Progress through Mechanics: Mechanics vs. Morphogenesis

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Over years of evolution, Mother Nature is able to produce precise, differentiable and intriguing morphologies in biological systems. The mechanisms underpinning the formation of these fascinating shapes and patterns have evoked scientists' interests for centuries. While there is no doubt that the biological and genetic factors significantly influence morphogenesis, the active role of physics and mechanics should not be underemphasized [1], as revealed by increasing recent works on the role of mechanical force in the regulation of plant morphology [2], cell growth and cell differentiation [3], and tissue morphogenesis [4], among others.

For example, self-organized mechanical instability provides promising explanation of the morphologies of some plants and tissue growth, where buckling could effectively reduces the system's strain energy during growth. The mechanical buckling principle has been employed to explain the formation of phyllotactic pattern in compressed tunica [5], primordium initiation in sunflower capitulum [6], and surface patterns during growth of anisotropic tissues [7]. Fibonacci patterns widely observed in flowering cactus and pine cones were reproduced through the mechanical buckling of spherical layered microstructures made of inorganic materials [8]. More specifically,

Morphogenesis in fruits, flowers, and leaves: Intriguing undulating surface morphologies are often observed in fruits (see Fig. 1), flowers, and the edge of leaves (see Fig. 2) during their growth. The Korean melon, ridged gourd and acorn squash distinguish themselves from others with 10 equidistant longitudinal ridges. Striped cavern tomatoes and bell peppers have 4-6 ribs, while cantaloupe shows a distinct reticular morphology. For flowers and leaves, global saddle-like shape (Fig. 2a), curled or intriguing spiral morphology (Fig. 2c-f) and local rippling margins (Fig. 2b-c) are often observed. However, they are not born with wavy or curled morphologies [9]. Some questions naturally arise: What is the driving force for the formation of ridged and reticular pattern in some fruits, curled and spiral morphologies in some leaves? What determines the fixed number of ridges in fruits? What governs the morphology transition from the global saddle-like to local wavy margins in leaves?

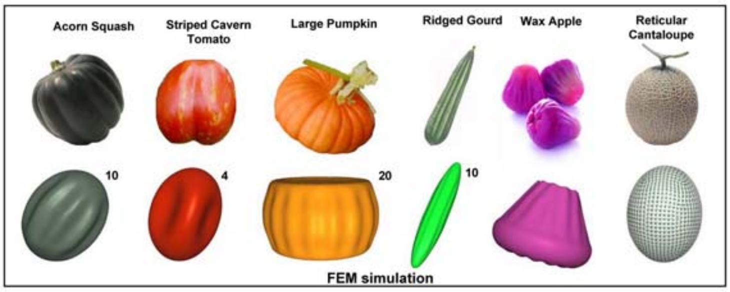

Fig.1. *The undulating morphologies of some fruits (top row). The corresponding simulated shapes of the fruits through buckling of spheroidal shell/core model with finite element method (FEM)(bottom row). On the right corner shows the ridge number.*

Fig.2. *Different morphologies of leaves and flowers observed in nature. (a) Saddle-like rhododendron leaf. (b) A pear leaf with local wavy edge. (c) The global curled and twisted morphology of pond weed leaves. (d) The tubular morphology of rhododendron leaf (same as (a) except the present one is in winter). (e) Doubly curled leaf. (f) Spiral morphology of a leaf. (g) Flowers with wavy margins in growth.*

The differential growth model of spheroidal shell (skin)/core (flesh) mimicking the real fruits can provide some insights, where the slower growth rate of flesh renders the skin in compression. When arriving at a critical value, a prolate spheroidal film/substrate system will buckle along longitudinal direction to release the higher hoop stresses. The study shows that the ridge number is determined by the geometrical dimension and effective material properties of skin and flesh [9]. Another plate model incorporating differential growth between the margins and centers can also shed some light on the understanding of rippling of flowers and leaves [10]. Therefore, buckles induced by mechanical forces might act as a template for confining or interacting with biology processes during the morphology development.

Morphology of human brain cortex: The cortical morphology has fascinated scientists for centuries. Unlike smooth kidney or spleen, cerebral cortex is full of wrinkles and folds (see Fig. 2b). However, in the fetus period it is smooth (see Fig. 2a). During the early stage, as neurons continue to divide, grow and migrate, the cortex folds and forms a recognizable but unique pattern of bumps and grooves. Without wrinkles, retardation and sickness may appear. The role of mechanical forces is recognized in the development of brain morphology [11]. From the laminate local buckling model, the cortical morphology was attributed to the differential growth between the outer and inner portions of the cerebral cortex [12]. The reorganization of mechanical forces in brain morphology supplies new opportunities for computational approaches of modeling the development of brain cortex morphology based on the buckling principles. The related research will improve the understanding in brain diseases such as schizophrenia and autism [13].

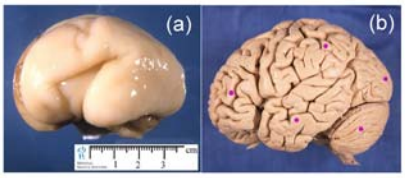

Fig.3. *(a) The smooth brain cortex of a fetus at 22 weeks. (b) The corrugated morphology of a normal brain cortex.*

Applications to mechanical self-assembly fabrication: Inspired by the fascinating morphologies in nature, efficient ways of shaping 3D structures and materials become possible, overcoming the limitations of conventional 2D micro/nanofabrication techniques based on photolithography [14]. Different 3D shell-like structures are formed through the laterally inhomogeneous growing or shrinking deformation in elastic sheets [15]. The understandings of the curling and spiral morphology in leaves make it possible to fabricate the similar structures through controlled self-rolling or buckling of films like single or multi-walled micro/nanotubes [16], nanodrills, nanospring, and nanohelices [17], which have potential applications in nanoelectromechanical system (NEMS) as sensors, transducers, resonators and photonics. When incorporated with a soft substrate, the microlens arrays [18] and different types of microgears [19] are possible to be fabricated with the controlled buckling of films on spherical and cylindrical substrates, respectively.

Mechanical instability of films or multi-layered film/substrate system with distinct geometry will provide us useful hints for exploring the formation of fascinating morphologies in nature, which spans from cell morphology development at the micro/nano scale [20], intriguing patterns in tissue growth and plants [5-7], wrinkling of fingertips immersed in water [21] to labyrinth brain cortex [12], and even to the ground morphology found in many cold landscapes at the macroscopic scale [22]. In return, the explored physical mechanism can provide potential guidance for the micro- and nano-fabrication of 3D multilevel thin-film devices, NEMS components [17], flexible electronics design [23] and control of cell growth direction [24], among others.

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