Mechanical metamaterials bend the rules of everyday physics

Devin Powell, *Science Writer*

Chiara Daraio played for Italy's junior national basketball team in the 1990s. But when a Swiss running-shoe maker called her up in 2015, it wasn't to talk about her athletic talents.

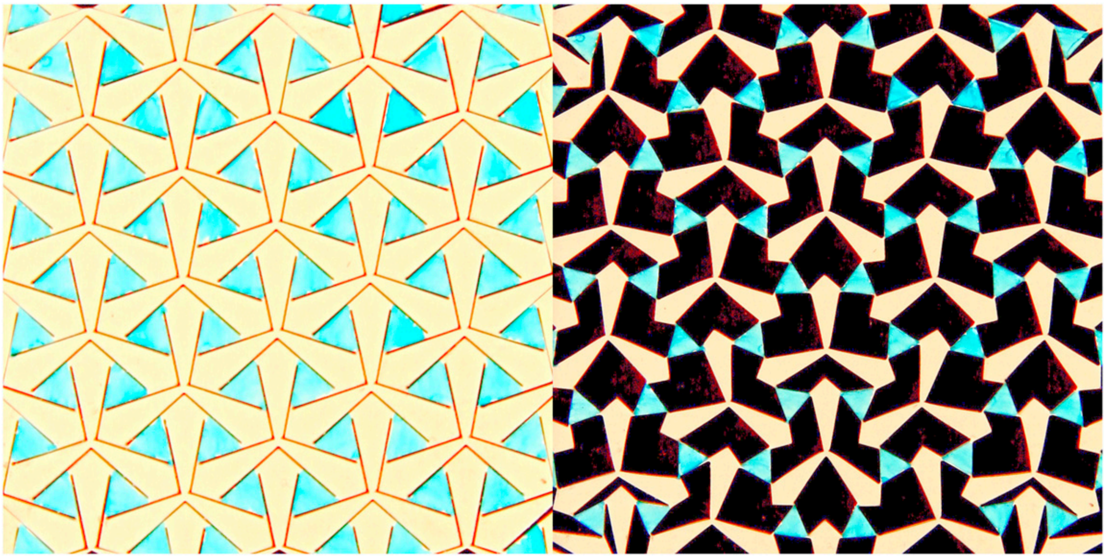
The company, called On, was looking for new ways to cushion its clients' feet by using 3D printing. On had heard about some strange materials Daraio and like-minded researchers had been fabricating in their labs: weird stuff that stretches and squishes in counterintuitive ways. "The sports equipment industry is relatively quick on the uptake," says Daraio, a professor of mechanical engineering and applied physics at Caltech. "It has been proactive in trying to use these materials."

The soles on Nike's recent line, Free footwear, offer an illustration. The bottoms of these sneakers don't look particularly special, just polymer cut into triangles. But the shapes are informed by science. Every time wearers take a step, their foot widens from the impact, stretching the shoes. Nike's sole responds by both widening and lengthening, to help absorb impact.

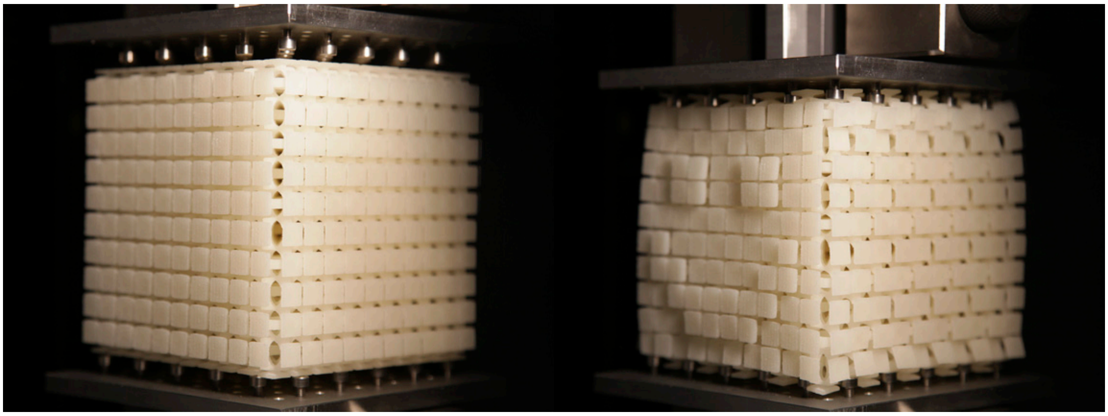
That shouldn't happen. Think of a rubber band pulled outward between your fingers; it narrows in the middle. Soft materials stretched wider should shrink in length. But the shoes exhibit bizarre behavior, thanks to materials made of simple patterns of repeating geometric shapes. And shoes are just the beginning, says Daraio. "A new field is emerging that creates unusual materials using simple geometrical architectures," she says.

Beyond Conventional

There's a name for this stuff: metamaterials, from the Greek word "meta," meaning "higher" or "beyond." The term was originally coined to describe things that interact with electromagnetic waves in counterintuitive ways—not because of their composition, per se, but because of their structure. Those optical metamaterials, first theorized by a Soviet researcher in the 1960s (1), can bend light in unnatural directions; their potential to hide objects from view has been frequently compared to Harry Potter-style invisibility cloaks.



Mechanical metamaterials, such as this Islamic-art–inspired metamaterial sheet, can pop into new configurations when stretched. Image courtesy of Ahmad Rafsanjani and Damiano Pasini (McGill University, Montreal).



A metamaterial cube built from small blocks transforms into a smiling face when squeezed. Reprinted from ref. 11 with permission by Springer Nature: Nature copyright (2016).

In the 1980s biomedical engineer Roderic Lakes found that structures with regular repeating shapes could also respond bizarrely to mechanical forces. Some foams, he discovered, fattened when stretched (2); they had a "negative Poisson ratio" in technical terms, a reference to Siméon-Denis Poisson, who studied the vertical strain an object feels when strained in a horizontal direction. These foams were later recognized as metamaterials; they owed their unusual mechanical properties to their internal geometry.

Daraio and other researchers have been trying to stretch the limits of what mechanical metamaterials can do. Imagine, for instance, a block that is hard like a brick on one side but soft like a sponge on the other. Working with colleagues in Switzerland, Daraio has made such a material (3). It consists of 3D-printed pyramids connected by hinges. The pyramids' response to vibrations is determined by the design and arrangement of hinges connecting them—as informed by the mathematics of topology, which provides guidelines on how to distort the pyramids to change the material's surface properties. (Such mathematics has also inspired the creation of materials that conduct electricity in unique ways called topological insulators—see www.pnas.org/content/113/37/10223.full.) This metamaterial has another ability that could be useful. Damage it—tear off a chunk—and what remains will still be hard on one side but soft on the other.

Martin Wegener's group, at the Karlsruhe Institute of Technology in Germany, has created plastic structures that behave like liquids; they deform easily when pushed on one side but refuse to be compressed to a smaller volume (4). This metafluid has led to what Wegener has called an "unfeelability" cloak; essentially a bumpless carpet that hides objects hidden below it (5). The design for this material dates to 1995 (6). But only in 2012 (7) had fabrication techniques advanced to the point of being able to fashion the delicate cones that comprise its structure—only a few micrometers wide at their thickest.

The Metamaterialists

The innovators behind these new materials are part engineer and part artist. They work at the intersection between science and design and find their muse in unconventional places.

Consider Ahmad Rafsanjani. Born in Iran, he grew up around the exquisite tile work that adorns Islamic mosques. Muslim artisans, prohibited from depicting people in holy places, developed this décor using sophisticated mathematical patterns. While a postdoctoral fellow at McGill University in Montreal, Rafsanjani wondered whether these designs could be put to use in metamaterials. "I borrowed a book from the library and used computational tools to check for interesting patterns," says Rafsanjani. His computer models checked for patterns that could snap to a stable new configuration when stretched. "Most of them didn't work."

Two designs from tombs in northern Iran built more than 1,000 years ago eventually proved interesting. As described in a 2016 article (8), he cut the shapes into rubber, leaving them hinged at their corners. When stretched widthwise, the rubber suddenly snapped into a new pattern—as the shapes swiveled around their hinges and holes in the pattern opened. After popping into this new configuration, the material had expanded lengthwise, like the soles of Nike's shoes.

Rafsanjani has since joined the lab of Harvard's Katia Bertoldi, a professor of applied mechanics. Bertoldi finds ideas for new materials while chatting with architects about their designs—or with physicists about nature's designs. One of her latest projects combines the biology of slithering snakes and the traditions of Japanese paper folding. "If you look closely at the skin of snakes, you will see that they change the tilting angle of their scales, which changes the friction and makes it easy to go forward but difficult to go backward," says Bertoldi. "We hope to replicate that with elements borrowed from kirigami," she adds, referring to a paper-folding art similar to origami but which also entails making cuts.

Other researchers have sought inspiration in everything from the structures that sand grains form when jostling against each other to the arrangements of atoms in crystals. Materials molded after spider webs (9) promise to tune out low-frequency sounds by creating a maze that slows down the movement of vibrations, and the layered nacre armor of seashells has spurred the development of foam–plastic hybrids envisioned as shin protectors (10). Like 19th-century Victorian naturalists gathering strange new animals from exotic corners of the world, the metamaterialists have been collecting exotic specimens wherever they can find them.

Some, like Martin van Hecke at Leiden University in the Netherlands, have also begun to combine different geometrical patterns—to make the next generation of metamaterials. Van Hecke makes big plastic cubes out of smaller plastic cubes; a simple geometry allows for many different combinations. By stacking the smaller cubes in different orientations, he can—with the help of design software—control, to some extent, what the big plastic cube does when squeezed. His favorite creation transforms from a cube to a smiling face when compressed (11). It looks like a child's toy. But the mathematics that makes it work is borrowed from physics; to understand what combinations of cubes would work, van Hecke studied the quantum configurations allowed in an exotic substance called spin ice.

A physicist by training, van Hecke believes that the complex geometries he is working with will allow materials to respond to their environments in complex ways—and potentially carry out a series of programmable deformations. He's interested in designing new kinds of prosthetic limbs more in tune with the body's movements. "Metamaterials could respond more flexibly to these movements," says Hecke, a professor of organization of disordered matter. "We're trying to make these materials active and more lifelike."

Material Results

Advances in 3D printers have helped drive much of this work. "The stuff that we can print now would have been pretty much impossible 5 years ago," says van Hecke. But, he notes, 3D printing has yet to reach the scale and cost of traditional manufacturing techniques. The future of metamaterials, van Hecke says, depends on future manufacturing advances.

Still, niche commercial applications for metamaterials have begun emerge. While Nike, Adidas, and Under Armour focus on shoes, Rolls Royce is working with Bertoldi to develop new jet engine components that can better withstand expansion and contraction caused by temperature changes, thanks to patterns of holes that change how the components deform. Chinese researchers hope to make helmets better at absorbing impacts, as the US military explores new kinds of body armor.

Researchers at Penn State are even looking into shielding buildings from earthquake damage. Cliff Lissenden, professor of engineering science and mechanics, recently received a small grant to test whether a massive metamaterial made of repeating elements—vertical rods jammed into the ground—can control seismic vibrations. Others have been experimenting with metamaterials inspired by origami that can fold themselves into predetermined shapes. One lab made headlines in 2014 with a simple robot constructed from a heat-sensitive plastic. When heated by a circuit, it shapeshifted and began to crawl (12).

Researchers have just begun to understand how mechanical materials work. Simple systems—arrangements of holes, for instance—have been well studied. But as one recent review put it, "many designs so far have relied on luck and intuition" (13).

Understanding what geometries to use to achieve hoped-for results—to fine-tune exactly how a material will stretch, snap, or shape-shift—remains difficult. "That's the big question everyone wants to answer: 'How do we go backward and make something from scratch that has exactly the properties we want it to have?'" says physicist Christian Santangelo, an associate professor at University of Massachusetts Amherst. "Right now we're all thinking that maybe if we make enough cool things, we'll be able to figure out the rules."

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