) - (vi), where the filler pieces are incrementally added until only the stiffest segment is not restricted. The gripper then undergoes repeated inflation, hold, and deflation cycles to complete the pre-stretching process. The results of the pre-stretched gripper is shown in Figure 4A,D.

The stabilization of the gripper through the utilization of the Mullins effect is highly effective. In addition to ensuring uniform deformation, it can further regulate the post-buckling behavior observed at 20 kPa and higher (Figure 4D).

5. Gripper performance characterization

While the previous sections focused on stabilizing the deformation patterns of soft cylindrical shell grippers, we now evaluate how these strategies influence their practical grasping performance. To this end, we conduct both controlled bench-top experiments and on-arm pick-and-place tests using a set of representative objects. To quantify grasping performance, we define two key metrics: *grasping center shift* $d_{c,shift}$ and *contact area percentage* $\%l_{contact}$.

The *grasping center shift* $d_{c,shift}$ quantifies the deviation between the center of the inscribed circle of the deformed soft inner wall $\mathbf{C}_{inner}$ and the center of the rigid outer shell $\mathbf{C}_{outer}$, i.e. $d_{c,shift} = \|\mathbf{C}_{inner} - \mathbf{C}_{outer}\|$. This metric reflects the extent to which an object is grasped at the intended center location of a gripper. Since control strategies typically assume that objects are symmetrically grasped at the center of the gripper’s outer shell, reducing this offset is essential for minimizing the sim-to-real gap in robotic applications.

Meanwhile, the *contact area percentage* $\%l_{contact}$ quantifies the fraction of the inscribed circle’s perimeter in contact with the soft inner wall, indicating grasping stability. Under uniform internal pressure, the grasping force follows $F_{grasp} = p \cdot A_{contact} = p \cdot A \cdot \%l_{contact}$, where A is the object’s surface area. A higher *contact area percentage* corresponds to a stronger grasp under the same pressure.

To extract these metrics, we analyzed video recordings of the gripper’s inflation process, using image processing to track the deformed soft inner wall and compute its inscribed circle. Contact points were identified by measuring the distance between points on the soft inner wall and the inscribed circle, with those within a predefined threshold classified as in contact. The proportion of these points along the circumference was used to calculate the *contact area percentage* $\%l_{contact}$.

As shown in Figure 4E, the stabilized gripper outperforms the unstabilized gripper in both metrics, demonstrating that controlled imperfections and material training not only enhance stability and predictability but also significantly improve grasping performance. At lower pressures, the unstabilized gripper performs slightly better, likely due to local modulus modifications from the material *training* process, which cause an earlier onset of certain buckling instabilities. However, overall, the stabilized gripper exhibits superior controllability and reliability, making it a more robust and effective design choice.

To further assess gripper performance, we evaluated its *self-centering effect*—an ability related to the previously discussed *grasping center shift* $d_{c,shift}$. As the gripper inflates inward from all directions, it naturally pushes the payload toward its center. Since the object is not always initially centered, this behavior improves tolerance to initial misalignment between the payload and the center of the gripper. We quantified self-centering by measuring the distance d_c between the payload’s center and the rigid outer shell $\mathbf{C}_{outer}$. Ideally, $d_c = 0$ indicates perfect centering during grasping. The experiments were conducted with 3D-printed objects of various shapes (circle, square, equilateral triangle) and sizes. Each object was initially placed near the inner wall—i.e., in an off-center position—before gripper inflation. After the gripper was fully inflated and closed in on the object, we recorded the final position of the object to quantify the *self-centering effect*.

Figure 5A shows experimental snapshots of the initial and final states, illustrating how off-center objects are pushed inward. Video tracking was used to compute the normalized distance d_c/R , with results averaged over five trials per object (Figure 5B). All tested objects achieved $d_c/R < 0.25$ in final states, with $d_c/R < 0.1$ when the characteristic length was no less than 4 cm. Larger objects exhibited stronger self-centering due to more uniform contact. In contrast, smaller ones were susceptible to asymmetries induced by post-buckling behaviors, which could cause the *petals* to deform and push the object unevenly, leading to less centered final positions. Among different shapes, triangles showed larger d_c/R , as their acute angles tended to "lock into" the gripper’s creases and resist further inward movement.

To experimentally evaluate the grasping capabilities of the stabilized grippers, we mounted a stabilized gripper on a robotic arm (UR3, Universal Robots) and conducted pick-and-place tests using a diverse set of objects with varying shapes and sizes (Figure 5D). The test procedure is illustrated in Figure 5C. Throughout all trials, the gripper successfully maintained stable grasps on the objects during manipulation (see Supplementary Movie S1). Photographs captured at the demonstration pose of each pick-and-place sequence (Figure 5E, Supplementary Materials) show that the gripper consistently achieves centralized, stable grasps across pre-buckling, buckled, and post-buckling states. This reliable performance is enabled by the gripper’s evenly distributed and symmetric morphology during deformation, resulting from the stabilization of both fold number and position, as well as the maximum deflection of each *petal*. These results highlight the critical role of stabilization of buckling instabilities in cylindrical shell grippers.

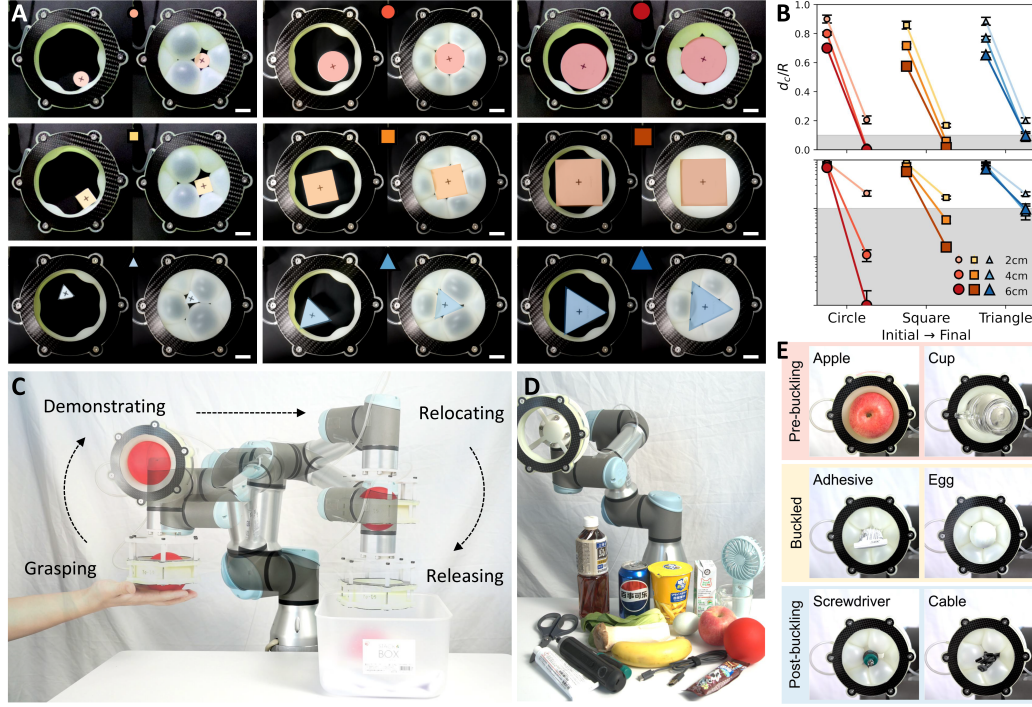


Figure 5: **Performance of stabilized grippers.** (A) Snapshots of initial and final states in *self-centering* experiments. Colored masks represent objects of various shapes and sizes identified via video analysis. Each object is labeled with a corresponding marker, whose shape and size match the cross-section and characteristic length of the object. Scale bar, 2 cm. (B) Normalized distance from center d_c/R for the initial and final states of objects with different shapes and sizes. To better visualize the final-state differences, a semi-log plot is shown below the linear plot. The gray shaded areas highlight the region where $d_c/R \leq 0.1$. The legend denotes the characteristic length of each object (i.e., diameter for circles, side length for squares and equilateral triangles). (C) Composite image showing four sequential steps—grasping, demonstrating, relocating, and releasing—captured during an on-arm test with a red sphere as example. The demonstration pose reorients the gripper for better visualization of its morphology. (D) Test objects used in grasping experiments, alongside the gripper in demonstration pose (without object) mounted on the robotic arm. (E) Snapshots of the gripper morphology with the gripper grasping various objects in the demonstration pose across pre-buckling, buckled, and post-buckling states.

6. Conclusions

In this study, we analyzed and stabilized the buckling instabilities of soft cylindrical shell grippers to enhance their predictability and performance. A theoretical model was developed to predict instability patterns based on geometric parameters, and its predictions were validated by FE simulations.

By introducing evenly distributed imperfections and applying a material *training* process leveraging the Mullins effect, we achieved tunable and uniform buckling patterns, resulting in more consistent deformation and improved gripper performance.

Experimental results confirmed that these strategies significantly enhanced grasping performance, self-centering capability, and grasping robustness across a wide range of objects. These findings contribute to the development of more robust soft robotic grippers, enabling better control over their mechanical response and broadening their practical applications.

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