Biomechanics

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Bio-inspired adaptive grasper by chiral wrinkling

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The modeling of non-linear morphological changes in biological systems is a challenging task. Motivated by the observation of exotic pattern formation processes on fruit surfaces, a chiral wrinkling topology is disclosed as a mechanical structural instability, which is then exploited for the design of enhanced adaptive graspers.

Physical processes encompassing growth, phase transition, and in general mechanical and non-mechanical loadings drive the deformation in solids and may even modify their morphology. Everything in the real world takes a form that minimizes the potential energy through laws of physics and chemistry. Examples are therefore present across different scales in nature, such as cells, seashells, skeletons, organs, fruits, and vegetables, but also in manufacturing at the microstructural level of metals and alloys, as well as metamaterials. Morphogenesis is a research field with the main objective to understand why a shape is generated. Although Aristotle initiated the field of morphology with taxonomic purposes two thousand years ago, a technical approach has only been addressed for the first time by Johann Wolfgang von Goethe (1749–1832) and by Bertrand Russell (1872–1970). The structuralism of Goethe and the functionalism of Russel set the background for the work by D'Arcy Wentworth Thompson (1860–1948) collected in his celebrated book *On Growth and Form*[1]. Since then, remarkable advances within this field have been made in the last century through the effort of mathematicians, physicists, biologists, chemists, and engineers, establishing a well-consolidated framework involving approaches from different research fields and capable of providing a scientific explanation about why objects display a specific shape[2]. Many secrets of nature to realize special shapes have been unveiled so far, including, for example, the spiral geometry taken by turritella shells, antelope horns, and nipponite shells. However, given the highly non-linear nature and multidisciplinary character, complex morphology evolutions require new models to be introduced and, more importantly, to be employed for an accurate control of morphology change for new bioengineering strategies. In this issue of *Nature Computational Science*, Fan Xu and colleagues[3] propose a mechanical model to reveal, via structural stability, a chiral surface morphology on spherical objects when subject to a spherically symmetric input, as observed on dehydrated passion fruits. The proposed model not only explains this morphology change, but also enables the design of adaptive graspers inspired by this interesting chiral wrinkling topology.

Structural stability is a subject where stability concepts from mathematics and rational mechanics are applied to structures with the aim of understanding whether an equilibrium state, and its related morphology, is stable. A symmetric morphology may change from being stable to unstable with an increasing symmetric input, which drives the system to a non-symmetric morphology state after energy minimization. Such symmetry breaking is ubiquitous, being possible to appear in all of the types of structural elements (rods, plates, and shells) due to the activation of flexural deformations when a critical value of mechanical input is attained. Euler buckling, appearing in elastic rods subject to external compressive forces, is basic evidence of symmetry breaking: the buckled state of the rod does not display the same symmetries featured by the applied loading. The definition of the critical condition and of the following post-critical response represent the main challenge in the stability analysis of structures towards the disclosure of unexpected behaviors. Indeed, although simple in its appearance, spherical shells under pressure display a complex non-linear post-buckling response with a high sensitivity to imperfections[4–6].

Within the framework of stability analysis, inspired by observations on dehydrated passion fruit, Xu and colleagues investigated the morphology changes of core-shell spheres under shrinking. They found that the first post-bifurcation path, along which a sphere displays a

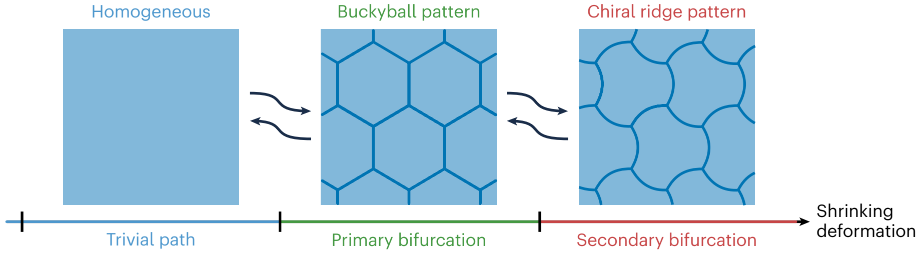

Fig. 1 | Sketch of the surface morphology evolution for an elastic core-shell sphere at increasing levels of shrinking deformation. The homogeneous deformation becomes unstable when the first critical deformation is reached and a buckyball pattern (evocative of the buckminsterfullerene molecule C_{60} structure) is displayed. Fan Xu and colleagues discovered that a secondary bifurcation can be attained by further increasing the deformation level applied to core-shell spheres characterized by $C_s = (E_s/E_f)(R/h_f)^{3/2}$ from 2 to 13 and along which the buckyball pattern transforms into a chiral ridge pattern. Since the process occurs elastically, the change in morphology is reversible and can be exploited in the design of devices for repetitive tasks.

buckyball pattern composed of periodic regular hexagons[7], may be followed by a secondary one, where chirality emerges through the buckling of the Y-shaped ridges along the previously realized hexagons (Fig. 1). From buckling analysis of the Y-shaped ridges modeled as bilayer plates, a scaling law was derived to define the critical shrinking deformation for the chiral bifurcation. A finite element code was then exploited to compute the post-buckling response associated with the chiral morphology. The coating shell and the core were both modeled as hyperelastic neo-Hookean materials and respectively discretized through shell and volume finite elements. Possible bifurcations with unstable equilibrium paths during the numerical integration were avoided by adopting the method of dynamic relaxation, which consists in solving an evolutive quasi-static problem within a dynamic context by considering auxiliary damping and inertial terms. The correlation between shrinking deformation and radial displacement was obtained as curves with varying dimensionless parameter $C_s = (E_s/E_f)(R/h_f)^{3/2}$, where E_s and E_f are the Young's modulus of the core and of the coating, respectively, h_f is the coating thickness, and R is the core radius. These curves display a highly non-linear response for core-shell spheres with C_s ranging from 2 to 13 and are realized through the spherical–buckyball–chiral morphology sequence in the shape evolution when increasing the shrinking deformation (Fig. 1).

Motivated by this chiral morphology, a smart adaptive gripper system was developed. This system was based on a silicon hemispherical shell having a small channel to control the internal pressure through air extraction from the cavity inside the shell. The grasping process was harnessed by fabricating on the shell surface a hexagonal pattern, similar to that in Fig. 1, which buckles into the chiral pattern when an object is in contact with the hemispherical shell. The adaptive system is realized through the simultaneous contact and air extraction from the cavity, providing a tight locking of the object within the emerging chiral pattern and allowing for a safe and smooth repositioning at its release. The grasped object can be eventually released by restoring the pressure difference, which elastically reverts the chiral pattern into the fabricated hexagonal network.

Although still limited to a purely mechanical setting, the results presented by Xu and colleagues may open new perspectives to tackle current scientific challenges in different technological fields. More precisely, the disclosed bioinspired chiral morphology and the developed theoretical tools can pave the way to new approaches in the mechanical design of shape-changing robots, soft actuators, high-performance microelectromechanical systems for energy harvesting, and flexible electronic devices. It would be of great interest to extend the present analysis to dielectric elastomers[8] towards morphology control via electromechanical coupling deformation mechanisms. The next challenge will then be to apply the present stability analysis framework to multidisciplinary problems, offering the possibility to consider a mechanical behavior coupled with an electrical field.

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Competing interests

The author declares no competing interests.