Bio-Mimetic Design and Mechanical Analysis of Soft Network Materials with Helical Microstructures

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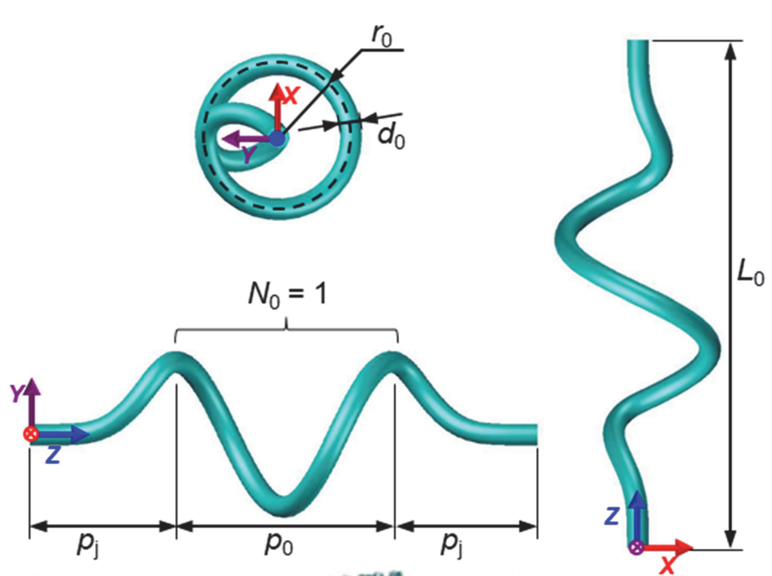
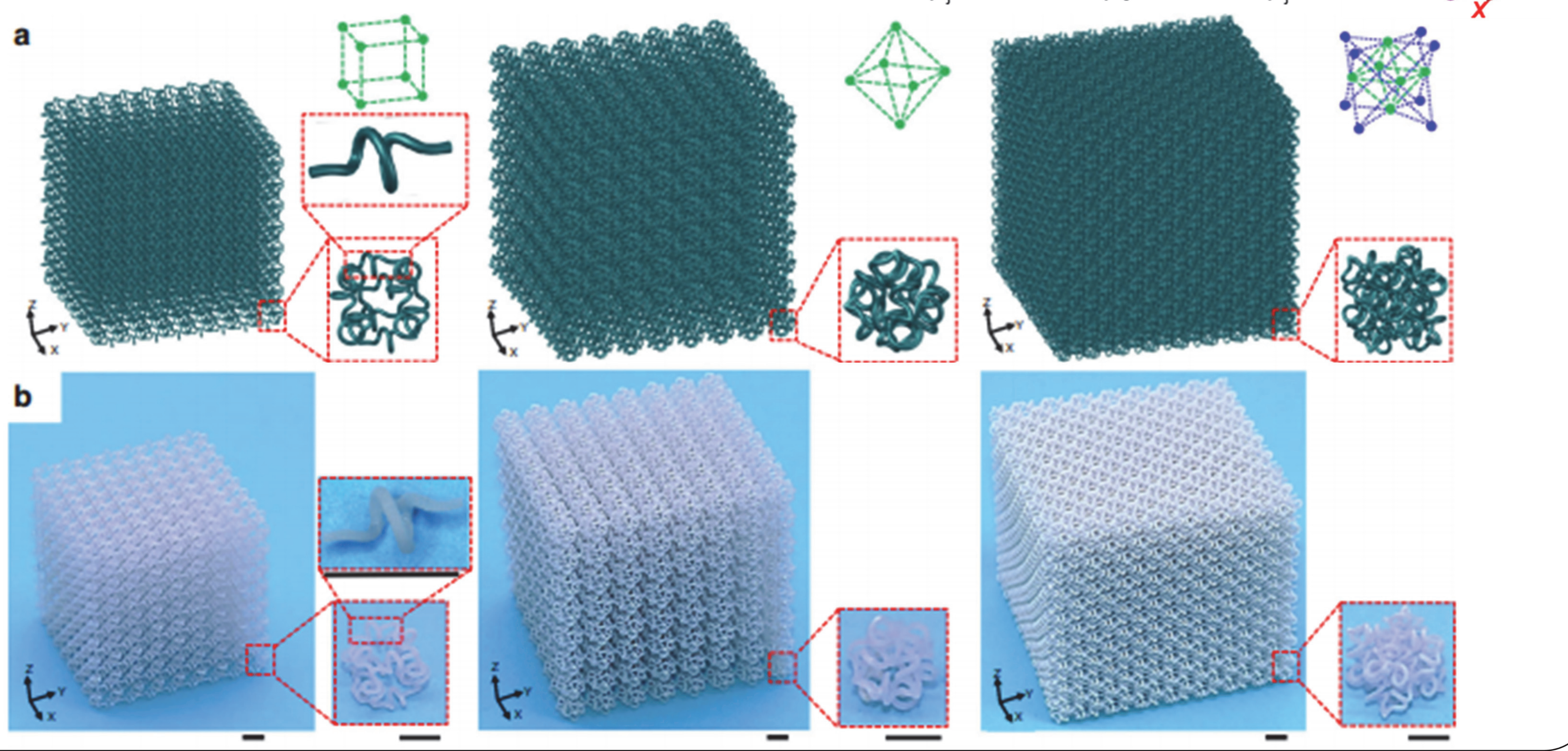
Introduction

Many artificial soft materials have been developed to offer similar bio-mimetic physical properties. These artificial soft materials hold promising application in tissue engineering, soft robotics, and other areas. Inspired by the transition from bending-dominated to stretching-dominated deform mode of many biological tissues under large tension, a class of .three-dimensional (3D) soft network materials was reported recently. The 3D soft network materials exploit a lattice configuration with different 3D topologies, where 3D helical microstructures that connect the lattice nodes serve as building blocks of the network. As validated by finite element analyses (FEA) and experiment, this rational bio-mimetic material design can offer high stretchability, defect-insensitive behavior and nonlinear mechanical responses closely matched with those of biological tissues. By tailoring geometries of helical microstructures and 3D lattice topologies, a wide range of desired anisotropic J-shaped stress–strain curves can be achieved and the target isotropic/anisotropic stress-strain curves of real biological tissues can be reproduced.

Geometric design

Inspired by the network constructions and helical microstructures of many collagenous tissues, we develop a 3D network design by exploiting a type of 3D helical microstructures as the building blocks that are extended with different 3D lattice topologies.





Mechanics model

Consider an ideal helix is subject to a uniaxial stretching along its helical axis.

$$F=\frac{E_s A}{2\cos\theta}\{-1+\mathcal{G}(\theta)\},\ \text{and}\ \frac{p}{p_0}=\frac{\cos\theta}{2\cos\Theta}\{1+\mathcal{G}(\theta)\}$$

$$\mathcal{G}(\theta)=\sqrt{1+4\frac{\hat{\Phi}^2}{E_s A}\frac{\cos\theta}{\sin\theta}\left[GI_p(\cos\theta-\cos\Theta)\sin\theta+E_s I(\sin\theta-\sin\Theta)\cos\theta\right]}$$

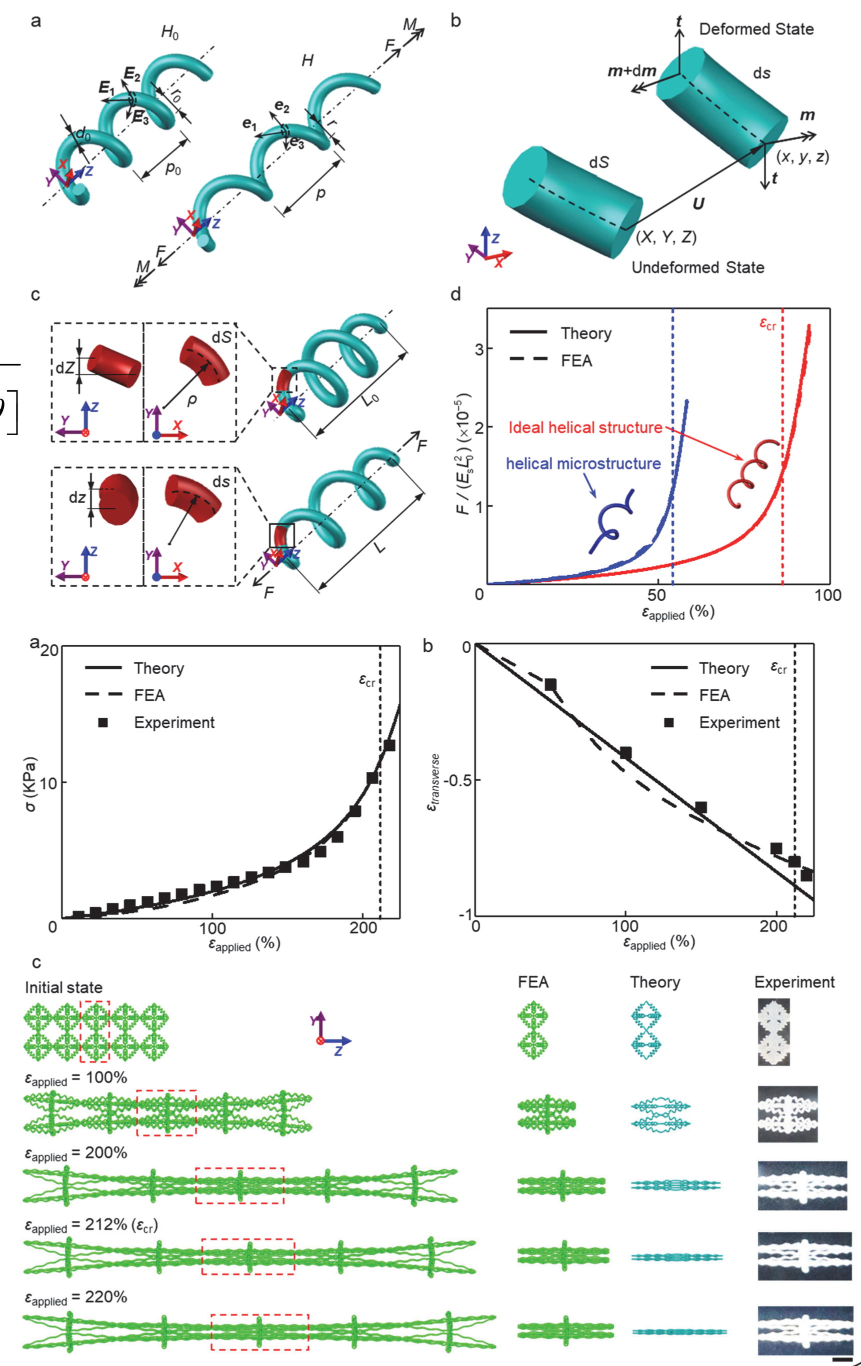
$$F=\mathcal{F}_{r_0,p_0,d_0}(\varepsilon_{\text{applied}})\qquad \varepsilon_{\text{applied}}=\mathcal{F}^{-1}_{r_0,p_0,d_0}(F)$$

Then we utilize the theory of ideal helical structure to resort to the concept of calculus to analyze the deformation of each unit segment in the complex helical structure.

$$\varepsilon_{\text{applied}}=\frac{\int_0^S\left[\mathcal{F}^{-1}_{\rho(S),\omega(S),d_0}(F)\frac{dZ}{dS}\right]dS}{\int_0^S\frac{dZ}{dS}dS}-1$$

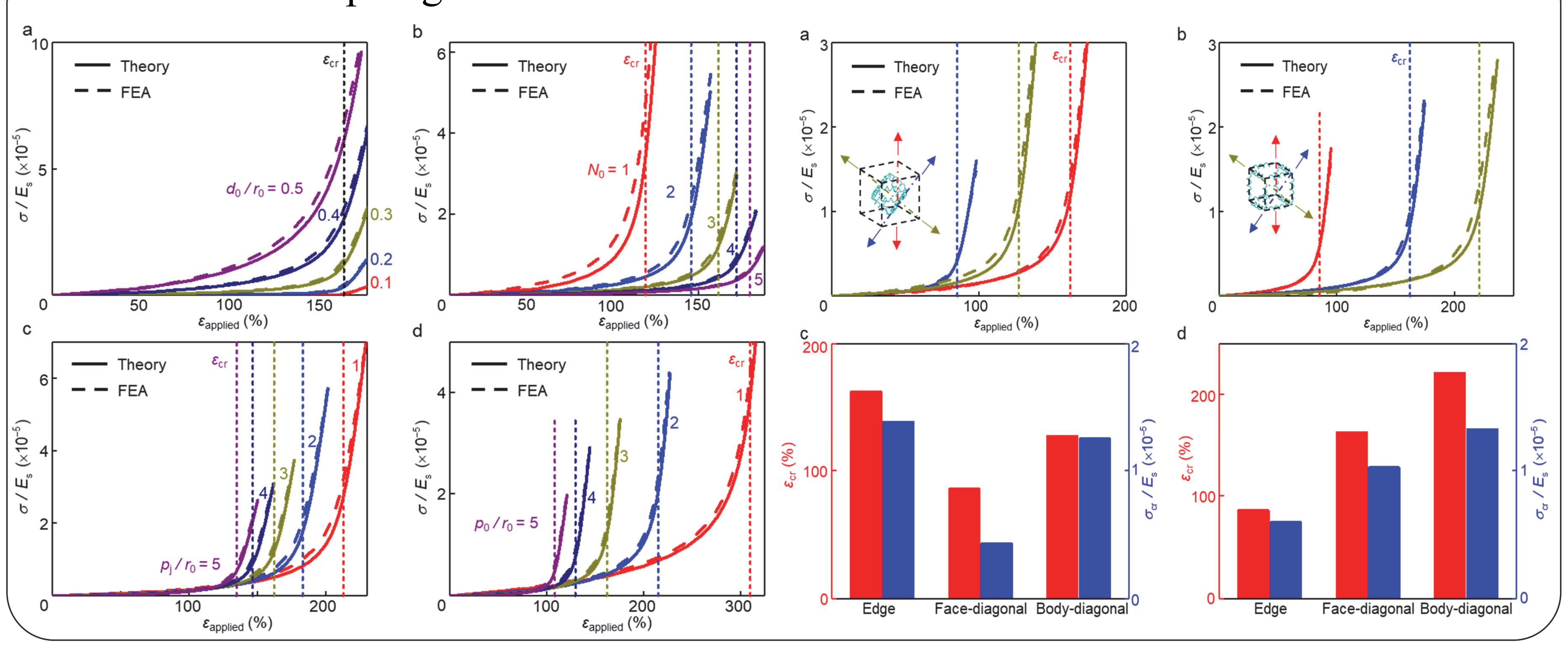
Then the mechanical responses of 3D soft network materials can be predicted.

$$\sigma=\frac{NF\cos\alpha}{A_{\text{eff}}}$$



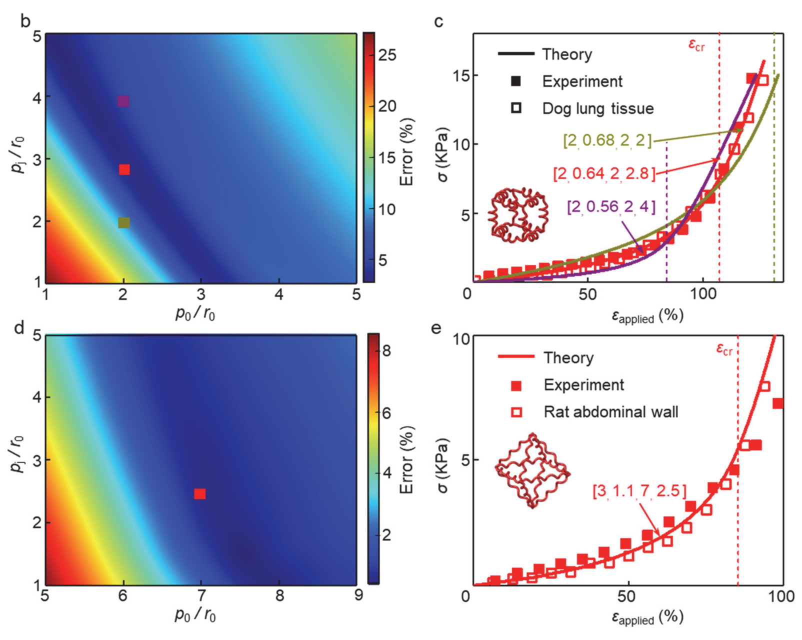
J-shaped stress-strain response

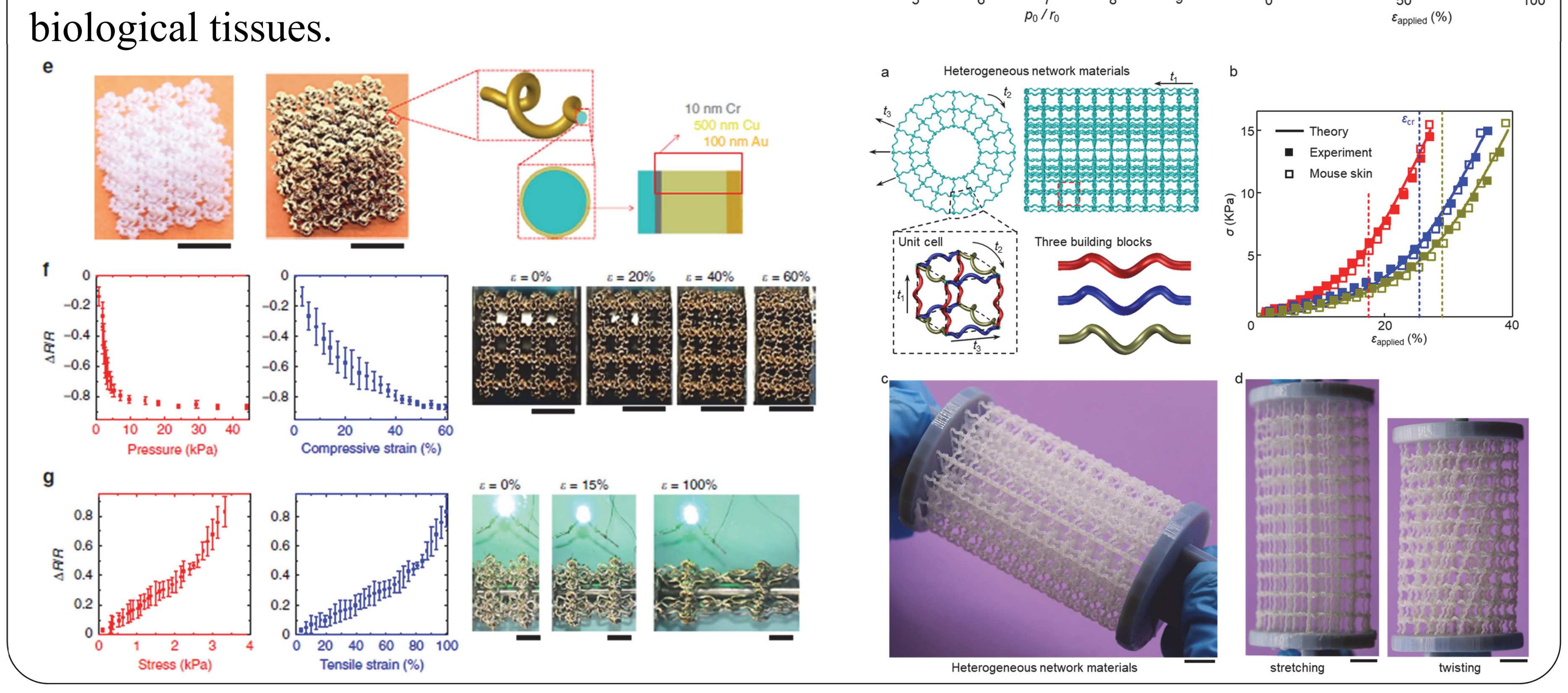
The geometry of the helical microstructure is fully characterized by four dimensionless parameters, including the normalized diameter (d_0/R_0) of the fiber, the number of the coils (N_0), the normalized pitch (p_0/R_0), and the normalized joint length (p_j/R_0), where R_0 is the radius of the helix. The theoretical model allows a clear understanding of different roles of microstructure parameters on the J-shaped stress-strain curve (that is characterized by the critical strain of mode transition, as well as the stress and the tangent modulus at the critical strain), which can be generalized to analyze the anisotropic mechanical responses of soft network materials with cubic, octahedral and other lattice topologies.



Applications

A bio-integrated devices of the conducting soft 3D network materials for potential uses as flexible pressure sensors and conductors can be obtained by magnetron sputtering. Furthermore, we demonstrate the utility of the theoretical model in the design optimization of 3D soft network materials to reproduce the target isotropic/anisotropic stress-strain curves of real biological tissues.





Conclusion

In summary, this work reports a class of rational bio-mimetic 3D network designs for soft architected materials consisting of periodically arranged helical microstructures, with abilities to reproduce accurately the anisotropic, nonlinear stress–strain responses of 3D biological tissues. the theoretical model can predict accurately both the nonlinear stress-strain curves and deformed configurations at large levels of stretching. These findings provide systematic guidelines for the 3D network design of architected materials and functional systems.

Reference:

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