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ROBOTICS AND NEUROPROSTHETICS

Smaller, Softer, Safer, Smarter Robots

IN SCIENCE FICTION, ROBOTS ARE OFTEN PORTRAYED AS HAVING INTELLIGENCE AND capabilities similar to humans, interacting with humans in a natural, often anthropomorphic way. Once only the subject of Hollywood blockbusters, today's robots are increasingly a part of everyday life. Historically, robots have been used in situations that are too arduous or too dangerous for humans or require skill or strength beyond human capabilities. The classical examples are assembly line robots, robotic manipulators in space applications, and battlefield robots that seek mines or improvised explosive devices. More recently, robots are appearing in people's homes as automated vacuum cleaners, lawn mowers, and toys. The core robotic technologies that were developed for these products (such as sensors, actuators, control algorithms, and mechanisms) are affordable and accessible and are now being applied to a wide variety of medical applications.

A prime example of medical robots is the da Vinci robot from Intuitive Surgical. The da Vinci is a multiarm, teleoperated, minimally invasive surgical tool that has found success in a variety of procedures from urology to cardiology. However, despite its impressive installed base, it costs too much to use outside of large medical centers and institutions. As such, there exists an opportunity to develop a new class of affordable robotic tools that are more dexterous and provide additional capabilities to physicians. For example, with smart, motion-compensating catheters and real-time motion tracking (such as three-dimensional ultrasound, it may be possible to perform minimally invasive cardiac surgery, without having to stop the heart, by making it appear still to the operator (*1*). Anastomoses of severed nerves or tiny blood vessels could be performed more easily with micromanipulators that can safely grip and manipulate these delicate structures. Last, we will likely see tentacle- and snakelike steerable needles and endoscopes that will be able to provide access to difficult-to-reach sites in the body. Overall, these robotic tools will have sensors that enable cooperative controllers to work as an extension of the physician.

The majority of existing biomedical robots—whether surgical or wearable—are rigid. This makes sense historically given the original use of robotic manipulation for fast, high-precision, repeated motions when manipulating heavy components during assembly. But the human body is, other than bone, mostly soft. This means that rigid biomedical robots must rely on precise sensor feedback and high-performance control systems to ensure the safety of the patient. It makes sense, then, to think about a new paradigm in robotics in which the robots themselves are impedance-matched to their environment: in other words, soft robotics. Creating robots from polymers—specifically, elastomers with moduli comparable with human skin (*2*)—automatically eliminates many safety concerns with human-robot interactions. However, there is a cost; with highly compliant, nonlinear materials come challenges with modeling, force production, and control, leading to imprecise motions. Yet, the promise of soft robots has motivated a nascent field at the intersection of materials, mechanical and electrical engineering, and biology aimed at embodying the core robotics technologies in composites as soft as skin.

Next-generation wearable robots will use soft materials such as textiles and elastomers to provide a more conformal, unobtrusive, and compliant means to interface to the human body. These robots will augment the capabilities of healthy individuals by improving walking efficiency or increasing grip strength. In addition, wearable robots could assist with patients who suffer from physical or neurological disorders. Unlike traditional exoskeletons, which contain rigid framing elements, these soft systems will be worn like clothing, match natural body movements, and yet still apply substantial forces and torques when required.

Another opportunity for biomedical robots is reduced physical scales. One side of this we alluded to in the manipulation of fine structures and tissues. However, micromanipulation is not necessarily done with small robots; indeed, many micromanipulation systems have substantial infrastructure. Alternatively, if the characteristic dimension of the system, or at least the end-effector, is reduced, new minimally invasive procedures become viable. In order to make surgical microrobots a reality, new micro- and mesoscale manufacturing paradigms must be developed with an emphasis on biocompatibility and monolithic integration of electrical and mechanical components. One recent solution, called "pop-up book MEMS" (*3*), combines micromachining with 3D assembly methods borrowed from children's pop-up books to achieve complex structures and electromechanical mechanisms without the need for more traditional "nuts-and-bolts" assembly. But the road to commercialization from these research examples is long, especially given the need for regulatory approval. Nonetheless, the first steps already exist in the form of capsule endoscopy—the "Pill Cam"—that passively traverses the gastrointestinal tract in diagnostic procedures (*4*) and steerable microrobots for intraocular drug delivery and related procedures (*5*).

Given the promise of robot-assisted health care, it is not surprising that there is a tremendous push in academia and the medical device industry to develop robots that are smaller, softer, and safer for use in clinical settings. Perhaps soon our diagnostic procedures will consist of a drink or an injection of microrobots, and physical therapy will be no more obtrusive than putting on a pair of pants.

– Robert Wood and Conor Walsh

1. S. B. Kesner, R. D. Howe, Position control of motion compensation cardiac catheters. *IEEE Trans. Robot.* **PP**, 1–11 (2011).
2. R. F. Shepherd, F. Ilievski, W. Choi, S. A. Morin, A. A. Stokes, A. D. Mazzeo, X. Chen, M. Wang, G. M. Whitesides, Multigait soft robot. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 20400–20403 (2011).
3. J. Whitney, P. S. Sreetharan, K. Ma, R. J. Wood, Pop-up Book MEMS. *J. Micromech. Microeng.* **21**, 115021 (2011).
4. G. Iddan, G. Meron, A. Glukhovsky, P. Swain, Wireless capsule endoscopy. *Nature* **405**, 417 (2000).
5. B. J. Nelson, I. K. Kaliakatsos, J. J. Abbott, Microrobots for minimally invasive medicine. *Annu. Rev. Biomed. Eng.* **12**, 55–85 (2010).