MECHANICS vs. MORPHOGENESIS

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Summary Numerous highly ordered patterns can be achieved by manipulating the self-assembled buckling of thin films on compliant substrates upon mismatched deformation. We establish the framework of elastic buckling of thin films on curved substrates, which is highly relevant to the morphology of quite a few natural and biological systems. Buckling patterns are driven by anisotropic compressive stresses in the film, and the undulation characteristics are related to the geometry and material property, which provide various ways to manipulate the undulations. It is shown that some global features of quite a few natural and biological systems, for example various fruits, vegetables, nuts, eggs, tissues, animal body parts, etc., can be reproduced by anisotropic stress-driven buckling on spheroidal film/substrate models. Furthermore, the mechanical principles can be extended to three-dimensional mechanical self-assembly and demonstrated for fabricating gear-like microstructures.

SHORT PAPER

Intriguing undulating surface morphologies are often observed in nature across a large scale. For instance, among fruits the Korean melon, ridged gourd, small pumpkin, and acorn squash have 10 equidistant longitudinal ridges; Large pumpkin has about 20 ridges; Striped cavern tomatoes and bell peppers have 4-6 ribs; Cantaloupe shows a reticular morphology which mixes ridged and latitude patterns. In nuts and dehydrated fruits the ridged or labyrinth undulations are distinctive. In the skin of large animals (e.g. elephants, rhinos) and reptiles, reticular, latitudinal, and/or ridged patterns are frequently observed; ridged patterns are also observed in the eggs of butterfly, bollworm and tobacco budworm. At the tissue scale, latitudinal undulations were found in intestines and arteries. At the cellular scale, wrinkle-like undulations were reported in human neutrophil cells, mineralized yeast cells and fish spawns, and venom infected sperm. In almost all examples above, these natural and biological systems can be modeled as spheroidal core/shell systems (some of them have derivational geometry, such as conical for wax apple, and cylindrical for elephant tail).

Despite the complex biological processes involved at deep levels [1], the distinctive yet elementary undulation features described above imply the possible existence of other relatively simple mechanisms. Buckling has been employed to explain the phyllotaxis and wrinkling of leave [2]; however, these studies were limited to the local pattern formation on a planar surface.

From a mechanics point of view, self-assembled buckling patterns of thin films on compliant substrates have been studied extensively. Various experimental works investigated the feasibility of quantitative control of the patterns for micro- or nano-fabrication [3], and theoretical efforts explored the competition between the herringbone, labyrinth, and stripe patterns, as well as the ways to control them [4]. However, most previous mechanics studies were again focused on planar substrates, and the study of buckling of closed thin films on curved substrates is scarce. The substrate curvature is not only important for the study of morphogenesis where most natural and biological systems have closed surfaces, but also critical for micro- and nano-fabrication of multilevel thin-film devices with non-planar geometries.

Among the limited previous studies on curved and closed substrates, numerical simulations were used to explore the qualitative effect of geometrical constraints of spherical [5] and spheroidal [6] substrates, respectively, on the formation of different buckling patterns. However neither quantitative nor analytical approach was pursued. Although buckling of thin shells is highly sensitive to its curvature, buckling of films bonded to curved/closed substrates is still an open area and the development of a quantitative and comprehensive mechanics framework could enrich the theory of solid mechanics, which is the main objective of this paper (via model curved film/substrate systems).

Perhaps the easiest approach of incorporating the substrate curvature effect is to introduce a uniform curvature along one direction of the initial planar substrate, and in this case the substrate becomes cylindrical. The geometry of cylindrical-like shell/core structure is often found in micro/nanowires, fibers, plant stem, animal body, as well as some tissues such as arteries and collagen fibers. When the principal curvature is uniform in all directions, the spherical substrate, which is widely observed in bubbles, brain cortex, cells, and nucleus, etc., deserves another fundamental case study. Spheroidal substrate, which may be regarded as a modification of the spherical one, is a good approximation of quite a few fruits, vegetables, eggs, etc. Finally, when the cylindrical substrate is combined with a spherical cap, a model fingertip emerges and its wrinkling pattern upon water immersion may be interesting. In this study, for each representative type of substrate, we demonstrate the interaction and coupling between the substrate curvature effect and other material and system variables, the ways to control the characteristics of buckles, as well as the potential applications and implications of these self-assembled buckling patterns on curved substrates in morphogenesis and three-dimensional fabrications.

As an illustrative example, Fig.1 shows morphogenesis of spheroidal-like natural and biological systems, where in each case, the observation (larger picture) matches reasonably with the simulation based on the spheroidal shell/core model established in this study (smaller picture).

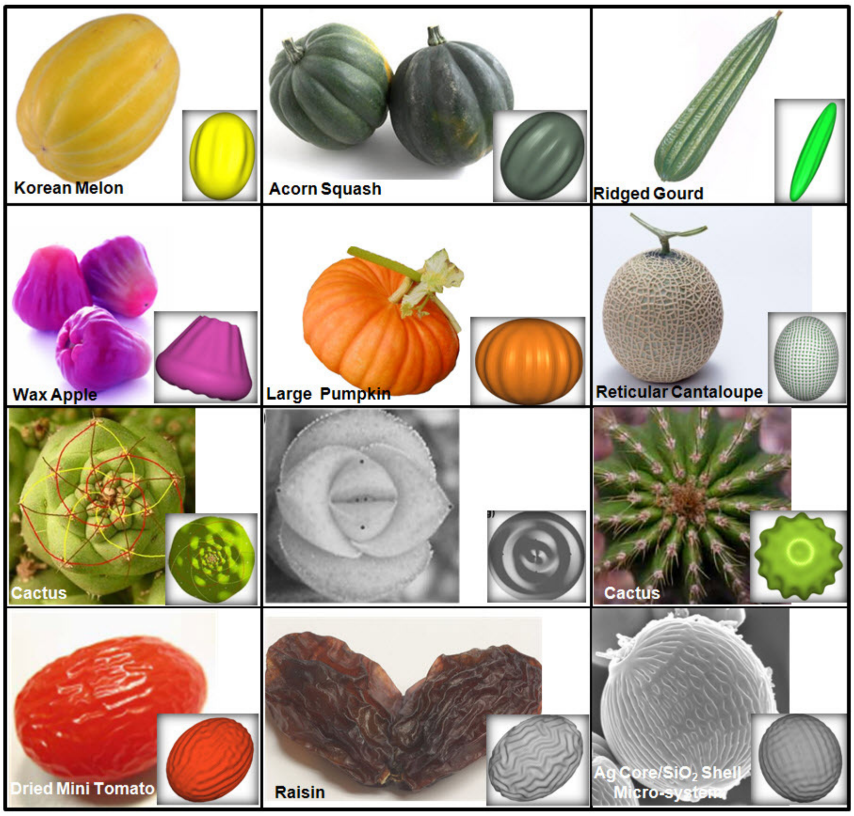

Fig.1 First row and second row: The morphologies of several fruits and vegetables, including Korean melon, acorn squash, ridged gourd, wax apple, large pumpkin, and cantaloupe, can be reproduced via the spheroidal shell/core model. Third row: plant phyllotaxis including cactus and succulent (1st and 2nd cases) can be explained using instability theory; the model of spheroidal elastic shell/foundation model may also explain the ridged pattern in cactus (3rd case). Last row: the same principles are applicable to dehydrated fruits such as dried mini tomato and raisin, as well as in 3D self-assembly application using SiO_2 film/Ag substrate.

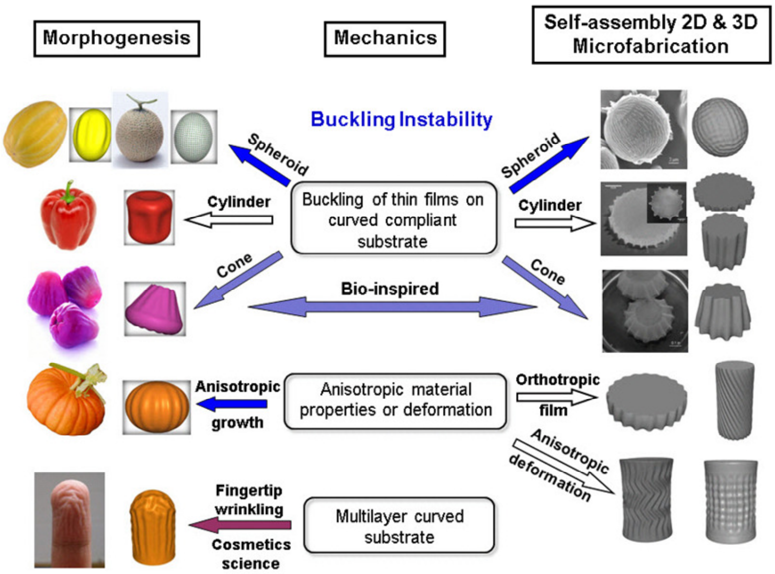

Fig.2 postulates the interactions among mechanics, morphogenesis, and fabrication. Mechanics vs. morphogenesis: Due to certain biological processes occurring at the cellular level in some systems [2] the film and substrate undergo mismatched deformation, and the resulting stress-driven buckling sets up a template for the overall system morphology. The processes of cell growth and cell differentiation may follow the mechanical template to help stabilizing the global pattern features. On the other hand, the bifurcation mode is also closely related to the effective material and geometrical properties (which are based on biological processes). Mechanics vs. fabrication: Mechanical buckling further underpins the novel technique of self-assembly fabrication of 3D microstructures, which is inherently simple, quick, and cost-effective.

References

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