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Engineering Sensation in Artificial Limbs

Advancements in mobile electronics have led to several prosthetics innovations in recent years, but providing reliable touch sensations to users remains an elusive goal.

RESEARCHERS WORKING IN advanced prosthetics, a field that draws on physics, biochemistry, and neuroscience, are attempting to overcome key engineering challenges and make potentially life-changing artificial limbs capable not only of moving as naturally as healthy human limbs but also of providing sophisticated sensory feedback for their users. Improvements in materials science, electronics, and sensor technologies, along with sizeable government funding in the U.S. and abroad, are contributing to these efforts. However, while leg prosthetics have advanced even to the point where it is now possible for amputees to rival the capabilities of nondisabled athletes in certain sports, the nuanced movements of the human hand remain the most difficult to replicate mechanically.

Advancements in portable power and mobile electronics have led to several prosthetics innovations in recent years. One example is the i-Limb, the result of a project that garnered much media attention when the device came to market in 2007 and was said to be the first commercially available hand prosthesis with five individually powered digits. While the technology for enhancing motor functions continues to improve, providing reliable sensory feedback to users about what an artificial hand might be touching remains a distant goal for scientists and continues to be an active area of research.

The U.S. Defense Advanced Research Projects Agency (DARPA) has been funding extensive work in this area, with the objective being to create artificial limbs that tie directly into the nervous system, facilitating more natural control and reliable sensory feedback. The charter of Advanced Prosthetics, the first DARPA-sponsored project in this field, was to produce a strap-on artificial arm built with the most advanced ready-to-use technology available. That program, run by DEKA Research, resulted in a prosthesis called the "Luke Arm." The second DARPA-sponsored program, Revolutionizing Prosthetics, focused on using new control technologies and neural interface strategies to create a modular arm that could match the performance of a healthy limb.

A prototype created by the Revolutionizing Prosthetics project in the Applied Physics Lab at Johns Hopkins University.

Stuart Harshbarger, chief science officer at Orthocare Innovations, directed DARPA's Revolutionizing Prosthetics project from the Applied Physics Lab at Johns Hopkins University. The research timeline of Harshbarger's program, which came to a close earlier this year, overlapped with DEKA's development and involved collaboration with more than 300 researchers at 30 institutions.

"The program made enormous strides in demonstrating that natural and intuitive control of increasingly anthropomorphic artificial limbs is indeed possible in the near term," says Harshbarger. "But there is much basic engineering work to do to make such systems reliable and affordable for clinical adoption."

DARPA projects typically fall into the high-risk, high-reward category, with the idea usually being to show that the impossible can be made possible. Harshbarger says that, by this measure, the demonstrations created for the Revolutionizing Prosthetics program succeeded. The project produced what Harshbarger calls the world's first closed-loop, multisite, multi-electrode cortical interface technologies and the world's first wireless, multi-electrode, motor-decoding applications designed to enable neurophysiology studies that have not been possible with wired setups.

"The science and technology components progressed, as proposed, and possibly with greater success that was originally contemplated," says Harshbarger. As with any advanced research, key challenges remain, such as the viability of cortical and peripheral neural interface technologies, but Harshbarger says these issues can be addressed incrementally in later research. The next DARPA-sponsored research in this area will focus specifically on brain-computer interface challenges, where Harshbarger says a significant amount of work remains to be done.

Modular Designs

Given that no two amputations are exactly alike, one of the objectives for researchers working in the Revolutionizing Prosthetics project was to create modular designs so the devices coming out of the lab could accommodate the reality that each user and prosthetic setup would be unique. One research team, for example, focused

PHOTOGRAPHS BY FREDRIK SEBELIUS, LUND UNIVERSITY on developing a targeted muscle reinnervation (TMR) procedure to restore natural touch sensations. The TMR procedure's modular sensor systems, which measure a mere 5 × 5 millimeters and contain 100 electrodes for recording nerve signals and stimulating nerve fibers, are now entering a commercial transition phase.

Harshbarger says that keeping these different projects synchronized and focused on a modular design philosophy required constant communication. "Most people, including myself, believed that coordination of these various research groups and their principal investigators would be like herding cats," he says. "In reality, however, I was surprised and exceptionally proud of how the team focused on the common goals and mission of the project."

Another researcher working in this area is Fredrik Sebelius, coordinator of the SmartHand project and a professor in the department of measurement technology and industrial electrical engineering at Lund University. The SmartHand project, spanning multiple research facilities at several universities across Europe, paralleled DARPA's Revolutionizing Prosthetics program in its ambitiousness, but focused exclusively on replicating the capabilities of the human hand. The goal for Sebelius and other researchers working in the project was to create an electromyography-controlled robotic hand that could deliver feedback to the user by stimulating what Sebelius calls the sensoric phantom map.

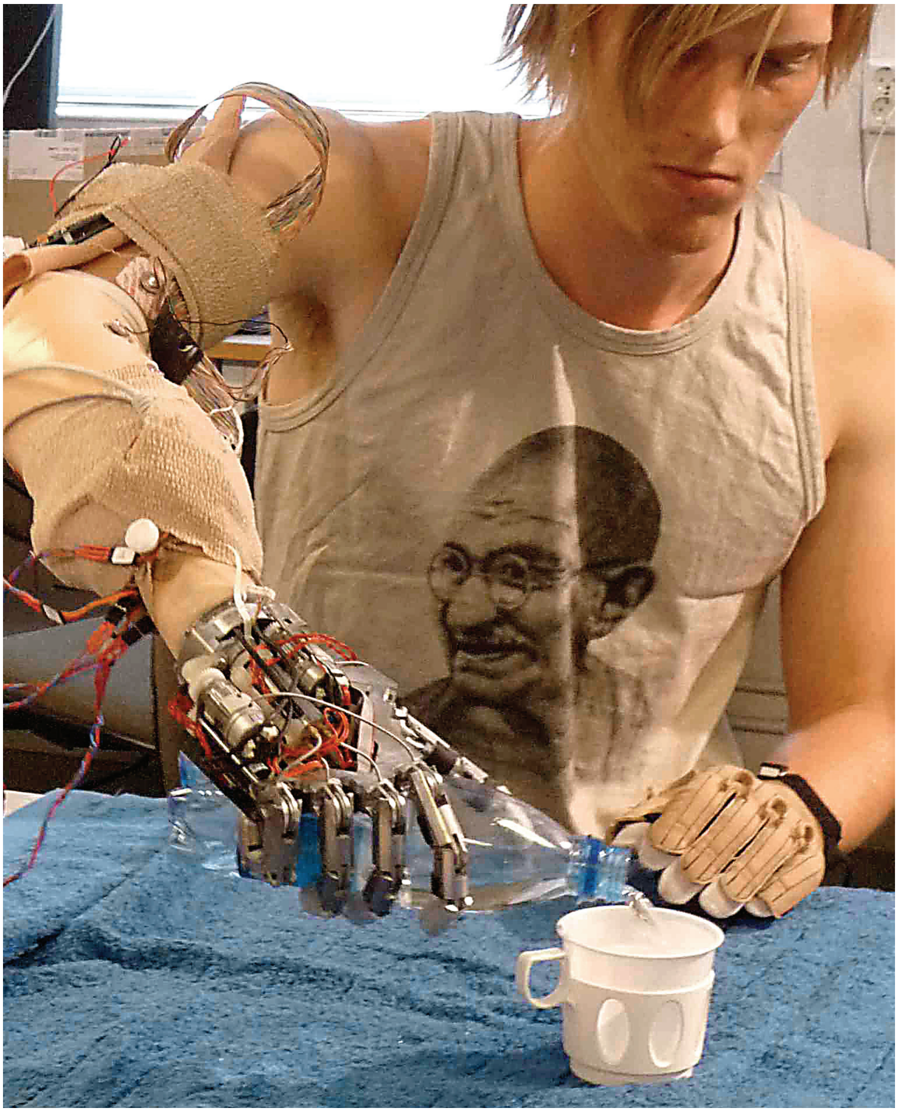
Sebelius describes the sensoric phantom map as a well-organized region of the brain that can be stimulated through nerves in the arm to produce feelings in a missing hand. The idea might appear to be straightforward, but the implementation is far from simple. Sebelius and his team developed and refined their approach to phantom maps by using functional magnetic resonance imaging and a modular neural interface designed to be attached to an arm's nerve bundles. "The sensors on the hand prosthesis deliver tactile information to the subject's phantom map via actuators and, voila, the subject experiences sensation from the missing fingers," he says.

The SmartHand project reached the proof-of-concept stage, but Sebelius says much work needs to be done before the technology can move out of the lab. The main challenges, he says, are biocompatibility and signal loss. As for the SmartHand prosthesis itself, Sebelius says the project will need more funding to make it ready for commercialization. "The robotic hand was only intended for research groups," he says. "It has not undergone production development." Still, Sebelius notes the research that led to the creation of the hand made it possible to achieve crucial advances for ongoing work in nerve-signal recognition and processing.

Like Harshbarger's Revolutionizing Prosthetics project leading to several new technologies that are now spinning off into different research teams, the SmartHand project formally came to an end last year with several subprojects gaining independent momentum. Sebelius says he and his team now will focus specifically on the sensory feedback system to design a new module that can integrate the phantom map concept into any prosthetic device. He says he remains optimistic about the work but is careful to note that current signal-processing technology and portable electronics cannot perfectly replicate the performance of a healthy human hand controlled by thousands of nerves.

"Hopefully," says Sebelius, "we will be able to achieve a level of sophistication so the user will not see the prosthesis as a tool but rather as an extension of the body."

While the potential benefit of such sensory-feedback technology is readily apparent, the cost of prosthetics designed for sensation may be prohibi-



A myoelectric prothesis created by researchers in the SmartHand project at Lund University.

tive. Today, advanced prosthetic devices can cost more than $20,000, putting them outside the buying range of amputees living in developing nations. Several organizations are dedicated to creating low-cost prosthetics, especially for nations with large numbers of people who have lost limbs due to landmines. One such project, Mobility for Each One, led by Canadian industrial designer Sébastien Dubois, has developed an energy-return prosthetic foot that can be locally produced for a mere $8. But as of yet, there is no project that operates as an analog to the One Laptop Per Child program, seeking to provide low-cost, sophisticated prosthetics to developing nations.

"For now, a sophisticated hand prosthesis will remain quite expensive," says Sebelius. Harshbarger offers a similar perspective. "This is a difficult issue and one that I believe in addressing, though our work has largely been on reducing costs for the highest-capability systems for domestic users," he says. As with any modern technology, production costs will come down over time, but the most advanced prosthetic devices are expected to remain expensive.

As the science of prosthetics matures, discussion about the ethics of using the technology as supplementary enhancement for healthy limbs rather than as replacement for lost limbs no doubt will become more complex. Artificial enhancement, a popular trope in speculative and science fiction, has a long history of advocates and detractors. What's likely to turn out to be the first experimental augmentation with a healthy human appears to have been accomplished by British scientist Kevin Warwick who, in 2002, had a device implanted in his arm to interface electrodes with his median nerve, allowing him to control a robotic arm by moving his own.

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Advocating such uses of prosthetics research might be called either visionary or far-fetched, but there is no disputing the notion that modern prosthetics breakthroughs have led to new ways of looking at ability versus disability. In 2008, for example, South African double-leg amputee Oscar Pistorius was ruled ineligible for the Summer Olympics because it was thought that his carbon prosthetics gave him a distinct mechanical advantage over runners with ankles. An appeal led to the ruling being overturned on the basis that there wasn't enough conclusive evidence. And, in the end, Pistorius didn't make the team. But many credit the brouhaha as helping to reshape global perceptions about disability.

Sebelius, for his part, says he remains convinced that, no matter how sophisticated prosthetics technology becomes, it will be difficult to rival the capabilities of healthy, functioning limbs. "Nature has done a pretty good job," he says. "An interesting parallel is artificial intelligence: although we have very fast computers, we are not even close to mimicking human intelligence or learning."

Further Reading

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Kirk L. Kroeker works in communications and has written extensively about the impact of emerging technologies.

Milestones

Japan Prize and Other Awards

The Japan Prize Foundation, National Academy of Engineering (NAE), and U.S. President Obama recently recognized leading computer scientists for their research and leadership.

JAPAN PRIZE

Dennis Ritchie, retired, and Ken Thompson, a distinguished engineer at Google, were awarded the 2011 Japan Prize in information and communications for developing Unix. Ritchie and Thompson will split the prize's $600,000 cash award.

NAE MEMBERS

The NAE elected nine members in the field of computer science and engineering. They are: Susan Dumais, Microsoft Research; Daphne Koller, Stanford University; Hank Levy, University of Washington; Jitendra Malik, University of California, Berkeley; Nick McKeown, Stanford University; Don Norman, Northwestern University; Ari Requischa, University of Southern California; Fred Schneider, Cornell University; and Mihalis Yannakakis, Columbia University. Jonathan Rose, University of Toronto, was elected as a Foreign Associate.

PRESIDENTIAL MENTORING AWARD

Maja J. Matarić, a professor of computer science at the University of Southern California (USC), received the U.S. Presidential Award for Excellence in Science, Mathematics, and Engineering Mentoring in recognition of her work with K–12 students, USC students, and faculty colleagues.

—Jack Rosenberger