Trees Flex Their Muscles

Strength is more than just a question of muscle mass – as proven by trees holding their branches up, or grains of wild wheat independently boring their way into the ground. **Peter Fratzl** *and his team at the* **Max Planck Institute of Colloids and Interfaces** *are studying the materials that enable the plants to undertake these feats of strength. And based on the principles they discover, they are building artificial muscles and extraordinarily stiff materials.*

To study the tiny structures in natural materials, Ingo Burgert and his colleague Antje Reinecke use a mighty piece of machinery – an environmental scanning electron microscope – to get up close and personal.

Photo: Norbert Michalke

Trees have no muscles – at least none made of flesh and blood. And yet they hold their own weight and grow up toward the sky. "When branches become boughs, they grow muscle-like wood cells to bear the increase in weight," says Peter Fratzl, head of the Biomaterials department at the Max Planck Institute of Colloids and Interfaces in Golm near Potsdam. It is these kinds of wood muscles that bend the trunks of mountainside spruce trees to a vertical position, pointing straight up. "We now understand how trees do this," says the physicist.

With this knowledge, the researchers developed an artificial muscle that is induced to move by a change in air humidity. The discovery was no mere coincidence: the scientists from Golm are systematically searching for inventions of nature – templates technicians can translate into new mechanical drives, microscopically small valves or light yet tough materials. The team members employ a veritable arsenal of lab equipment and mathematical calculation methods in their quest; after all, Mother Nature likes to keep her cards close to her chest.

Peter Fratzl explains why nature's inventions are so hard to copy: it's because organisms are way too complex in their construction. Take robots, for example: "They used to walk stiffly and look ungainly," says Fratzl. "Stiff legs and joints are simply incapable of replicating the smooth gait of a human being." This only becomes possible with the sophisticated interaction of rigid bones and elastic muscles and tendons. "Technicians first had to understand the role of the various components in the overall 'movement machine' before they were able to build a robot that walked like a man."

There is another reason why simple duplication is rarely possible. "From an engineer's perspective, nature does not always offer the best solution," says Fratzl. For instance, an engineer might want to replicate a bone to come up with a robust yet light material. However, bones are more than just supporting pillars for the body – they also serve as the body's ion accumulators and bone marrow stores.

"A single biological tissue can have many functions," says Fratzl. Bones, muscles or branches are multitalented – the answer to the countless problems that assailed the organism in the course of evolution. "What environmental conditions a given tissue had to adapt to during its evolution is something we do not know," says Fratzl. The Dutch bioengineer Rik Huiskes puts the problem in a nutshell when he says, "If bones are the answer, what was the question?"

Water Gives Wood Muscles Strength

The researchers do not even know which of its roles the biological tissue fulfills the best and which are merely satisfied 'on the side.' To find out, the scientists from the Max Planck Institute in Golm are studying parts of plants, cells and bones under the conditions they encounter in nature. "We are trying to shed light on the essential core of the tissue's individual functions," says Fratzl. This will result in functional

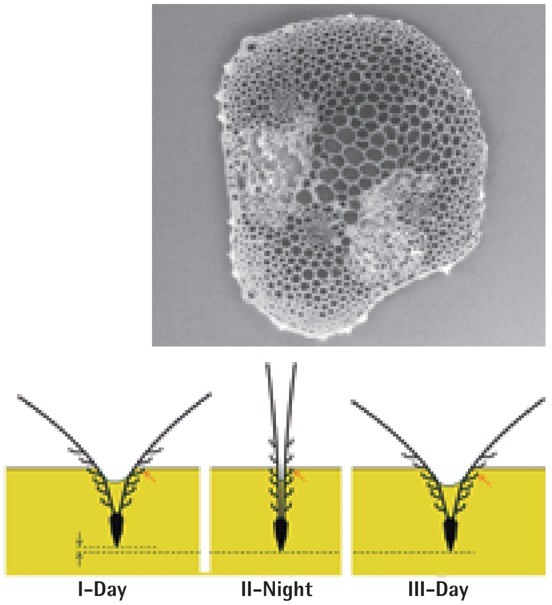


Fig.: MPI of Colloids and Interfaces

A seed bores its way down: The position of the cellulose fibers in its antenna-like awns – a cross section, above, in which two random areas are visible – make the appendages kick out as the humidity of the air changes. The barb helps the seed burrow down into the ground.

principles that engineers can then modify to create a technical solution that best fits its purpose.

The scientists are now hot on the heels of the functional principle of wood muscles. The cell wall of the tubular wood cells can absorb water like a sponge. What makes this possible is a porous bundle of hemicellulose, a macromolecule similar to cellulose. "The cellulose fibers, which are oriented like cables of a suspension bridge, are embedded in this hemicellulose 'sponge.' The fibers are hundreds of thousands of times thinner than a human hair, yet they are extremely rigid and can thus bear huge weights without stretching. They are about a hundred times stiffer than the surrounding sponge to which they are firmly attached.

The hemicellulose sponge swells as it absorbs water. The crystalline cellulose fibers, on the other hand, do not absorb any water. The direction of the cellulose fibers determines whether the wood cell expands or contracts. Since the wet cellulose fibers do not stretch, the wood cell can expand only in a perpendicular direction. Therefore, if the fibers lie transversely to the branch, the wood cells expand lengthwise along the branch. And if the fibers run parallel to the branch, something different happens: "Although the cell does swell up overall, it contracts in the direction in which the branch is pointing," says Ingo Burgert, one of the scientists in Peter Fratzl's department. That's because of the cell wall organization and the geometrical constraints of the cell. Cells with these kinds of fibers can thereby pull on the branch. "If the weight a branch has to bear increases, 'pulling cells' form on its topside while 'pushing cells' form on the underside," explains Burgert.

The living tree keeps the cells constantly supplied with enough water to maintain their pulling or pushing force. Dead branches, on the other hand, absorb moisture from the air. Man has used this fact since time immemorial as a means of forecasting the weather: we nail a twig about the width of finger onto a board. We then carve the word 'rain' into the board a few centimeters above the end of the twig and the word 'sun' just below the twig. If rising levels of humidity herald rain, the cell walls in the wood will become saturated with water. In this case, the cells on the underside of the twig will expand while those on the topside contract. The twig thus bends up several centimeters.

Kicking to the Rhythm of Day and Night

The twig does this even though each of the billions of wood cells expands or contracts by no more than a few thousandths of a millimeter. The researchers from Golm observed this miniscule change with a high-resolution video camera. And now they want to investigate the cells in more detail. "We want to know how the cellulose fibers change if we stretch the wood cells," says Burgert. "Individual molecules are the building blocks nature uses to construct tissue. We are interested in the correlation between mechanical properties such as elasticity or flexural strength and the molecular makeup of a tissue."

To enable them to find this out, the scientists built a type of stretching bank to stretch the individual cells. While the wood cells expand inside the apparatus, the researchers also irradiate them with laser light. The scattered light reveals how the chains of molecules change under the stress inflicted on them. In addition, an ultrasonic meter is used to measure the stiffness of parts of the plant. And they determine the orientation of the cellulose fibers using X-ray diffraction.

Rivka Elbaum used X-rays to investigate another feat of nature, one based on the humidity of the air, which falls during the day before rising again at night. The Humboldt fellow's work at the institute in Golm revealed how grains of wild wheat bore into the earth. The two antenna-like appendages, called awns, are the active parts of the seed dispersal unit and kick out like a frog's legs, albeit much slower – following the rhythm of the humid night and the drier day.

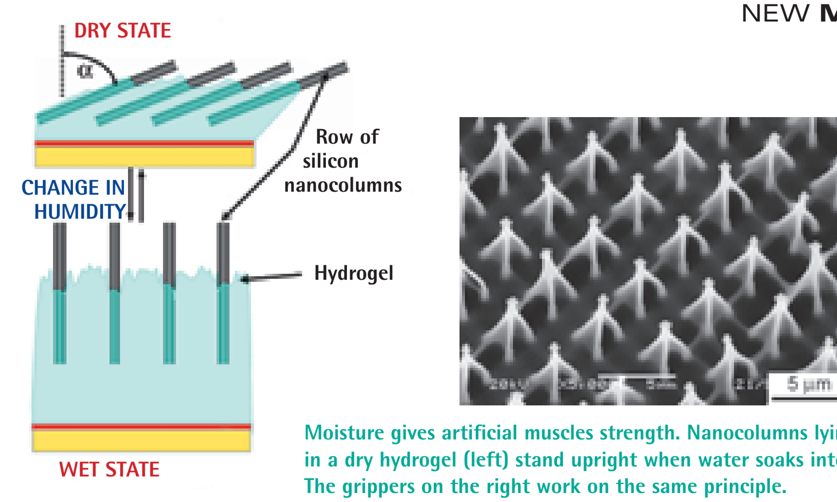
The awns have a kind of joint just above the seed, consisting of cells similar to those in wood muscles. In the cells on the inside of the joint, the cellulose fibers are oriented parallel to the awn, while those on the outside form a random bundle. When the air humidity increases at night, the awn becomes saturated with water. This causes the orderly cellulose bundle to swell without longitudinal elongation. The random bundle, on the other hand, expands in all directions – including along the awns. The outside of the awn thus elongates and the awn stands upright. This brings the two appendages very close together.

During the daytime, the opposite happens: the antennae bend away from each other. However, this form of kicking to the rhythm of day and night is, on its own, not enough for the wheat seed to be burrowed down into the ground. The awns are also covered in tiny, spiky silicified hairs, all pointing away from the seed. The spikes act like barbs, and they feel like barbs, too: if you run your finger along the awns moving away from the seed, they feel smooth; stroke the awns in the direction of the seed, however, and the resistance of the tiny hairs is noticeable. The spikes help the awns become anchored in the soil. When the antennae bend away from each other in the daytime, the barbs dig down a little deeper into the ground. And when the awns stretch upward at night, the tiny hairs become embedded in the soil, with the result that the seed bores a little deeper into the earth instead of slipping out of the ground. The next day, the awns bend away from each other again to tauten the wheat seed's inbuilt ratchet once more.

"It's the same principle behind the muscle-like wood cells and the mobile awns," says Fratzl. "The cells consist of a stiff, inflexible component that is embedded in an elastic gel. The two components are firmly connected." The drying and shrinking of the gel creates tension in the structure similar to what happens in a network of rubber fibers when they contract. "This tension stores energy and can therefore perform work," says the physicist.

Fig.: MPI of Colloids and Interfaces (3)

Inspired by nature: Peter Fratzl reveals how machines of vegetable origin function and why biomaterials are so stable, and designs new materials based on these principles.



Moisture gives artificial muscles strength. Nanocolumns lying down in a dry hydrogel (left) stand upright when water soaks into the gel. The grippers on the right work on the same principle.

Engineers can form active materials out of different stiff and flexible components. These new composite materials differ fundamentally from the artificial muscles and motors known to date. "Materials and motors are one and the same thing," says Fratzl. They are not a machine assembled from individual components. Furthermore, the active material works on its own without needing to be controlled or operated. "As with the wheat awns, the drive system could be controlled by the daily cycle of air humidity," says Fratzl. "Although the work the material did would not be available arbitrarily, it wouldn't cost anything." Fratzl can imagine active materials one day being used to turn solar cells to follow the motion of the Sun throughout the day, in much the same way as the wood muscles or the awns work.

Such artificial muscles would be built along similar principles to the natural models provided by plants, while consisting of a completely different material. In fact, Fratzl thinks they should. After all, in the course of evolution, plants and animals had to make do with just a few raw materials and with whatever environmental conditions they encountered. "Nature cannot make metal alloys, for example, because that often requires temperatures of a thousand degrees Celsius," says the physicist. Engineers, on the other hand, have many more raw materials at their disposal than a spruce finds on a barren mountainside. This is an advantage the researchers at the Max Planck Institute of Colloids and Interfaces and the American firm Bell Laboratories recently took advantage of.

They developed an active material that takes only its underlying principle from nature: one stiff and one soft component, firmly connected. For the rigid part, the scientists chose silicon columns thousands of times thinner than a human hair and only a few thousandths of a millimeter long. The flexible component, a hydrogel, is similar to the gel in plant muscles: it consists of a bundle of synthetic fibers with the ability to absorb water.

Like Reeds in Water

Like the natural gel, this gel swells up dramatically as it drinks in water. The researchers spread the wet hydrogel over a glass base in a film a few thousandths of a millimeter thick. They put the silicon columns in the gel so that they stood up like reeds in water. Then they heated the sample slightly to bind the columns chemically with the hydrogel and set them fast.

When the gel dries and contracts, the silicon nanocolumns tilt. In doing so, they reduce the distance between them, thus yielding to the pull of the shrinking hydrogel. The researchers noticed the formation of areas in which all of the columns lay parallel, like in a field of wheat after heavy rain. "And as you spread the hydrogel thinner, you even get all of the nanocolumns tilting in the same direction," says Fratzl. ▸

PHOTO: NORBERT MICHALKE

You can really learn something here: Ingo Burgert investigates the mechanism that causes pinecones to open.

In a humidity chamber, the researchers controlled the water content of the hydrogel, thereby controlling the degree of tilt of the silicon columns. The columns always returned to an upright position when the air humidity reverted to its original level. This is very important for the purposes of technical application: only when a movement is reversible can the new material do a job – otherwise it is just like a stuck cog.

Having got their first active material to work, the team of researchers went one step beyond the natural principle. They wondered what would happen if the silicon columns bent. To find out, they created a field full of the nanocolumns firmly attached to a sheet of silicon. Between the columns they spread a thin film of hydrogel, leaving about half of the length of the nanocolumns sticking out.

As the gel dried, the effect was similar to what happens to a thin film of water on a smooth surface: the gel formed droplets to reduce its surface area. Each of the droplets collected between four silicon columns. When the gel dried even more, the pearls of gel shrank and bent the four silicon columns toward each other like the jaws of a gripper. And this microscopic grip can be opened as the bent nanocolumns, free to move in the gel, return to an upright position. “Such complex movement patterns cannot be achieved with the artificial muscles created so far, which use electric and magnetic fields to move synthetic parts,” wrote the researchers in the journal SCIENCE in January 2007.

The researchers in Golm now plan to use a different function of the muscle-like plant cells, one that could be useful for the construction of aircraft or bicycles. Working in conjunction with the Institute of Textile Technology and Process Engineering in Denkendorf, near Stuttgart, and the University of Freiburg, the Max Planck scientists are developing a new fiber composite material, which they hope will be tougher and stronger than existing materials of this kind. Fiber composite materials already have much in common with the principles found in their vegetable origins: rigid glass, carbon or ceramic fibers are embedded in a soft synthetic material. The fibers give the material its stability, while the synthetic material makes it moldable. The result is a lighter material that is simultaneously more capable of withstanding stresses. The new Boeing 787 is one example of a system built from a carbon composite material of this kind.

RESILIENT TANGLE OF VEGETATION

However, its light weight also entails a disadvantage: the fiber composite materials start to vibrate easily. Vibration does more than just create noise. “It is lethal for a material,” says Markus Milwich, scientist at the Denkendorf Textile Technology Institute. “Vibrations make a material brittle over time, until it finally breaks,” explains the engineer.

Although wood cells have a structure similar to fiber composite materials, trees put up tough resistance to many storms and do not break just like that. “Plant cells have a trick they use to maintain resilience,” says Ingo Burgert. The hemicellulose fibers in the soft sponge are firmly attached to the stiff strands of cellulose. There are short fibers and long ones, which are embedded in the sponge to different depths. The tangle of hemicellulose fibers therefore becomes increasingly light as it gets further away from the cellulose fibers. This gradually transfers the stiffness of the cellulose fibers into the softness of the surrounding sponge. The stem breaks only if a vast number of the microscopic fibers are torn.

Engineers at the Institute for Textile Technology and Process Engineering have created a model of the natural principle with the help of silicon oxide nanoparticles. They immersed glass fibers in a nanoparticle solution before embedding it in artificial resin. The nanoparticles fastened themselves onto the fibers in a thin layer. “The shell of nanoparticles is softer than the glass fiber, but stiffer than the resin,” says Milwich. Thus, as with plants, there is a transition between stiff and soft.

In testing the material, the scientists made an unexpected discovery: the nanoparticles not only made the glass fiber material suppler, but also caused the test columns to vibrate less easily. “Now, we would like to try to get even closer to the natural model.” They plan to pack the glass fibers into several shells of nanoparticles with a stiffness that declines toward the surface, so that the fibers eventually merge into the resin. The researchers hope that the material will then be even better at dampening vibrations.

If they succeed, using fiber composite materials in construction could become much cheaper, says Milwich. “In aircraft construction, the vibrations are dampened with additional films,” says the engineer. “If the composite material itself prevents the vibrations, this extra cost could be avoided.”

And so engineers are rediscovering wood. Not just as a material, but as a major source of ideas as well.

CHRISTIAN MEIER