SOFT ROBOTS

Tensegrity metamaterials for soft robotics

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3D-printed flexible tensegrities with metamaterial properties enable customizable complex locomotion in soft robots.

Since Buckminster Fuller coined the term "tensegrity" (a structural principle that connotes both structural integrity and flexibility) in the 1960s (*1*), researchers have identified tensegrity structures throughout the natural world, from the cytoskeletons of primitive microorganisms to the flexible muscles that wrap the rigid skeletons of large mammals (*2*, *3*). Tensegrity is essential for animal biomechanics because it allows for a high degree of both structural mobility and robustness. For these reasons, the principle also has immense potential for applications in the field of soft robotics. There are, however, existing challenges that limit the broader application of tensegrity in soft robots. For example, a simple approach to rapidly manufacture flexible tensegrity structures with diverse compounds is needed, and demonstrations of a soft robot designed with tensegrity units and complex geometries that can achieve enhanced mechanical performance are rare. Writing in *Science Robotics*, Lee and colleagues developed an approach that can rapidly produce three-dimensional tensegrity structures at various scales that combine magnetic soft tendons with rigid beam elements (*4*). They designed and manufactured these structures as "metamaterials", or materials that display exciting mechanical properties beyond what is possible to achieve with conventional homogeneous ones. Through simple magnetic actuation, these tensegrity metamaterials endow soft robots with locomotion.

Lee and co-workers used a commercially available 3D printer with two nozzles for fabricating the tensegrity structure. Within a sacrificial mold (polyvinyl alcohol), they simultaneously printed a continuous internal channel network and isolated rigid struts (polylactic acid) (Fig. 1A). They then injected a soft magnetic material (iron oxide (Fe_3O_4) particles mixed with elastomer) to fill the channel system. After the structure solidified, water was used to dissolve the sacrificial mold for a network of soft magnetic material seamlessly integrated with rigid struts. Ideally, their approach could create complex tensegrities with arbitrary topologies at a variety of scales within a 3D printer's capability.

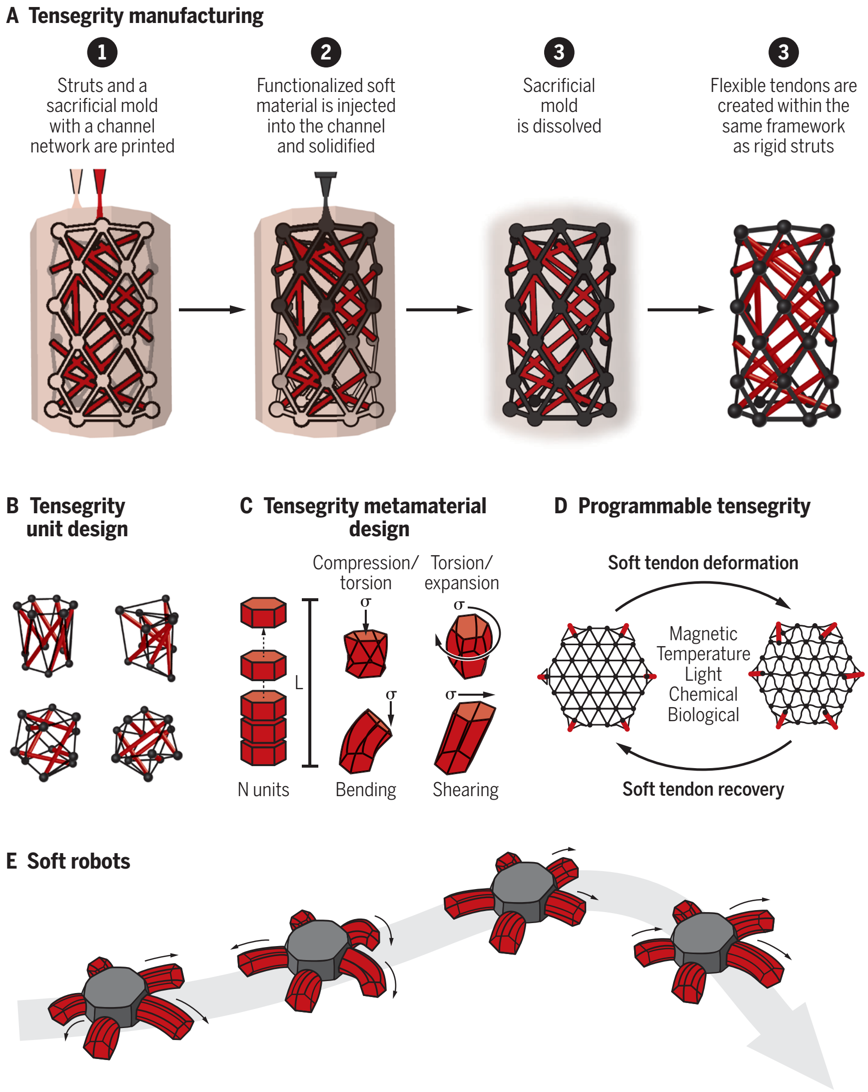

Fig. 1. A tensegrity metamaterial approach to soft robotics. (**A**) The manufacturing process of the flexible tensegrity. (**B**) The basic tensegrity unit can be designed by adjusting geometry, topology, and complexity. A few tensegrity units are demonstrated as examples: hexagonal prism (top left), hierarchical trigonal prism (top right), Cuboctahedron (bottom left), and Icosahedron (bottom right). (**C**) Tensegrity towers constructed of individual units exhibit exotic metamaterial properties. (**D**) A programmable tensegrity with stimuli-responsive soft tendons. (**E**) A soft robot made of tensegrity metamaterials can crawl and achieve directional steering.

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To construct a multilayer, cylindrical tensegrity tower, the researchers used a polygonal prismatic tensegrity as the basic structural unit (Fig. 1B). With this design, a tower can compress, stretch, and bend to a high degree. Notably, their tower design exhibited some exotic mechanical properties of metamaterials, such as having a Poisson's ratio of zero (no lateral expansion when compressed) and compression-torsion (or tension-torsion) coupling (Fig. 1C). Additionally, the multiple design parameters of the structure allowed the researchers to program the mechanical properties of the tower. Simply by tweaking these parameters, the researchers could adjust axial stiffness, shear stiffness, and deformation coupling. By modifying geometry, topology, and complexity, the researchers designed diverse units and applied these units to build three-dimensional structures with complex, novel architectures (e.g., planar cellular, chiral loop, and cubic lattice structures). Because of their extraordinary structural and mechanical diversity, these tensegrity metamaterials can function well as the locomotor body or appendages of a soft robot. With simple magnetic actuation, the tensegrity metamaterial can also deform and recover rapidly (Fig. 1D). The researchers also developed a "starfish"-type walking robot with multiple tensegrity metamaterial legs. Each leg could compress and bend via cables driven by two independent motors, allowing the robot to crawl and achieve directional steering (Fig. 1E).

One major contribution of this work is that the researchers' manufacturing method successfully integrates a functionalized soft tendon material with isolated rigid beams. This approach paves the way for fabricating programmable tensegrities across many scales and with a wide variety of materials. For example, "smart" materials such as responsive gels (activated by light, heat, and chemical stimuli) (*5*) and biological materials (living cells and tissues) (*6*) are promising future candidates for actuating the soft tendon network of the tensegrity (Fig. 1D). These new materials, integrated into a specialized tensegrity structure, could drive myriad innovations in soft robotics. The tensegrities could also be actuated in an untethered manner, which could broaden the applicability of autonomous soft robots for space exploration, biomedical engineering, and wearable devices (*7*).

Another important element of this research is that it provides a guide to design flexible tensegrity metamaterials to intentionally define the mechanical capabilities of soft robots. Flexible metamaterials offer the shape-changing functionality of soft materials and other properties that conventional materials cannot achieve (*8*). Tensegrity metamaterials in particular enable the analytical and algorithmic design of flexible structures that allow for customizable complex locomotion in soft robots. The specifics of this design methodology are still little understood. To optimize the design and manufacturing of tensegrity metamaterials in the future, faster parametric modeling, such as theoretical models based on multi-scale mechanics (*9*) and calculation models based on machine learning (*10*), would be promising tools to employ. Most importantly, accelerating the development of tensegrity metamaterials could improve the actuation, adaptability, and programmable stiffness of a variety of soft robot designs.

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