Super soldiers
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Nanotechnology general: Edwin Thomas, director of the new Institute for Soldier Nanotechnologies, foresees materials breakthroughs.
PHOTOGRAPH BY KATHLEEN DOOHER

SUPER SOLDIERS

IF THE ARMY'S $50 MILLION INITIATIVE GOES ACCORDING TO PLAN, FUTURE SOLDIERS WILL SUIT UP IN UNIFORMS THAT, THANKS TO NANOTECHNOLOGY, GIVE THEM SUPER STRENGTH AND PROTECTION FROM BULLETS AND BIOWEAPONS. IT'S A FAR-OUT VISION, BUT KEY MATERIALS TO MAKE IT HAPPEN ARE ALREADY IN HAND. BY DAVID TALBOT

Late last year the U.S. Army went shopping for some new uniforms. It wasn't interested in camouflage jumpsuits and olive drabs or even in better versions of the high-tech gear worn by the troops in Afghanistan. What the army wanted was a lightweight combat uniform capable of stopping bullets and toxins, monitoring a soldier's health, communicating with remote commanders—even enabling superhuman strength. But despite the extravagance of that vision, and even though they were looking to academic research institutions for help, army officials made another key desire clear. As MIT materials scientist Edwin Thomas recalls, they "didn't want just papers in *Science* or *Nature*. They wanted real stuff."

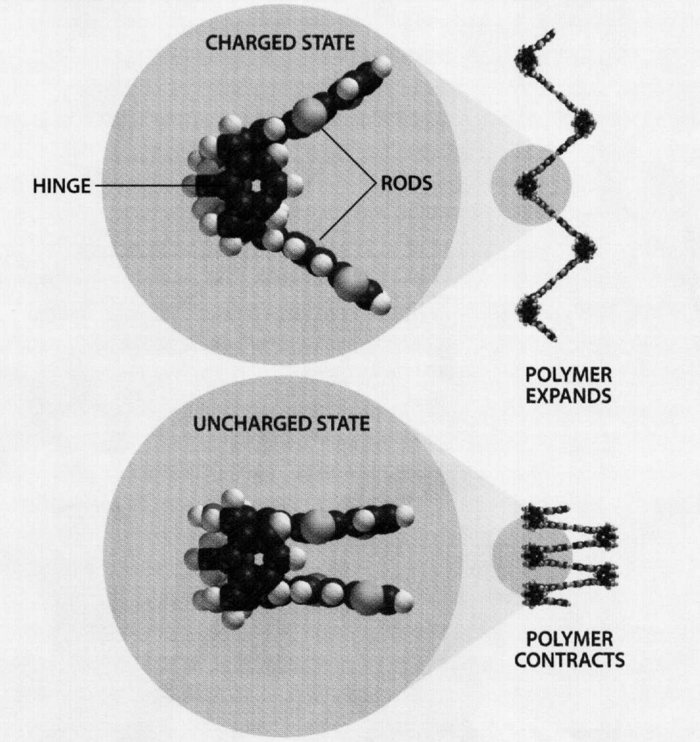
Real stuff is exactly what MIT researchers presented last January to a visiting army team. Mechanical engineer Ian Hunter played a video of a twitching piece of black ribbon—an expanding and contracting "artificial muscle" that could, in a combat uniform, form a tourniquet or boost leg strength. Materials scientist Yoel Fink showed off some shimmering optical threads capable of reflecting and absorbing different wavelengths of light with great specificity—a property that could be exploited for remote infrared communication that might, for example, allow soldiers to silently identify themselves to allies at night. Faculty members explained the workings of a microscopic sensor MIT chemist Tim Swager had built, just a few molecules wide, that could sniff a soldier's breath for chemical signs of stress.

Six weeks after that presentation, MIT got the job—a five-year, $50 million contract to establish the Institute for Soldier Nanotechnologies, under Thomas's direction. MIT, industrial partners DuPont and Raytheon, and Boston's Massachusetts General and Brigham and Women's Hospitals collectively pledged an additional $30 million. As the institute's name implies, the army is pinning its ambitions on nanotechnologies—devices and materials that are engineered with features at the nanometer (billionths of a meter) scale. The power of this approach, in theory at least, is that controlling a material's smallest features will allow researchers to build an array of functions and protections into a simple, lightweight outfit.

The effort also provides a clear proving ground for nanotechnology at a time when funding for the young field is surging worldwide. In the United States, for instance, the new army institute is part of a national nanotechnology initiative that distributes about $700 million annually. But the new army initiative is "unique in the sense of the magnitude of the grant at a single university," says Richard W. Siegel, director of the Rensselaer Nanotechnology Center at the Rensselaer Polytechnic Institute in Troy, NY. Indeed, the army sees the new institute as a ripe opportunity to bring together disparate but rapidly maturing nanotechnologies. "The nation has been investing in nanoscience for 20 or so years," says Michael Andrews, the army's chief scientist. "It's time to start harvesting."

Even if it works—and that is still a big if—the high-tech fighting uniform will take time. The institute's five-year goal is to get the various functions ready and perhaps deployable as add-ons to existing military systems. Putting all the technologies together in one mass-producible garment could take a decade or more. Along the way, though, the effort could yield such nonmilitary advances as health-monitoring garments for the elderly, lighter bulletproof vests for police officers and new trauma-care gear for paramedics. "We have a mission: to make it safer for soldiers to do their job. But there will be spinoffs every which way," says Swager, who is associate director of the institute.

Molecular Muscle



A polymer that contracts and expands as much as human muscle uses molecular "hinges" and "rods." The rods repel and attract one another when a charge is applied (top) and removed (bottom).

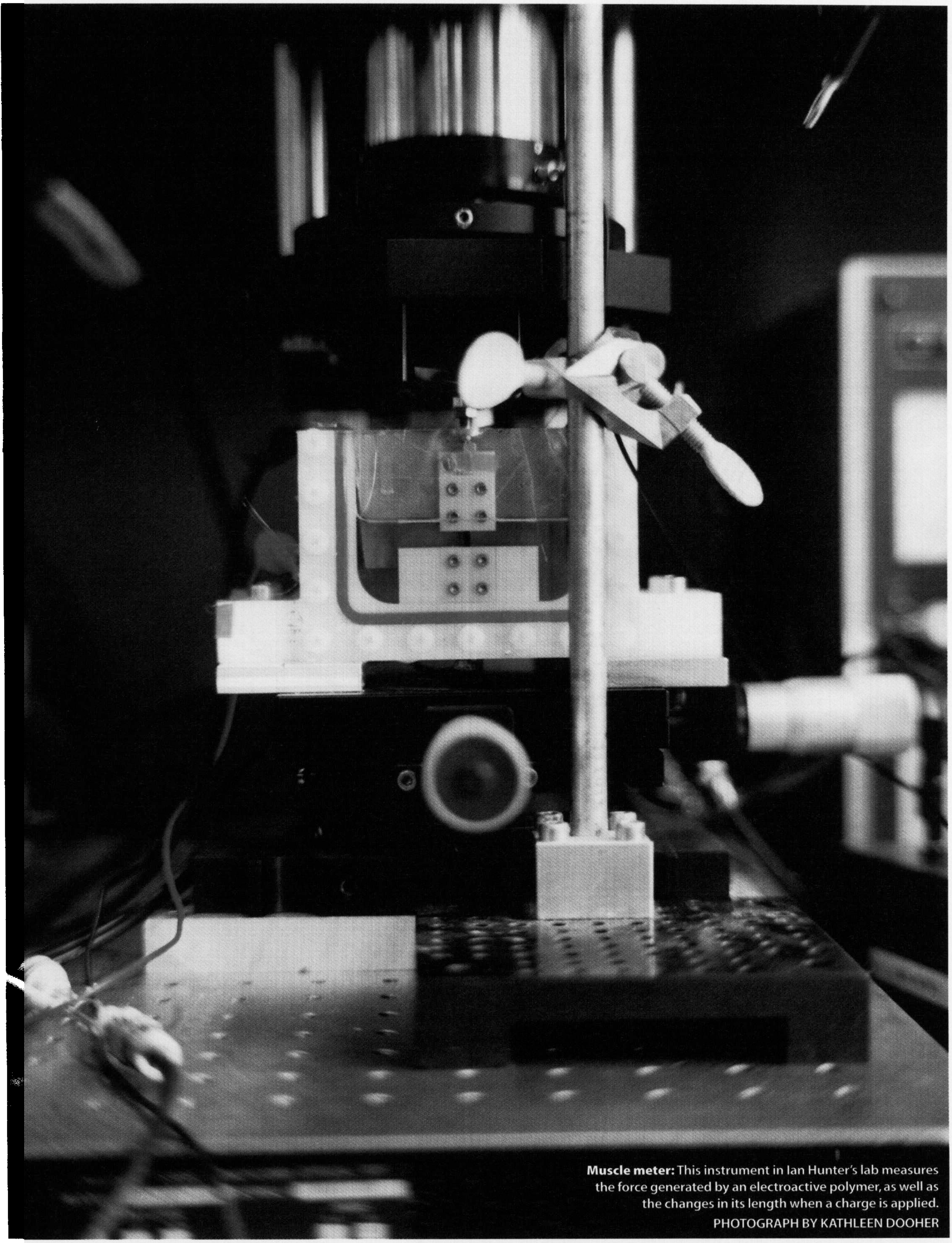
JOHN MACNEILL; SOURCE: MIT'S BIOINSTRUMENTATION LAB

STRENGTH

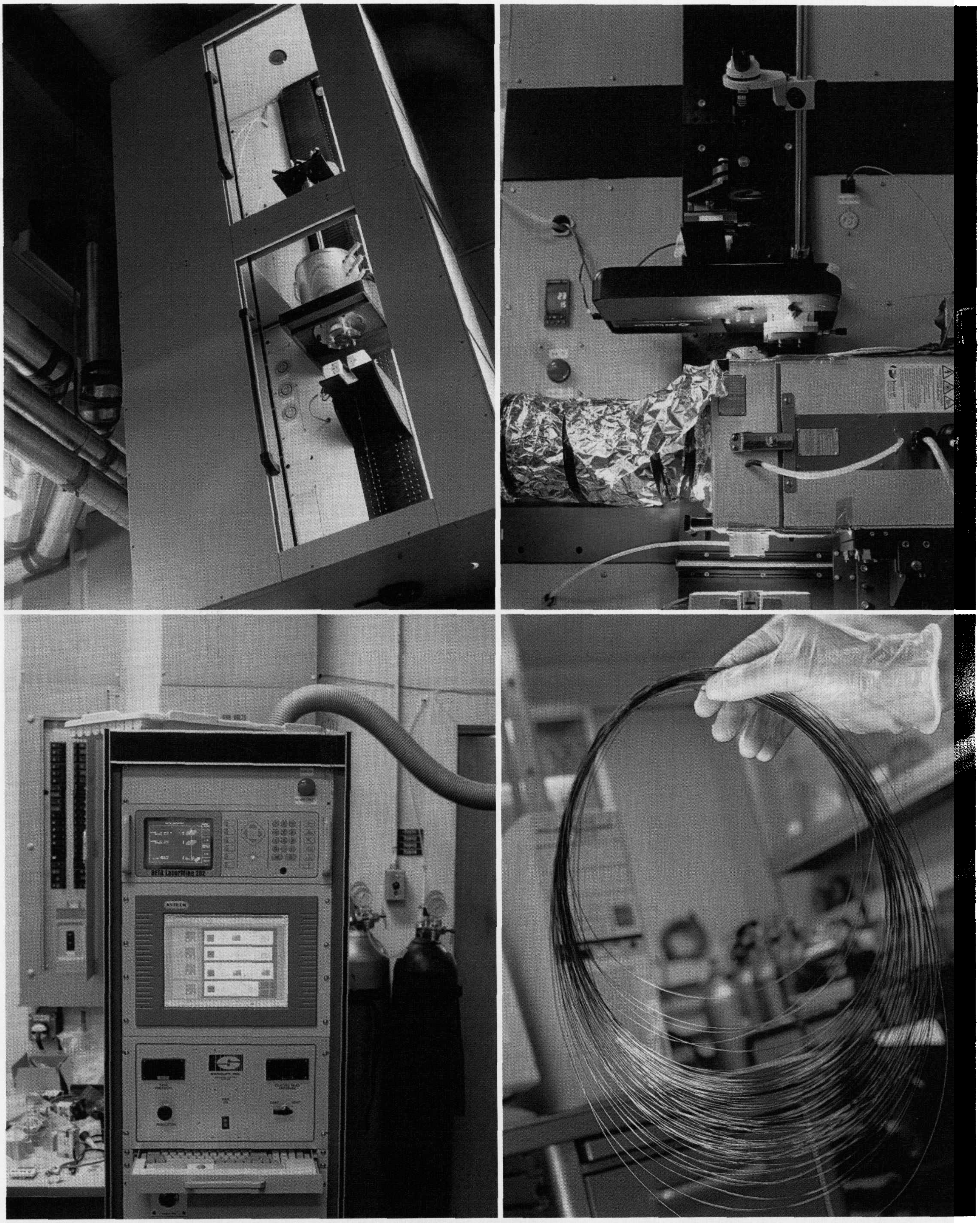
A chief objective of the new institute is to create a combat uniform that has built-in strength—the strength to help a soldier lift heavy objects, to pump cooling fluids through embedded channels or to stiffen around a bleeding wound. Hunter's twitching black ribbon is an early indication that nano materials might be able to deliver that sort of strength.

The ribbon is made of an electroactive polymer that can move or change shape in response to an electrical signal. Researchers have long envisioned using these polymers—which can be 100 times stronger than human muscle—as artificial muscles. But so far, they've proved impractical as musclelike machines, largely because their movements are relatively sluggish and also because they've been able to contract or expand by only a few percent of their length. Human muscle can contract and expand by 20 percent.

In Hunter's and Swager's labs, however, researchers have recently worked together to make great strides toward a material with enough range of motion to be useful. The key is a series of molecules that operate like rods and hinges. Pivoting on the hinges, the rods repel or attract one another when a charge is applied or removed. By attaching millions of these rods and hinges end to end like segments of a folding ruler, the researchers were able to create polymers that lengthen and shorten in response to electrical stimuli *(see "Molecular Muscle," this page).*



Muscle meter: This instrument in Ian Hunter's lab measures the force generated by an electroactive polymer, as well as the changes in its length when a charge is applied.
PHOTOGRAPH BY KATHLEEN DOOHER



From rod to thread: In Yoel Fink's lab, centimeter-scale rods are thinned as they are pulled through a furnace known as a "draw tower" (top left and right). The process, which is monitored on a control unit (bottom left), produces optical threads just 400 micrometers in diameter (bottom right). PHOTOGRAPHS BY WEBB CHAPPELL

A film made of these polymers produces musclelike movements. "Within the last few months," says Hunter, "we've doubled the range of motion," approaching that of human muscle cells.

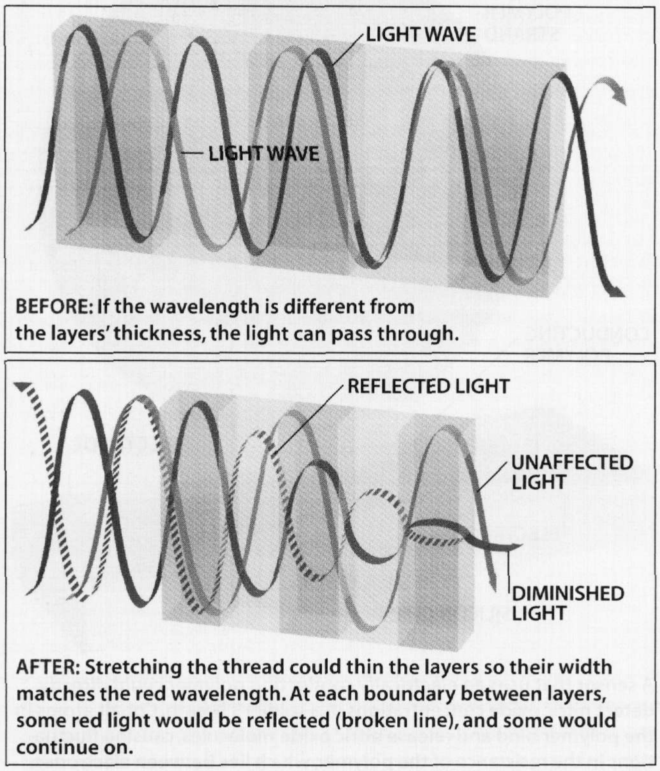
That increase in how much the polymer can expand and contract, combined with its impressive strength—which the researchers haven't measured yet but predict to be ten times that of human muscle—could conceivably allow a combat uniform embedded with 1.4 kilograms of the material to lift 80 kilograms one meter high. In other words, a soldier could effortlessly hoist a heavy piece of equipment or even a fallen comrade. The problem: this would take at least a minute, says John Madden, an electrical engineer at the University of British Columbia in Vancouver, who until recently headed electroactive-polymer research in Hunter's lab.

Giving these electroactive polymers useful speed is the next hurdle. It will require cutting back on the materials' electrical resistance, so an applied charge can do its work more rapidly. The researchers plan to reduce resistance by incorporating carbon nanotubes —long, pipelike molecules—into future generations of the materials. Certain versions of carbon nanotubes are excellent electrical conductors that could deliver charge throughout the material much more rapidly. The Hunter and Swager groups hope to make artificial muscles that are as fast as human muscle in five years.

Integrating the muscle material with the rest of the soldier's suit is the larger challenge. The electroactive polymers need, for instance, to be wired into a power distribution and signaling system; conventional wiring is simply too rigid for the job of hooking up a twitching, flexing material. So in the past year, Hunter and his coworkers have developed ribbonlike wires made of flexible electrically conducting polymers. "Instead of stiff copper wires going into polymer 'tissue,' we will have tissuelike wires going into tissue," Hunter says.

Fine Tuning

A cross section shows the outer layers of optical materials coating a polymer thread. The layers' thickness determines how light is reflected.



BEFORE: If the wavelength is different from the layers' thickness, the light can pass through.

AFTER: Stretching the thread could thin the layers so their width matches the red wavelength. At each boundary between layers, some red light would be reflected (broken line), and some would continue on.

COMMUNICATION

Other technologies will be needed to allow the suit to communicate with the outside world. Earlier this year, MIT's Fink announced development of coated polymer threads that might be just the thing, enabling silent communication with remote allies or commanders through the use of visible or infrared light.

Fink's threads are able to selectively reflect or absorb different wavelengths of light, thanks to their coating, which incorporates numerous ultrathin layers of two transparent materials—one organic, the other inorganic. The two materials slow light at different rates. In the resulting riot of reflections within those layers, some wavelengths are strongly reflected back out of the fiber, and others are canceled out. Just which wavelengths get reflected depends on the thickness of the layers, which can range from 100 to 1,000 nanometers and can be precisely controlled.

While most photonics researchers are working on chips and other gadgets for optical telecommunications, Fink's group is the first to build a photonic thread that could be made into a textile, says Eli Yablonovitch, an electrical engineer at the University of California, Los Angeles, and a pioneer in optical materials. One possible use for these threads: a portion of a combat uniform that strongly reflects a specific signature of ambient infrared light. During the confusion of a nighttime firefight, for example, such an "optical bar code" could identify a soldier as friend to fellow troops equipped with night vision goggles tuned to the right reflected light. And Fink's team would also like to come up with a way of tuning these materials on the fly, so that the wavelength could be changed electrically (and remotely) in case an enemy got his hands on a uniform.

This presents a special challenge, Yablonovitch says. "There are many solutions. Just no good ones. They have their work cut out for them to make it practical for the army," he says.

For now, Fink's group is pushing ahead with several approaches to making the optical fibers tunable. One strategy involves creating a sort of stretching rack that could pull the fibers taut. The tension would thin the layers, changing the reflected wavelength *(see "Fine Tuning," this page)*. A second approach takes advantage of the fact that one of the materials in the layers—arsenic triselenide—slows light at a different rate in the presence of an electric field; change the field and you change the reflection of the whole fiber. These approaches, Fink says, could produce a tunable fiber within two years.

PROTECTION

Of course, the overarching job of the uniform is to protect the soldier, and the ability to jump from harm's way or to silently announce oneself to allies would do that indirectly. But the army's vision is of a suit that would also provide direct protection against everything from bullets to anthrax. Improved ballistic protection is mostly theoretical at this point, but some very real tools against biological and chemical attacks are already in hand.

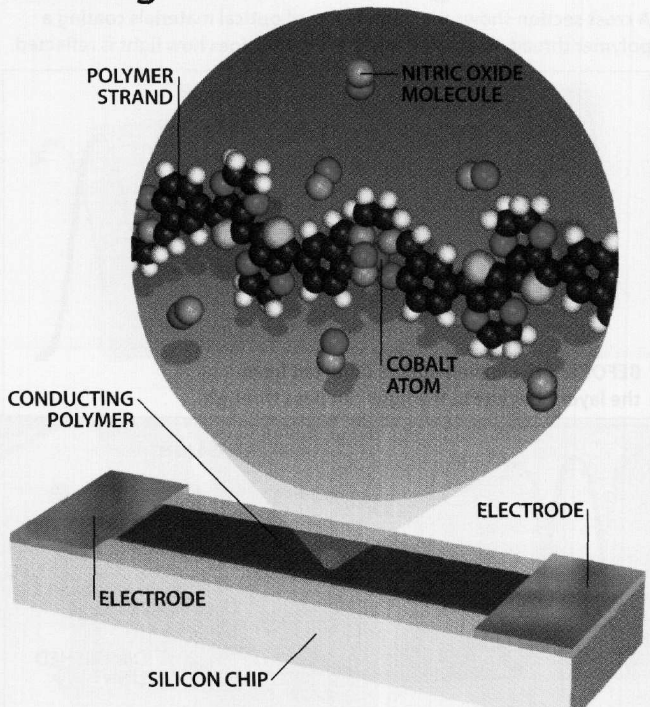
JOHN MACNEILL; SOURCE: YOEL FINK

One such technology is based on highly branched polymer molecules called dendrimers. By modifying the ends of a dendrimer's branches so that each of them sticks to a dangerous molecule and renders it harmless, army researchers have already created a protective substance with great absorptive power for its weight. But so far, they've been able to use the substance only by mixing it into a sunblock-like cream. The problem with adding this technology to a soldier's suit is that dendrimers don't easily stick to each other and thus are difficult to form into a stable material that would stand up to the abuse of a battlefield—and a washing machine.

To help make a more rugged material, MIT chemical engineer Paula Hammond designed dendrimers with "tails." These tails, several times longer than the dendrimers' branches, tend to entangle with one another, keeping the molecules latched together without blocking the branches from doing their jobs. It's like an extensive root system for a forest of molecular trees, and it could allow the anchored dendrimers to make a tough protective film. "These technologies are just budding right now. We can take them and begin to incorporate them into fabrics and coatings," Hammond says.

MIT researchers are also working on technologies that could help monitor a soldier's health remotely, regardless of what hazards he or she might encounter. Built-in sensors that detect changes in body chemistry, for example, might help determine whether a fallen soldier is critically wounded or can wait for aid. Such sensors would have to be extremely sensitive but also robust and simple to operate.

Sensing Health



A sensor that uses an electrically conducting polymer could directly detect nitric oxide concentrations in a soldier's breath. Cobalt atoms in the polymer bind and release nitric oxide molecules, causing fluctuations in the resistance of the polymer, which lies between electrodes.

And Swager has made a good first step. Using specially designed polymers as the detector, Swager has recently developed a device to sense concentrations of nitric oxide, a chemical present in human breath. Nitric oxide spikes when the body is stressed *(see "Sensing Health," this page)*. Taken alone, a nitric oxide measurement might not tell the whole story, but the sensor "is a first element that could be part of ways of assessing the physiological state of the soldier," Swager says.

The nitric oxide detector uses nanoscopic polymer wires capable of conducting electricity. When nitric oxide binds to the polymer, it produces a change in electrical resistance that can be readily detected. Additionally, the nitric oxide molecules quickly fall off the sensor, giving the device the ability to provide continuous measurements of the chemical's concentration.

Although just a prototype today, Swager's device could eventually be incorporated into a mask or the fabric of a soldier's suit to detect other chemicals—such as hydrocarbons and ketones—that can be indicators of stress or disease, or to detect biological and chemical agents.

INTEGRATION

Even as Swager and the other researchers in the institute continue to churn out such new materials and devices, they are already thinking about what will ultimately be their biggest challenge: making all their inventions work together in a mass-producible suit. "It will be a systems and integration problem that we've never seen before," Swager says.

That's where DuPont could help. The company has decades of experience developing such ultrastrong materials as Kevlar, used for bulletproof vests. Now it will help create new processes for integrating several nano materials into one textile. One problem: not all polymers are compatible. "They are not the same, and they don't behave the same," says Wayne Marsh, research manager at DuPont Central Research and Development in Wilmington, DE. "Some are made very differently; the same process could degrade one polymer while forming another." Reconciling these differences will require tweaking the polymers' chemistry or adding coatings to protect them from one another. All in all, "this is really 'edge' stuff," Thomas says. "It's like Jack Kilby of Texas Instruments in the early 1950s, thinking about making just tens or hundreds of transistors on a single silicon chip. You have to say, 'How would we do that?'"

Army brass and the civilian medical community have high hopes that Thomas and his MIT colleagues will find the answer, figuring out not only how to perfect new materials and devices, but also how to weave them together with revolutionary results. But they're realistic. "I don't know that all of this is going to yield what I want, when I want it, and do it at an affordable price," the army's Andrews says.

For sure, the new institute won't produce the full integrated combat uniform in five years. Instead, success on that time scale will mean a much lighter bullet-resistant vest or rugged "friend-or-foe" optical material, says Thomas. "One measure of success will be if we have gotten the attention and confidence of army folks to believe in using nanotech for the individual soldier," he says. "Big success will be if we actually put something tangible in a soldier's hands." It won't be easy. But given the institute's head start on materials development, the U.S. Army has at least a fighting chance of getting the uniform it seeks. TR

JOHN MACNEILL; SOURCE: TIM SWANGER