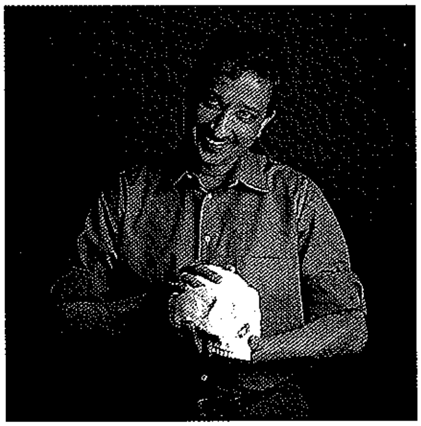
# *Charting the Terrain of* TOUCH

**BY RICHARD WOLKOMIR**



AT MIT'S LABORATORY FOR HUMAN AND MACHINE HAPTICS, RESEARCHERS ARE PROBING THE INNER WORKINGS OF OUR HANDS

MANDAYAM SRINIVASAN'S LABORATORY AT THE Massachusetts Institute of Technology studies the human hand. Srinivasan tells me when I visit that some people, blind and deaf since toddlerhood, have learned to "listen" by resting a hand on a speaker's throat and cheek. One such blind-deaf man "listened" to Srinivasan. "I was flabbergasted," Srinivasan says, his intonations only hinting at his native Bangalore. "He asked if I was Indian!"

He holds up his right hand, so I can marvel at so sensitive an instrument. He waggles his fingers. He curls them forward, first one row of knuckles, then the next, forming a fist. He twists the fist clockwise, counterclockwise. "I think about it like an engineer," he observes. "This is a system—how does this system work?"

To answer that question, he created MIT's Laboratory for Human and Machine Haptics—"haptics" is the Greek-derived word for studies of the properties of touch, including particularly the hand. Srinivasan's laboratory is nicknamed the Touch Lab. Researchers here use potent new ultrasound devices to peer into their own hands' skin, attempting to examine buried touch sensors. They build machines that mete out precise pricks and pressures and buzzes to fingers, usually their own, to measure the tiniest sensations hands can discern. And these scientists are investigating the physical responses that underlie the functioning of our fingers and skin. Exploiting their data, they have helped create devices that let you "feel" objects that exist only digitally. And then they use those devices to further probe the mysteries of our hands.

Robot hands that are sensitive enough to pick up pins could emerge from this lab. So could bionic hands for amputees. Surgeons could practice new scalpel procedures by harmlessly slicing air. Touch Lab research could lead to new art forms. It will certainly spawn weird games.

"Go ahead, hold that stylus like a pen, use it to explore," researcher Chih-Hao Ho tells me gleefully. We sit in front of a turned-off computer screen. I am holding a stylus resembling a dentist's drill on its long, flexible arm. "It's like a blindfolded person who is going to use a stick in order to explore the world," Ho says, grinning with anticipation.

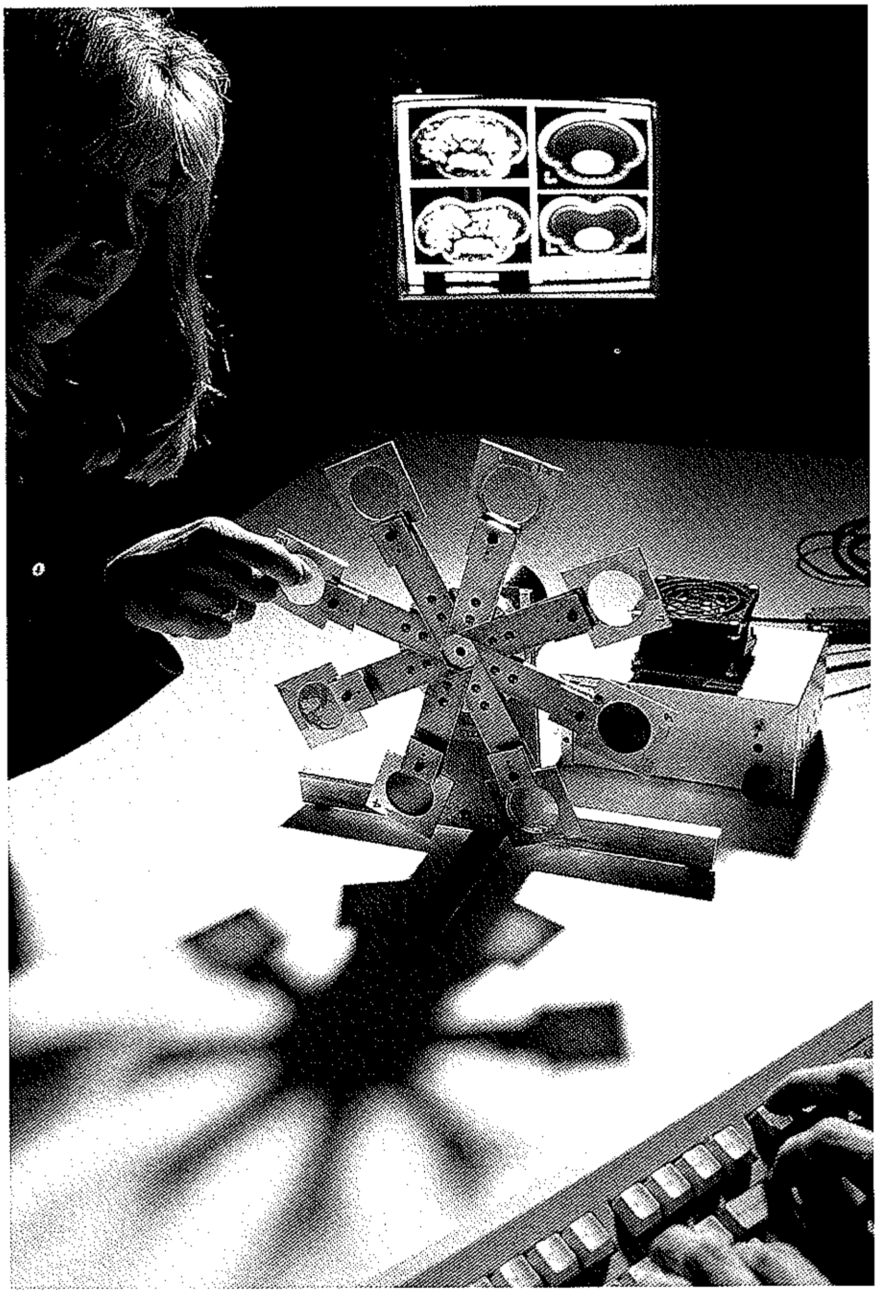
I move the stylus and sense that it rests on a plane, like the top of an invisible desk. When I push down, it resists, although it moves freely in all other directions. As I push the stylus across the plane, however, I feel it bump something.

"What is that?" Ho asks.

PHOTOGRAPHS BY RICHARD SCHULTZ

"It feels like a dome set into the plane," I say. He turns on the computer screen, and I see the "virtual reality" world in which I have been moving my stylus. "Virtual" is the computer scientist's term for objects that exist only inside a computer. And, sure enough, using just my sense of touch, I have been exploring a plane with an imbedded hemisphere, "feeling" objects that exist only as computer code. When I try to push the stylus through the plane or the dome, the computer activates tiny motors, exerting a counterforce against my hand, simulating the resistance of a solid surface. It feels uncannily real.

*The lab uses its findings to invest virtual environments with the sense of touch.*



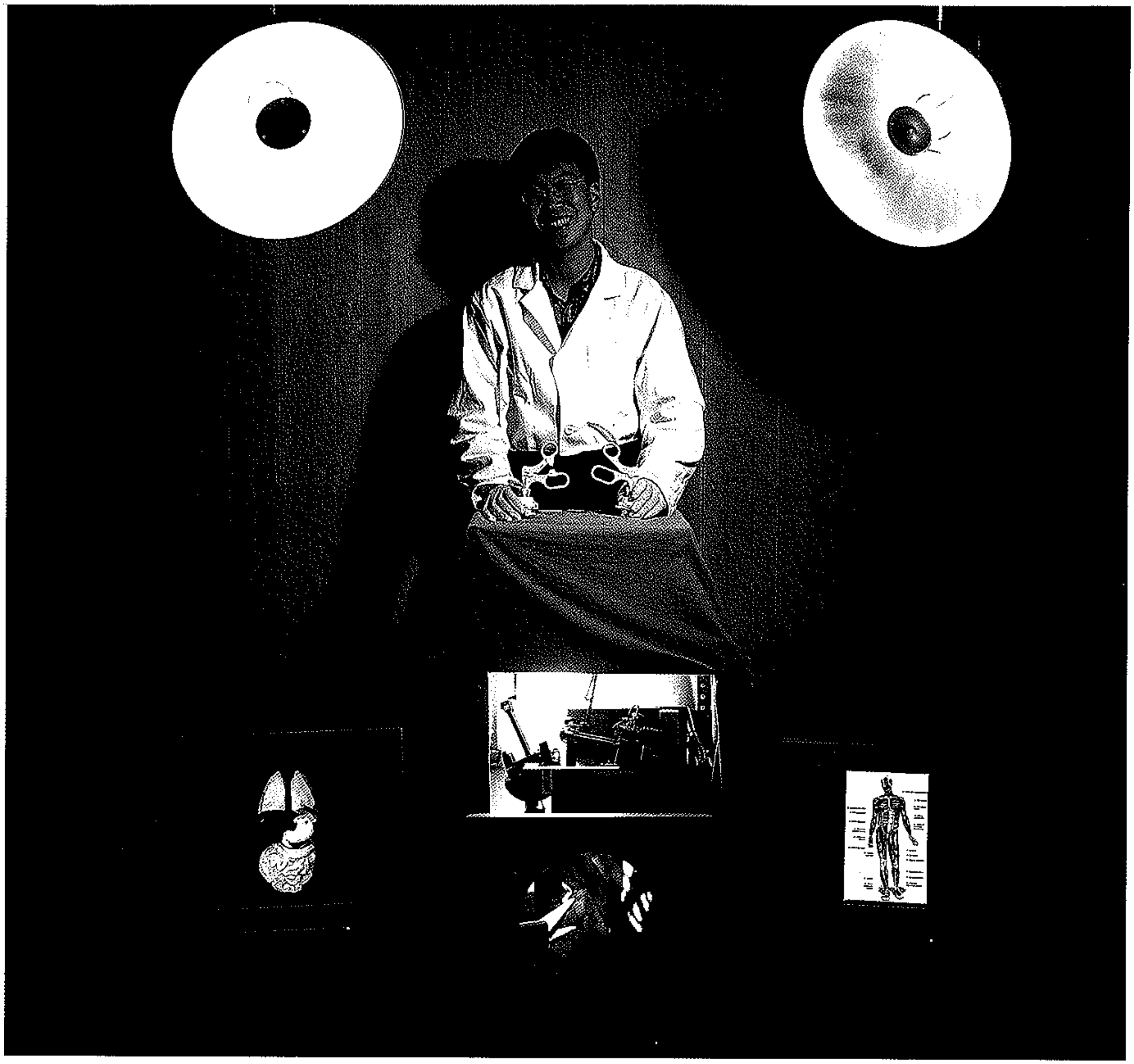
Ho puts a sphere on the screen. I move the stylus-controlled screen cursor all around it, and through the stylus I "feel" its roundness. He puts a virtual button on the computer screen and then instructs me to push it with the stylus tip. It feels just like pushing a real button. "See?" Ho inquires. "With this, you could control your computer in 3-D!"

Virtual reality—or, as the researchers prefer to call it, "virtual environment"—is hot in high-tech circles. NASA, for instance, uses virtual environments to train astronauts in such skills as firing their backpack thrusters to return to the shuttle if their tether should disconnect. Usually, you enter such virtual environments by donning goggles that show you images, plus earphones for sound and a wired-up glove that tells the computer where you are pointing or grasping. But Srinivasan's lab is using its findings about how the hand works to invest virtual environments with something new, the sense of touch. And he believes this use of haptic research is about to "explode."

On the computer screen appears a ball with a rough-looking surface: it feels like sandpaper under the stylus. Here is a doughnut with a surface that feels like corduroy. "Look," says Ho. "Lungs! Liver! Stomach! Intestines! Kidneys!" I poke the virtual organs with my stylus and feel the tissues give and then resist as I push deeper. On the screen, under the stylus-controlled cursor, I see the organs dimple where I poke, and watch them bobble in the virtual torso.

Ho and I play a game, each using a

**To investigate the extraordinary sensitivity of our finger pads, scientists use a rotating, multiarmed device to present varying surfaces to a research subject. The computer screen displays MRI images of the person's finger-pad cross section.**



**Assuming his role as "surgeon," graduate student Jung Kim takes up virtual instruments to perform virtual surgery on a virtual organ, the gallbladder (center computer screen). This device is being developed to train surgeons in laparoscopic procedures.**

stylus: we must cooperate to tilt a virtual table with our styluses, so that a ball rolls down the incline, bumping into a series of prongs. I "feel" the table's bulk under my stylus, feel it tip, feel when my stylus is working against Ho's. "So, two people could work together in one virtual environment," he notes. He cites a hypothetical example: an engineer in Tokyo, say, is working on a new car with a designer in Detroit. Both of the collaborators could "feel" the contours of the new model.

We play another game: a doughnut-shaped virtual ring rests upon a wire running through the hole. Using our styluses, we must cooperate to lift the ring and slide it along the wire. "We use this to try to understand how humans can interact through touch in a virtual environment," Ho explains. I suggest this could be a cool computer game. "Someday," Ho concurs. "Right now, it's an *expensive* game!"

Games will come. For now, the laboratory has more serious aims. Ho shows me a box draped with a green operating room cloth, with what look like two scissors handles poking out the top. Mandayam Srinivasan, who has joined us, says wryly: "This is a laparoscopic surgery patient." He tells me the laparoscopic instruments sticking out of the cloth are for making tiny, virtual incisions. A screen shows the "patient's" liver, with the stomach below. When a surgeon uses the instruments to practice surgery on the liver, he "feels" the liver's tissues press against his knives. "We invited a surgeon to try it, and he said it was pretty good, but the image on the screen is not yet realistic and we have to improve the 'feel' of the tissues," says Ho. "So it won't be a usable tool soon, but we're making progress!"

Progress grows from the lab's new gadgets, which perform such tests as applying precise pressures to fingers or seeing how hands interact with

**Wielding a computer-controlled stylus, another graduate student, Thao Dang, employs a sense of virtual touch to trace the outlines of a virtual rectangle, a shape that actually exists only as computer code.**

virtual environments. Gadgets aside, however, it is surprising that Mandayam Srinivasan studies the human hand, because he is an engineer. "In India, for kids like me who were good in math, you could be either a doctor or an engineer," he tells me. "I'm from a Brahman background, in which hurting animals is frowned upon, and student doctors must dissect animals." Srinivasan earned a bachelor's degree in civil engineering and a master's in aeronautical engineering in India, then a Yale doctorate in mechanical engineering. But wanting to apply engineering to biology, he joined Yale scientists studying the skin's touch receptors.

"When they hired me, they probably thought I'd maintain their equipment, but I found the science so fascinating that for the first three months I just read papers," he says. "I didn't know what a neuron was, but I discovered that my basic interest was understanding the science of natural phenomena." We are talking in his MIT office. It might be any corporate chief engineer's office, with two computers and two tables neatly stacked with books and reports. But one item resting nonchalantly atop a stack of papers is surreal: a rubber hand. "I got that as a curio, but I've used it in some tests," he says.

It is eclectic, this lab that uses instruments so advanced they must be invented here and also something as mundane as a rubber hand. And that breadth is reflected in the funding sources for the 14 researchers, ranging from the National Institutes of Health, Massachusetts General Hospital and Harvard University, to the Office of Naval Research and the Defense Advanced Research Projects Agency. "'Haptics' really refers to touching and feeling with any part of the body. For me, haptics is associated with almost anything you can do with your hands," Srinivasan says. Ultimately, his research leads us to the brain.

"Where does the hand end?" Srinivasan asks. "Not really at the wrist, because tendons in the forearm control hand movements." That reminds him—hand components mostly come in twenties. Depending on how you count, he says, each hand comprises about 20 bone segments, joints that allow for 20 degrees of movement, 20 forearm muscles controlling the hand, 20 muscles in the hand itself, and about 20 nerve types. "And nerves from the hand go all the way to the brain," Srinivasan explains. "So the hand really ends at the brain."

From your fingertip, information travels up your nerves as an electrical impulse. "It's very slow compared with our man-made electrical stuff, just 100 to 150 feet per second, versus the speed of light," notes Srinivasan. "There are pain fibers that transmit at only three feet per second, so you don't pull your hand away until you've already burned it!"

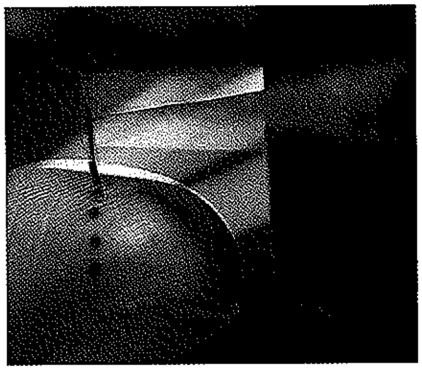
Srinivasan looks thoughtful. "The

brain is in a dark chamber, with no information except for those electrical impulses that are coming in from the nerve fibers," he observes.

This aspect of the hand remains an arena of great mystery. "We have no idea how these electrical impulses translate into perceptions and feelings," Srinivasan says. "We don't even know how to talk about consciousness." But the lab's engineers *can* study the mechanics of the hand—its characteristics as a physical object. And touch, Srinivasan points out, is unique among the senses. Seeing or hearing or smelling or tasting, you take in information, either photons or air-pressure pulses or molecules, he says. But when you touch something with your finger, you not only take in information to relay to "headquarters"—the object's hardness or roughness or coldness, for instance—but you also exert force against the object. Your coffee cup's weight stretches your fingertip skin, but your fingers squeeze the handle. "We use our hands to explore the external world, and then we use our hands to manipulate the external world," Srinivasan says. "And just as optics are important for the study of sight and acoustics for the study of sound, mechanics are important for studying touch."

Back in the lab, I watch researcher Balasundar Raju slide colleague Tim Diller's wrist under the tip of an instrument that looks like a large, complicated Erector set contraption. It is a powerful ultrasound imaging system the lab developed, running at 50 megahertz, versus 1 to 10 megahertz for conventional hospital ultrasound devices. "Originally, we used it to image fingertip skin, but now we're looking for clinical applications, such as seeing if we can detect melanoma at very early stages, and we're trying to get the parameters of normal skin," Raju says, as he pulses inaudible sound waves into Diller's wrist. "No sensation," Diller reports. "We are all subjects in each other's experiments," he adds amiably.

*"Each fingertip has about 2,000 receptors just for touch."*



**Another device measures properties of the finger pad: red dots indicate the site on the pad that is being studied.**

As the humming machine's tip slowly moves over Diller's wrist, graph lines zigzag across a screen. "It's showing us the skin about two millimeters deep," says Raju. He can translate the graph lines into data about the structure of the subterranean layer of skin he is examining. By studying the skin of many people, he hopes to establish normal skin's characteristics. Eventually, the machine should be able to spot skin abnormalities, early warning for skin cancers. "But originally we used this machine to look at tissues—to find out how thick the epidermis is, for instance," says Raju. "And just as you have fingerprints and ridges on the outside of your skin, it turns out the epidermis also has ridges inside, at its lower boundary."

I am back in Srinivasan's office. He is telling me what the researchers see as they aim their ultrasound device at a fingertip, burrow down through the fingerprint ridges, through the epidermis and the buried ridges along its underside, into the dermis layer, then down into layers of fat. "There are thousands of nerve receptors of all kinds in the fingertips," Srinivasan tells me. Some of those nerve receptors are for touch, but not all touch receptors are the same: each responds to its own kind of stimuli.

"There are also receptors that sense the forces against your skin. There is one kind of receptor for heat and another kind for cold," Srinivasan points out. Heat receptors respond to temperatures above body temperature, cold receptors to temperatures below body temperature. "And there are receptors specialized to detect mechanical pain or thermal pain or chemical pain, and still other receptors are for itch," Srinivasan says. Some receptors seem to sense the stretch of skin around your joints as you move, providing one of the cues for kinesthetic sense—even with your eyes closed, you know whether your fingers are splayed or clenched, for instance, or where your hands and arms are in relation to your torso.

Fingertips are particularly dense with touch receptors. "Each fingertip has about 2,000 receptors just for touch," notes Srinivasan. And then there are receptors that detect other sensations, such as pain. "The density of receptors falls off rapidly by the time you get to the palm." Each touch receptor transmits the limited sensations in which it specializes to the brain. "And the brain blends it all," says Srinivasan. "We do modeling in a supercomputer, trying to figure out how all this works."

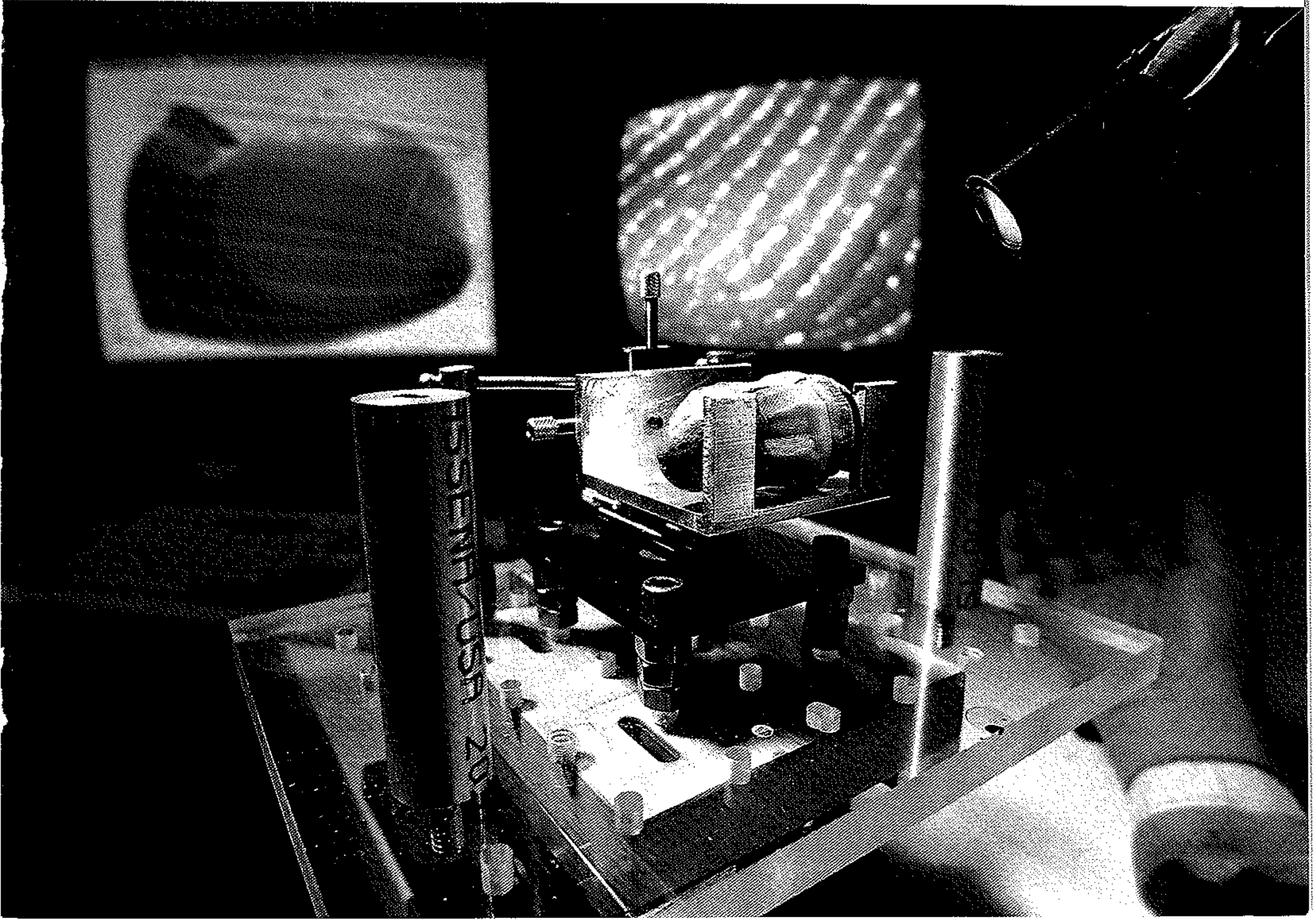
Our hands, it turns out, are stunningly sensitive. When he was a postdoc at Yale, Srinivasan reports, "we etched a single dot on a glass plate and rubbed it across fingers." Researchers there found that the human hand can detect a dot just three microns high—a human hair's diameter is 50 to 100 microns. Using a texture rather than a dot, the researchers found the hand can detect roughness just 75 nanometers high, which is tiny indeed. A nanometer is only a thousandth of a micron. Visible light has a wavelength of about 600 nanometers. "And using your fingernail, you can feel things that are even finer!" says Srinivasan.

In the retina, visual acuity is greatest at the center, the fovea centralis. As Srinivasan puts it: "Fingertips can be thought of as the fovea of touch." Fingerprints have piqued the researchers' curiosity. It is possible that the fingerprint ridges and the invisible ridges buried at the epidermis layer's bottom act as amplifiers, stretching sideways as the fingertip slides across, say, one of the lab's etched dots. Receptors buried in the fingertip skin detect the distortion of the ridges, then transmit the information to the brain.

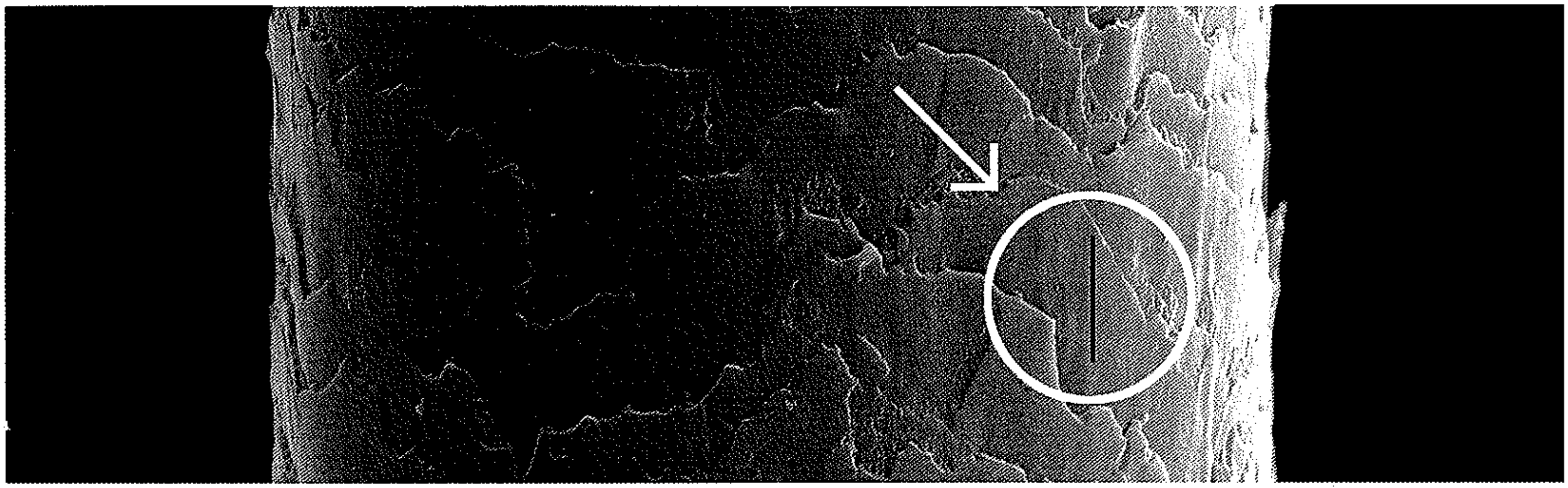
Back in the laboratory, researcher Silmon James Biggs has airbrushed my right index finger with black ink and strapped it into one of the lab's machines. I am giving my finger to science. I feel a buzz in my fingertip, like a tiny electrical shock. A moment later, I feel a second buzz, slightly stronger. My task, each time I feel these paired buzzes, is to twist a knob until the two buzzes feel equal. This is an experiment aimed at improving virtual environments: in one of the buzzes I feel, the probe has contacted my fingertip head on. In the other, the probe has hit my finger tangentially. My data turns out to further verify what the lab has been discovering: fingers detect tangential impulses and straight-on impulses equally well. That will make it easier to add touch to virtual environments. But the research also encompasses a further study of fingerprints.

"It's unknown what role the ridges at the bottom of the epidermis play in this kind of touch, so we're looking at cadaver tissues," Biggs explains. "Observe how the ridges on the sur-

**A video microscope magnifies the structure of a fingertip: the computer screen at right offers a view of a detail; the screen at left shows a computer model of the fingertip. The rubber hand, bottom right, often seen lying around the lab, is a kind of talisman.**



*How did a mere paw evolve into an appendage so sensitive it can perform a Mozart sonata?*



This close-up image of a human hair contains a black line superimposed on its surface: this line represents approximately 1/300 the width of a hair, or about 300 nanometers. The human finger can distinguish textures as small as 75 nanometers.

RICHARD SCHULTZ AND ANTHONY GARRATT-REED/MIT

face of the skin and the ridges underneath compress and stretch." Perhaps I grimace. "I don't care to cut up monkeys myself," Biggs says. "Cadaver tissue may be gruesome, but it's more my speed."

He tells me that skin ridges may also help to enhance grip, even though the ridges on your palm and fingers actually decrease the surface area of skin touching an object. "But there are a lot of sweat glands in the fingertips, perhaps more than in any other part of the body," Biggs tells me. He says that our skin, when we grip something, may act like a sponge on glass. "When the sponge is moist, there's more friction and a better grip," he observes. He shows me an electron microscope photograph of a fingertip's ridges, enormously enlarged. Each ridge is dotted with white specks, each a sweat gland. "So finger ridges might be for holding moisture," Biggs explains.

It is a complex gadget, our hand. And that raises a question: How did a mere paw evolve into an appendage so sensitive it can perform Mozart's violin sonata in E-flat major?

In his book *The Hand*, neurologist Frank R. Wilson, of the University of California at San Francisco School of Medicine, outlines current thinking about the hand's evolution. As Wilson puts it, "no serious account of human life can ignore the central importance of the human hand." In fact, he believes our hands and brains evolved together. According to Wilson, the hand (and brain) took a step forward about 60 million years ago, when squirrel-size early primates took to living in trees and made appropriate physical alterations. For one thing, their paws changed: the thumb—although not yet opposable—became more mobile, the better to grip branches. Also to make feeding easier, nails replaced claws. And palms developed sensitive skin ridges.

By about 10 million years ago, our tree-living ancestors had "learned" that making one's way across the top of a branch is a precarious transportation method. Better to hang from a branch and swing along below it, a technique called brachiation. But swinging required a loosening of the attachment between the wrist and the major forearm bone, the ulna, to allow extra arm twist and wrist tilt. By about 5 million years ago, when the hominids got going, the use of the hand assumed an even more primary importance.

Currently, anthropologists believe our earliest ancestor was the hominid genus *Australopithecus*, personified by the famous "Lucy." These creatures were bipedal, walking on their two hind legs. Lucy could join her thumb, index finger and middle finger to form a three-fingered grip, the baseball pitcher's "three-jaw chuck," enabling her to pick up and hold oddly shaped objects, such as stones. And Lucy's hand could repeatedly pound a rock, say on a nut, possibly because her new wrist for brachiation also absorbed more of the pounding's shock. Meanwhile, bipedalism gave Lucy an edge: her arms and hands, no longer essential for locomotion, could throw stones.

Perhaps the final piece in the human hand's modernization was the ability of the pinkie and the ring fingers to oppose the thumb. That made it possible for early hominids to swing a stick as a club. But modifications for stone-pitching and club-swinging conferred yet another advantage: our ancestors could manipulate small objects with just their fingers, without clenching them to their palms. Now they could go into the toolmaking business.

Wilson points out it was not just the hand's structure that changed for club-swinging and stone-chipping. So did the brain. For instance, swinging from branch to branch required enhanced hand-eye coordination. Touch also needed enhancement, demanding more brain rewiring. And the swinger needed a refined kinesthetic sense of how its arms and hands and legs were positioned as it flew through the air toward the next branch. In other words, says Wilson, to be a successful aerial acrobat, and then emerge as a stone-chucking and club-wielding predator, "demanded a bigger brain with very specialized control characteristics."

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In the Touch Lab at MIT, I tell Mandayam Srinivasan that one thing puzzles me. I can see how the mammalian paw might evolve into a hand capable of knapping flints and throwing spears. But if a driver of evolution is the likelihood that survival-enhancing physical changes will get passed on to offspring, what about accomplishments that don't help you to survive? How did the human hand get to play a mean violin?

Srinivasan shrugs. "I see no problem with that," he says. "Hands develop the basic capability of, say, chipping stones—to grasp, to apply forces over time and over space, pressing with this finger, then another finger." Once bones and muscles have adapted to such tasks, and the brain's "wiring" has adjusted, it is up to the brain to learn the hand's new repertoire of movements, in order to perform a new task. And so I spent several childhood years trying to learn to play the piano. I failed, but it was not my hands' fault. "Rock-throwing and violin-playing are on a continuum," says Srinivasan.

I decide to end my foray into hand research by visiting a palmist. As we sit in a coffeehouse, the palmist prods my hands and examines my fingers. He is a tie-wearing administrator in state government, with nothing to suggest so arcane a spare-time hobby. "I look at the skin texture, and the hand's flexibility, and the individual fingers and lines and the overall shape," he says. "You're a person who sets very high goals for yourself, and then you measure yourself by what you don't achieve—that's how you approach life," he says. Except for two short telephone conversations setting up this session, we met just five minutes ago. And he has hit upon one of my core traits.

He cites attributes and faults he reads in my palms' hollows and lines and my fingerprint whorls. Easy generalities, applicable to almost anyone? Who knows? As he continues to "read" my palms and fingers, odd thoughts bubble up.

"Give this man a big hand—you've got to hand it to him," I think. And I think about how we make contrasts by saying "on the one hand," and "on the other hand." We say someone "writes a good hand." Ships are crewed by "all hands." Horses stand so many hands high. "A bird in the hand," we say, and "firsthand information." We may go cap in hand, or hand in hand, or climb a rope hand over hand. "Hands up," says the robber. Our best employee is our right-hand man. We have situations in hand. We take responsibility in our own hands. Sometimes our hands are tied. We work hand in glove with trusted associates. We give our daughters' hands in marriage. We may bite the hand that feeds us, or get the upper hand, or have a free hand, or live from hand to mouth. We wash our hands of problems. Sometimes we act high-handedly—or win hands down.

Mandayam Srinivasan, at the MIT Touch Lab, said "the brain is in a dark chamber." It must be that our enchambered brain has created so many hand phrases because it relies on our hands for a feel of the world, and to get a grip. And I wonder about this polite man in the coffeehouse, trying so hard to report what he "reads" in my hands in words that are not hurtful. Did his art arise because the ancients, knowing nothing of neurons and electrical impulses, still grasped that our hands begin in our heads? Dr. Frank Wilson told me about a time when he addressed a group of doctors: "I reminded them that a surgeon operating on a violinist's hand is doing brain surgery."

Leaving the coffeehouse, we do the natural thing, the palm reader and I. We shake hands.

*Richard Wolkomir, a regular contributor, is based in Vermont. Photographer Richard Schultz works from Boston, Massachusetts.*