REPORT

METAMATERIALS

Handedness in shearing auxetics creates rigid and compliant structures

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In nature, repeated base units produce handed structures that selectively bond to make rigid or compliant materials. Auxetic tilings are scale-independent frameworks made from repeated unit cells that expand under tension. We discovered how to produce handedness in auxetic unit cells that shear as they expand by changing the symmetries and alignments of auxetic tilings. Using the symmetry and alignment rules that we developed, we made handed shearing auxetics that tile planes, cylinders, and spheres. By compositing the handed shearing auxetics in a manner inspired by keratin and collagen, we produce both compliant structures that expand while twisting and deployable structures that can rigidly lock. This work opens up new possibilities in designing chemical frameworks, medical devices like stents, robotic systems, and deployable engineering structures.

Many biological materials, such as DNA, keratin, and collagen, are composed of repeated patterns of simple monomers that form handed structures (*1*). Handed structures come in mirror-image pairs. The same underlying handed materials generate rigid, compliant, or flexible mechanical properties through variations in intermolecular bonding (*1*). Examples include collagens, which form rigid materials such as bone and teeth, as well as compliant structures like cartilage, tendon, and skin; and keratins, which form hair, horns, and hooves (*1*, *2*). These structures become stronger by increasing the amount of interlayer bonding; these are disulfide bonds and hydrogen bonds in the case of keratins (*3*) or collagen (*4*). Both collagen and keratin align and bond the termini of substructures to form larger structures. We used this same principle of coupling the termini with strong bonds, and using variable bonds along the length to rigidize composite handed auxetic tubes and spheres.

Similar to keratin and collagen, auxetic structures are composed of a repeated tiling of a basic unit cell (*5*). Their defining mechanical property is a negative Poisson's ratio, meaning that they expand perpendicular to the direction of tension when stretched (*6*). They can form planes (*7*–*9*), cylinders (*9*–*11*), spheres (*12*, *13*), and complex surfaces (*14*). The underlying geometric patterns that lead to auxetic behavior are scale and material independent (*5*). The patterns are naturally occurring at the nanometer scale in molecules and crystals (*15*–*17*), they exist at the millimeter scale in stents (*18*), and they occur at the meter scale in large structures (*19*). The material-agnostic nature of these patterns can potentially enable unconventional auxetic metamaterials to be designed (*20*).

Conventional auxetics are limited in a key way; the stiffness of an auxetic is predefined. It is derived primarily from the interplay between a fixed topology and the predefined energy required to deform the joints or struts of the structure (*7*, *8*, *21*). As a result, the same structure cannot switch between rigid and compliant states.

We used the biologically inspired technique of selectively bonding handed structures to form rigid or compliant structures from handed shearing auxetics (HSAs). We produced handedness in two-dimensional shearing auxetic material patterns that tile the surface of planes, cylinders, or spheres. We demonstrated a rigid deployable structure through concentric alignment of different HSA cylinders. We made compliant actuators via parallel arrangement of right- and left-handed cylinders. We can globally actuate the structures by applying a twist or linear stress. The ability to twist the auxetics allows us to actuate them with conventional motors.

The unit cell of an auxetic is a set of rigid links with variable relative angles (*5*), but with fixed connectivity. The cell's auxetic trajectory is controlled by a single number called the phase angle, which defines the continuous deformation of the unit cell (Fig. 1). Conventional auxetic structures are isotropic and expand uniformly under applied tension (*5*). Shearing auxetics, however, expand at different rates in different directions while shearing and therefore do not have a single Poison's ratio. The ratio varies as a function of direction and phase angle (*7*, *8*). For an auxetic pattern to shear and expand simultaneously, the unit cells must have C_2 or C_1 symmetry (*22*). In addition, no net shearing of the structure occurs if there are reflections or glide reflections continuously in the tiling pattern along the auxetic trajectory. This constrains shearing auxetics to 2 of the 17 wallpaper group tilings, 2222 and o in orbifold notation (*23*). In orbifold notation, * represents a reflection, and integers represent rotation centers of the integer's order. Integers before or without a * are not on a line of reflection, and those after a * are on a line of reflection. x represents a repeated mirror image without a line of reflection, and o represents only translations. In the notation, integers are listed next to each other, so 2222 represents four separate rotational centers of order 2 without reflections, and o represents a pattern with only translational symmetries.

Various auxetic structures behave differently along their auxetic trajectories (Fig. 1). All auxetics reach their maximum auxetic extension at a phase angle θ_{max}. Further deformation from this point causes them to either cease being auxetic or to contract. Because unit cells can change their shape throughout deformation, an auxetic tiling can transition from a 2222 or o symmetry to one that has reflections for a single point along the auxetic trajectory. The development of a line of reflection at a point along the auxetic trajectory allows a shearing auxetic that is shearing to the right to transition to shearing to the left. This produces a symmetric auxetic trajectory and thus an unhanded shearing auxetic. Such structures continuously shear from one direction to the other, which is equivalent to mirroring the entire structure (Fig. 1). Shearing auxetic trajectories that never develop a reflection at θ_{max} characterize the handed shearing auxetics. Therefore, preventing reflection symmetries at θ_{max} generates handedness. Handed auxetics come in right- and left-handed pairs. Because their mirror images are equally valid tilings of space, their left- and right-handed versions have distinct auxetic trajectories. The configuration of a left-handed auxetic cannot match that of a right-handed auxetic by choosing a different θ on the auxetic trajectory.

Handedness in a shearing auxetic structure can emerge at three different levels: in the joints, in the patterning itself, or in the placement of the pattern on an oriented surface. By limiting the joint angles to exclude θ_{max}, the symmetry of an unhanded shearing auxetic trajectory is broken. This prevents a shearing auxetic cell from transitioning between handedness. We removed the symmetries from the constituent elements of the unit cell (Fig. 1) to turn a shearing auxetic into a handed shearing auxetic. By turning one of the rectangles into a parallelogram, we prevented lines of reflection from developing. The components of the unit cell never align to form a global symmetry at θ_{max}. We performed similar modifications to make handed shearing auxetic patterns from rigid links and links with polygons (fig. S3) (*22*).

We constructed a handed cylinder made from an unhanded shearing auxetic pattern (Fig. 1 and movie S1). The circumferential and longitudinal

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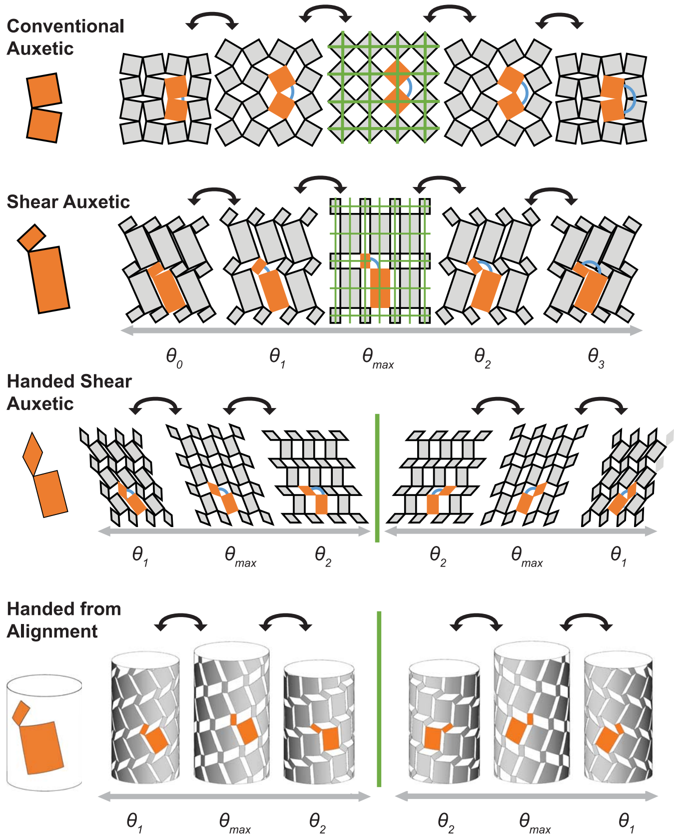

Fig. 1. Auxetic trajectories with and without mirrors. Shearing and handed shearing auxetics are made by changing the symmetries of the conventional auxetic patterns. The cells move along the auxetic trajectories by varying θ, marked in blue. At the point of maximum auxetic extension, θ_{max}, the trajectory is either symmetric or ceases to be auxetic. To be symmetric, θ_2 must be a reflection of θ_1. If an auxetic shears and it is not symmetric around θ_{max}, it is a handed shearing auxetic, and a vertical mirror switches between the handed patterns. Unhanded shearing auxetics tiled on a cylinder can produce a handed auxetic cylinder.

directions of a cylinder provided a natural coordinate system. A planar unhanded shearing auxetic pattern has a natural orientation along the direction of its emergent line of reflection. When the lines of reflection align with the circumferential or longitudinal directions, the cylinder has no net handedness. When the lines of reflection do not align with the circumferential or longitudinal direction, the cylinder has a net handedness, and the sign of the angle between the lines of reflection and the longitudinal axis determines handedness.

A shearing auxetic tiling on a cylinder or sphere couples the shape's radius, height, and orientation to a twist action around the shape's central axis (see movie S1). Tiling cylinders or spheres to make shearing auxetics requires changing the constraints on the structures. Planar and space filling auxetics have zero principal curvature and can be made of rigid links. However, the surface of a sphere or cylinder has directions of nonzero principal curvature. As the surface expands, the radius of curvature on its surface changes. This necessitates tiling the surface with flexible links that can bend and twist.

We fabricated handed auxetic cylinders and spheres using strips of 0.254-mm-thick spring steel (Fig. 2A). We constructed spheres with a 44 symmetry (fig. S6E). We made cylinders with a 224 pattern constructed from the planar pattern in Fig. 2B, which was based on the unit cell of the reentrant honeycomb auxetic tiling. We found that the cylinders expanded by 613% in length and 284% in width between their fully contracted and fully extended states. Prebending strips of spring steel can bias the structure to specific points on the auxetic trajectory (fig. S6). We made cylinders with 223 symmetry from tubes of polytetrafluoroethylene (PTFE) using a laser cutter (Fig. 3A), demonstrating that these structures can be fabricated automatically from continuous materials.

We created composite-handed auxetic structures by combining right- and left-handed cylinders or spheres. We aligned three concentric cylinders or spheres along a central axis. The middle structure turns counter to the inner and outer structures to produce left-right-left (LRL)– or right-left-right (RLR)–handed composites (Fig. 2F). We bonded the ends by constraining the poles or edges of the constituent structures to share the same position and orientation. This step ensures that if there is a twist, or compression, the ends of each layer move in unison.

Locking the poles or edges affects the entire composite structure. When the LRL or RLR composite structure is twisted or loaded, two antagonistic layers compress into each other (Fig. 2F). Either the innermost layer expands while the middle layer contracts, or the outermost layer contracts while the middle layer expands. Strong mechanical bonds form where the two antagonistic layers come into contact (Fig. 2D). As the structure is loaded, the forces between the antagonistic layers increase, fixing them relative to each other. Because of the mechanical bonds, the structure is unable to expand or contract under a load without buckling. This is analogous to the disulfide bonds of keratin or the hydrogen bonding on collagen that prevents the constituent elements from separating or sliding past each other.

When locked (the structure has been constrained to some particular θ), the primary resistance to deformation in the constituent layers is the energy needed to deform the links and hinges. In this state, other deformation modes, such as buckling of the links, must store the energy. Often the alignment of the different layers effectively shortens the links' length by introducing node points where two layers are in contact (Fig. 2, D and E). The LRL cylinders had 1.5 times the ultimate compressive strength of LLL and 6.8 times that of the single HSA cylinders (Fig. 2C). The LRL and LLL composite cylinders had the same effective stiffness, which was 6.2 times the stiffness of the individual cylinders and 2.7 times that of right-left (RL) composites. Unlike a bistable auxetic pattern (*24*), the rigid LRL composite state can exist at any point along the auxetic trajectory.

A simple RL composite cannot be rigid without torsional preloading because it may not form the mechanical bonds. Without preloading, the layers can separate when the outer layer expands and the inner layer contracts. This produces a notably more compliant structure under loading. Similarly, the left-left-left (LLL) or right-right-right (RRR) structures do not generate interlayer mechanical bonds, because there is little to no normal force on the contact points, allowing the structure to globally twist and collapse.

We made compliant structures by eliminating bonds along the lengths of differently handed cylinders while maintaining the end bonds. We composited cylinders of different handedness parallel to each other, but with mechanically coupled ends. The cylinders were hollow tubes of Teflon, 16 cm long, 25.4 mm in diameter, 1.59 mm thick, and cut with a 223 pattern. Each tube required a net torque or external force to maintain state. In Fig. 3C, we see the external loading relative to extension of a single tube. The two tubes required an equal and opposite torque because they were right- and left-handed, respectively. By connecting the ends to each other, the structure self-frustrated and remained opened. Because they were parallel and not concentric, they did not interfere with each other under flexural loading and therefore could flex substantially.

We created a linear actuator using the compliant parallel tube structure with one pair of cylinder ends connected to a rigid plate and the other to a set of gears (Fig. 3A). The ends with the gears could rotate counter to each other but maintained a fixed distance. When the gears rotated, the structure elongated. The two counter-rotating cylinders oppose each other, ensuring no net torque on the rigid plate. This actuator had a 30% elongation and can deflect under external forces (Fig. 3B). We arranged four cylinders in a two-by-two grid of alternating right- and left-handed cylinders (Fig. 3D and movie S2).

This configuration yields a 4-degree-of-freedom composite actuator. One end of each cylinder is connected to a rigid plate, and the other end is constrained to a plane and attached to a servo. This arrangement allows subsections of the actuator to activate, enabling control over linear extension, twist, and bending in two directions. The handed shearing auxetic structure converts the rotation into linear displacement without a screw and nut, rack and pinion, or linkage system typically found in a linear actuator. The actuator itself is hollow, allowing wiring or other structures to occupy the center of the actuator.

We can produce HSAs from a variety of materials to tile the plane, spheres, or cylinders. The

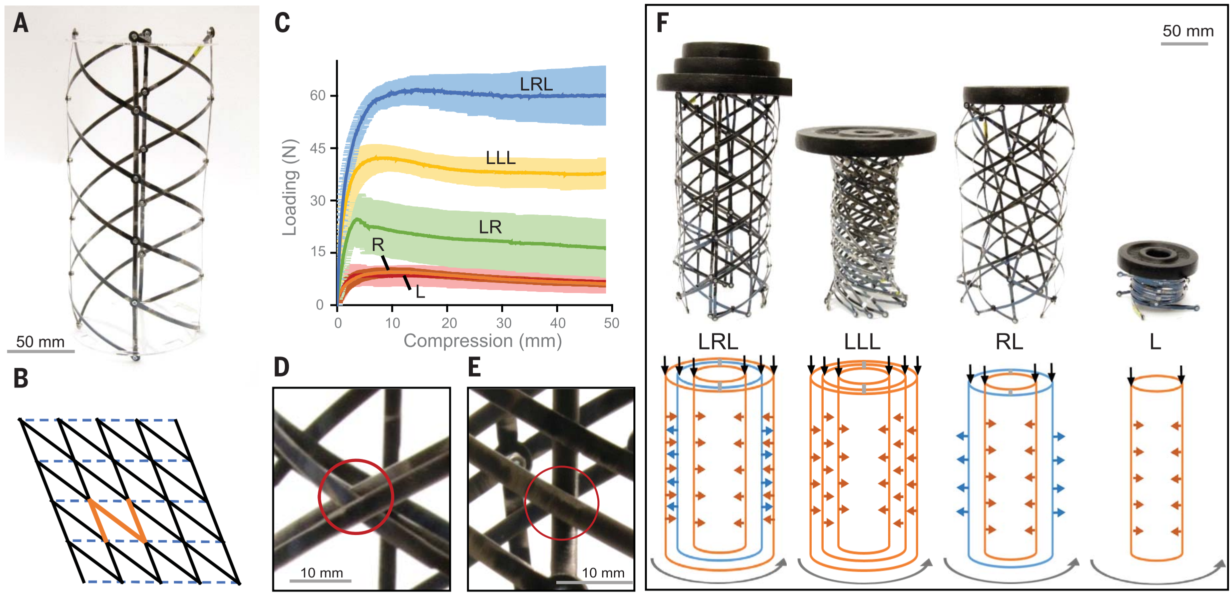

Fig. 2. Concentric handed shearing auxetics produce rigidity. Rigid and compliant structures made from handed shearing auxetic patterns. (**A** and **B**) A 2222 shearing auxetic tiling (B) can cover the plane and make HSA cylinders (A). (**C**) Composite HSA cylinders of different handedness have different strengths based on their structure. (**D**) LRL or RLR make mechanical bonds by self-interfering. (**E**)The LLL or RRR layers do not make mechanical bonds. (**F**) Under loading, the composite HSA performs quite differently. The LRL composite holds 4 kg without notable deformation. The LLL twists and collapses inward under 2.3 kg. The RL structure delaminates and can only hold 1.1 kg with deformation, and the single-layer HSA fully collapses under 0.57 kg of mass.

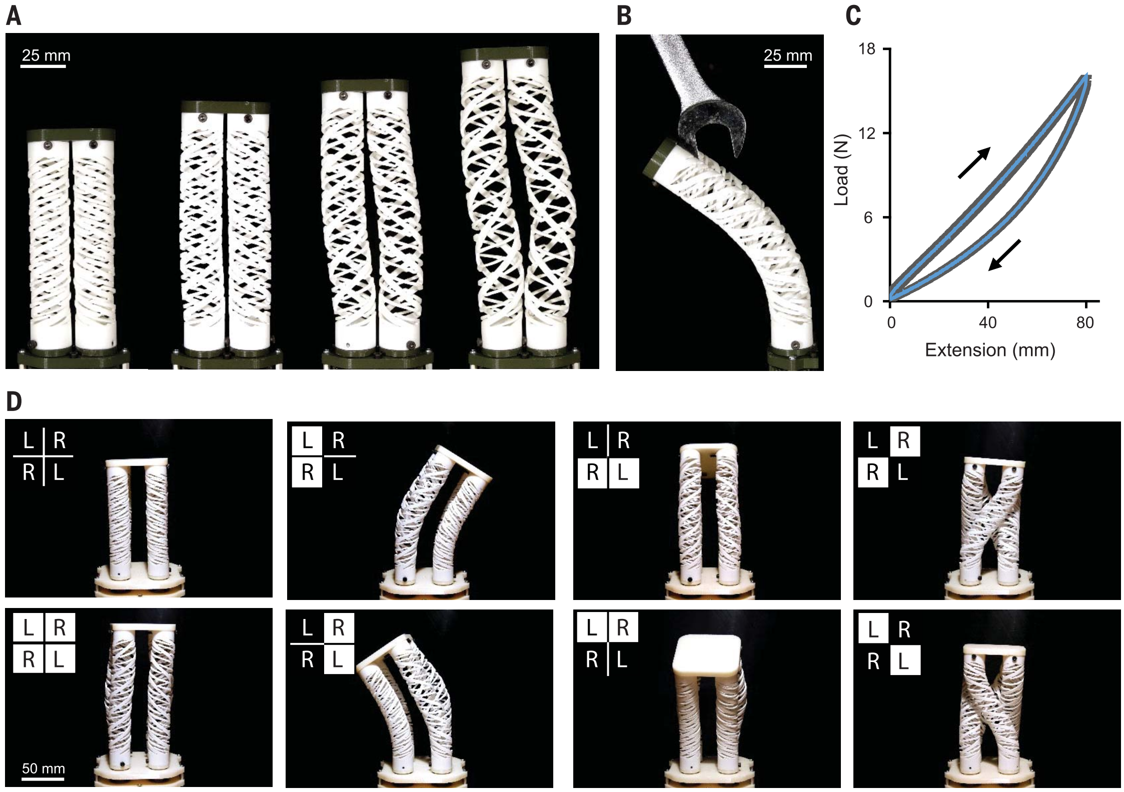

Fig. 3. Compliant handed shearing auxetic actuators. Actuators made from handed shearing auxetics. Right (R)– and left (L)–handed shearing auxetic (HSA) cylinders make compliant or rigid structures. (**A**) Counterrotating right and left HSA cylinders that are parallel to each other generate linear extension with no net torque. (**B**) While extended, these actuators remain compliant. (**C**) External loading of an HSA cylinder has hysteretic loss. (**D**) Four HSA cylinders combined to make a 4-degree-of-freedom actuator. Controlling the twist of each HSA allows the system to move up and down, side to side, and front to back and to twist left and right.

scale independence of this strategy could find application in engineered DNA structures, chemical microstructures, medical stents, or large engineered structures. We have shown that HSA spheres and cylinders can produce rigid structures that resist torsional and axial loading by exploiting global locking. Such deployable and rigidizing structures could be useful in biomedical, architectural, and space applications. Space structures made from HSAs may match the deployability of existing mast designs (*25*, *26*) with greater structural simplicity and reduced fabrication effort. If applied to stent and shunt design, smaller punctures could be used to implant rigid tubing. We have also harnessed the response of HSA cylinders to global twist to realize actuators that use conventional motors but are compliant like soft robotic actuators.

REFERENCES AND NOTES

1. E. Renuart, C. Viney, *Pergamon Materials Series* **4**, 223–267 (2000).
2. M. Feughelman, *Mechanical Properties and Structure of Alpha-Keratin Fibres: Wool, Human Hair and Related Fibres* (UNSW Press, 1997).
3. A. N. Parbhu, W. G. Bryson, R. Lal, *Biochemistry* **38**, 11755–11761 (1999).
4. M. D. Shoulders, R. T. Raines, *Annu. Rev. Biochem.* **78**, 929–958 (2009).
5. C. Borcea, I. Streinu, *Proc. Math. Phys. Eng. Sci.* **471**, 20150033 (2015).
6. R. Lakes, *Science* **235**, 1038–1040 (1987).
7. J. N. Grima *et al*., *Proc. Math. Phys. Eng. Sci.* **468**, 810–830 (2011).
8. J. N. Grima, E. Manicaro, D. Attard, *Proc. Math. Phys. Eng. Sci.* **467**, 439–458 (2010).
9. R. Gatt *et al*., *Sci. Rep.* **5**, 8395 (2015).
10. A. Lazarus, P. M. Reis, *Adv. Eng. Mater.* **17**, 815–820 (2015).
11. N. Karnessis, G. Burriesci, *Smart Mater. Struct.* **22**, 084008 (2013).
12. J. Shim, C. Perdigou, E. R. Chen, K. Bertoldi, P. M. Reis, *Proc. Natl. Acad. Sci. U.S.A.* **109**, 5978–5983 (2012).
13. W. J. Spenner Dolla, Rotational expansion auxetic structures. US Patent 8,652,602. (February 2014).
14. M. Konaković *et al*., *ACM Trans. Graph.* **35**, 89 (2016).
15. A. Yeganeh-Haeri, D. J. Weidner, J. B. Parise, *Science* **257**, 650–652 (1992).
16. A. Alderson, K. E. Evans, *Phys. Rev. Lett.* **89**, 225503 (2002).
17. K. Evans, B. Caddock, *J. Phys. D Appl. Phys.* **22**, 1883–1887 (1989).
18. M. N. Ali, J. J. Busfield, I. U. Rehman, *J. Mater. Sci. Mater. Med.* **25**, 527–553 (2014).
19. K. E. Evans, A. Alderson, *Adv. Mater.* **12**, 617–628 (2000).
20. T. Frenzel, M. Kadic, M. Wegener, *Science* **358**, 1072–1074 (2017).
21. J. Rossiter, K. Takashima, F. Scarpa, P. Walters, T. Mukai, *Smart Mater. Struct.* **23**, 045007 (2014).
22. Materials and methods are available as supplementary materials.
23. J. H. Conway, H. Burgiel, C. Goodman-Strauss, *The Symmetries of Things* (CRC Press, Boca Raton, 2016).
24. A. Rafsanjani, D. Pasini, *Extreme Mech. Lett.* **9**, 291–296 (2016).
25. M. E. McEachen, T. A. Trautt, D. M. Murphy, The ST8 SAILMAST validation experiment. *46th AIAA Structures, Structural Dynamics and Materials Conference* (2005).
26. N. Knight *et al*., 2012. FAST Mast structural response to axial loading: modeling and verification. *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA* (2012).

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SUPPLEMENTARY MATERIALS

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Materials and Methods
Figs. S1 to S10
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Giving a hand to metamaterials

Auxetic materials expand in an unusual way: perpendicular to the direction in which they are stretched. Lipton *et al.* engineered a type of auxetic material that also has handedness. When this material is sheared, it twists either to the right or the left. By tiling the underlying patterns onto spheres and cylinders, rigid or compliant structures can be made. Linear and 4-degree-of-freedom actuators can thus be made from hollow tubes, which could be valuable for a variety of engineering and medical applications.

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