SOFT MATERIALS

Inflating to shape

An elastomer sheet with programmed inner channel architecture swiftly shapes into a desired three-dimensional geometry upon the application of pressure.

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Traditional actuators and robots achieve their tasks much in the same manner the human hand works, by rigidly moving stiff components relative to one another. Soft machines, however, follow a different paradigm — inspired by the smooth deformations of soft tissues, such as the motion of the tentacle of an octopus or the opening of the petals of a flower, all parts of a soft machine deform to achieve its task. Despite the significant efforts invested in recent years and the impetus of applications, man-made soft machines still hold limited functionality due to slow actuation time, low load capacity or constrained modes of motion. Now, writing in *Nature Materials*, Benoit Roman and colleagues[1] describe a pressure-mediated shaping strategy for the fast and reversible transformation of mesostructured thin elastomer sheets into a variety of desired three-dimensional (3D) shapes. Upon air inflation or suction the deforming material, termed a baromorph by the authors, assumes programmed geometries that display high load capacity.

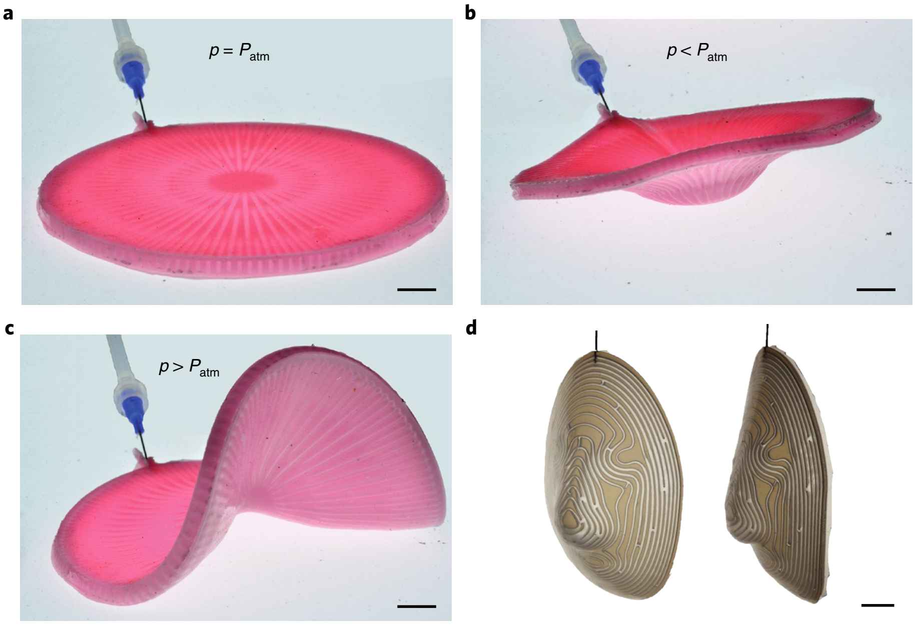

Fig. 1 | 3D shape versatility of baromorphs. a–d, These bioinspired materials consist of a thin elastomer sheet in which a specific pattern of air channels has been imprinted so that upon air inflation or suction, the initially flat sheet (**a**) assumes a desired 3D structure depending on the difference between the inner channel pressure (p) and that of the ambient atmosphere (P_{atm}). A bowl (**b**), a saddle (**c**) and a face (**d**) are shown. Scale bars, 1 cm (**a**–**c**) and 2 cm (**d**). Adapted from ref. [1], Springer Nature Ltd.

While pneumatically activated soft machines that demonstrate high load capacity and fast response time have been successfully realized in the past, their architecture remained limited to uniaxial deformations[2,3]. This restricted range of motions is contrasted by the elaborate shapes and versatile motions of biological soft tissues such as those displayed by sea slugs, octopuses or the human tongue. In these examples, the tissues differentially contract and expand to smoothly assume a series of desired conformations. Inspired by this shaping mechanism, responsive materials have been designed to produce predetermined differential elongation and shrinkage profiles[4–8]. Local relative distances are externally set by imprinting spatial chemical composition gradients in thermally responsive hydrogels[4,5] or by using the uniform but anisotropic actuation of nematic elastomers[7] so that upon a stimulus, the material shapes itself into a certain structure that best fits the prescribed distances. While capable of producing elaborate shapes, these distance-prescribing methods suffer from a long response time and relatively small load-bearing capabilities, limiting their use in practical applications.

Faced by the shortcomings of existing approaches, Roman and colleagues combined the advantages of pneumatic approaches with those of hydrogel and nematic-responsive materials to produce the baromorph, a fast and strong soft actuator. The baromorph is composed of a thin elastomer sheet in which a carefully designed pattern of air channels is imprinted. The air channels' response to (positive or negative) pressurization is highly anisotropic and thus the spatial variation in their orientation can be used to programme geometric shapes into the baromorph in a similar fashion to how shape is defined in nematic elastomers actuators. Moreover, by varying the air channel density and geometry, the degree of local response to pressurization can be independently tuned, providing an additional scalar field to control the geometry. These allow one to harness the power of pneumatic actuation with the versatility of shaping by length prescription.

Unlike shaping by mould-casting, where the exact position of each element is prescribed, objects shaped by local distance prescription typically assume frustrated structures that exhibit residual stress since no shape can simultaneously comply with all the prescribed distances. These geometric incompatibilities and residual stresses, which are typically avoided in traditional applications, become valuable advantages in the context of self-shaping, allowing the production of intricate shapes and elaborate structures from simple or very partial inputs. Roman and co-workers explore these effects to bend structures in three dimensions by prescribing two-dimensional (2D) geometries that contain no curvature information (Fig. 1).

Designing a self-shaping object amounts to finding the collection the intrinsic relative distances (that is, the material's metric) that will result in a desired shape when activated. However, for most cases, direct approaches to prescribe the metric are not available. This gives rise to the self-shaping inverse design problem — given a desired set of local distances in the material, how could these be realized using the constrained length-prescribing mechanism available? This problem poses a great challenge in the case of nematic elastomers, where actuation causes a biaxial anisotropic shrinkage that is uniform throughout the material and non-trivial metrics arise due to spatial variation in the principal shrinking direction. The relation between the spatial variations in the orientation field and the resulting metric has been addressed by several groups[6,8] and a numerical scheme to generate an orientation texture that results in a desired metric has been recently proposed[7]. In the case of the baromorph, the local geometry and orientation of the imprinted air channels can be independently defined, allowing for a fine control of the scalar and directional shaping mechanisms. The ability to tune both the direction and intensity of the expansion allowed Roman and colleagues to provide an analytical approach to the inverse design problem. While a general solution to the inverse problem still evades us, by exploiting a projection method the authors were able to map any desired 3D geometry to a 2D channel texture that would realize the desired geometry upon actuation. They demonstrated this capability by fabricating baromorphs that reversibly shape into a bowl, a saddle and even a face upon application of pressure (Fig. 1). The availability of such a recipe for the production of arbitrary metrics closes the gap between the demonstration of a new design principle and the applicative realization of its full potential to create a new generation of geometrically versatile, fast, high-load and cheap soft machines and actuators. ❐

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