Future Tech in Retrospect

Soft robotics for human health

Ritu Raman[1,*] and Cecilia Laschi[2,*]
[1]Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA
[2]Department of Mechanical Engineering, National University of Singapore, Singapore, Singapore
*Correspondence: ritur@mit.edu (R.R.), mpeclc@nus.edu.sg (C.L.)
https://doi.org/10.1016/j.device.2024.100432

In this entry into Future Tech in Retrospect, Ritu Raman and Cecilia Laschi look back at the past 50 years in soft robotics in order to reflect on the present state of the field and map out a trajectory for soft robotics in medicine over the next 50 years. Their look back to the origins of soft robotics—many rooted in healthcare and predating the term "soft robot"—provides context that will be highly valuable to researchers looking to advance this vibrant area of research.

Soft robots have greatly expanded the scope of autonomous machines in practical applications, with a particularly notable impact on advancing human health. We anticipate that soft machines will first find applications as physical-digital twins of human bodies and begin interfacing with the human body via active wearables and implantable assistive devices. As technologies progress, tethered and untethered surgical robots will be deployed as precise therapeutic interventions *in vivo*, and biohybrid implants will be integrated with patients to provide longitudinal health monitoring and modulation. We are highly optimistic about the increased safety, efficacy, and sustainability that soft robotics will bring to medicine and hope that the global community will embrace a biohybrid human future.

Soft robotics is a young research area proposing novel paradigms with potential beneficial impact on a range of applications. We aim to look back at the past 50 years in soft robotics, reflect on the present state of the field, and map out a trajectory for soft robotics in medicine over the next 50 years. Given the youth of this discipline, it is challenging to analyze its history over the time span of several decades, but we acknowledge many achievements in this field that predated the term "soft robotics" and are optimistic about its potential for accelerated impact on human health in the coming years.

Past

Soft robotics as we know it today is recent, but *ante litteram*, soft robots date back several decades. The invention of pneumatic actuators by Joseph McKibben in the 1950s marked a milestone in the way robots are built and controlled, putting forward continuum deformations and stiffness variations. McKibben actuators have been used in robotics since then, even if not specifically referred to as "soft." Interestingly, McKibben actuators were initially developed for applications in artificial limbs, indicating an early interest in deploying compliant machines and mechanisms for applications in human health.

The term "soft" was first used to refer to deformable robots in a seminal paper in 2008[1] that classified soft robots as a special case of continuum robots built with soft materials. After that, following the fast growth of the field and related body of knowledge (Figure 1), a number of review papers have proposed definitions and classifications of soft robots as soft-bodied robots, soft-matter robots, robots built with soft materials, or robots with deformable structures.

Robots started becoming soft when the increasing need for using autonomous machines in everyday life drove scientists to look to nature for inspiration. Most animals are soft. Not completely soft—unless they live underwater or underground where gravity is attenuated—but mostly soft (muscles and tendons have Young's modulus below 10^9), except for rigid skeletons or exoskeletons (Young's modulus over 10^{10}) that provide support against gravity and account for a small percentage of body mass ($\sim$11% in human beings). Soft tissues let movements emerge from the interaction of the body with the surrounding environment. From the simple observation that we need compliant joints for walking and running, to demonstrations that soft fingertips make grasping adaptive and stable, to more complex models of locomotion and manipulation, there is plenty of evidence that soft materials enhance robot abilities.[2]

Just as biological creatures have inspired soft robots, soft robots have advanced the study of living species. Compliant machines became ideal tools for handling and manipulating complex and delicate biological specimens, unveiling the natural mechanisms that provide organisms with effective and efficient controllable behaviors that readily adapt to surrounding conditions. Soft robotics-enabled observations of biological creatures iteratively yielded new generations of bioinspired robots, built by mimicking principles observed in nature, recursively spurring new insights on the dynamic adaptive behavior of biological motor control systems.

Present

Soft robots continue to advance basic understanding of natural biological systems but have more recently also found practical applications in advancing human health. Real-world use of compliant machines in healthcare ranges from soft medical instruments deployed inside

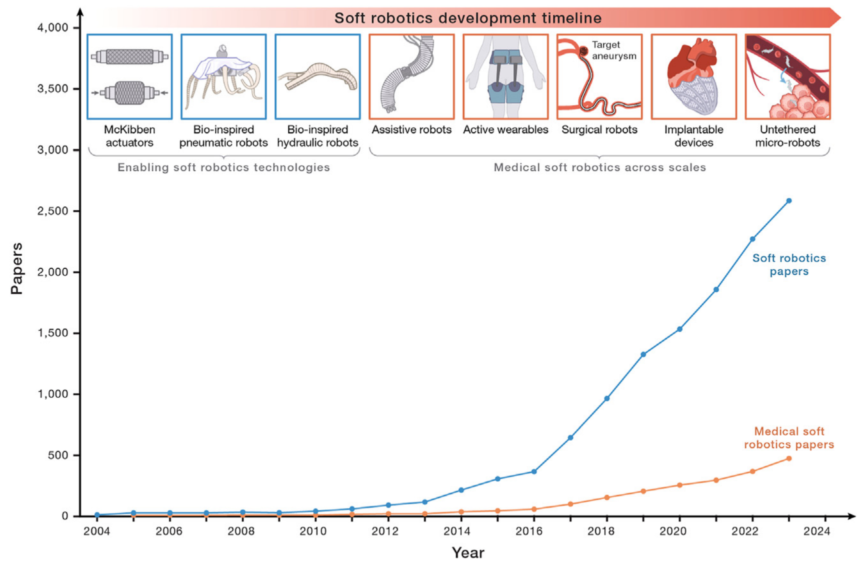

Figure 1. A visual timeline of soft robotics development, and its applications in human health, over the past few decades

The history of soft robotics begins in the 1950s with the development of the McKibben actuator—a pneumatically controlled actuator for artificial limbs—and other enabling technologies such as bio-inspired pneumatic and hydraulic robots. As the number of publications on soft robotics has grown, so too have the number of medically relevant soft devices, including assistive robots, active wearables, surgical robots, implantable devices, and untethered micro-robots.

the human body to simulators of body organs to external rehabilitation devices.[3] For example, soft endoscopes navigate safely around internal organs while taking images and doing complex operations. Soft arms help in physical therapy by accompanying and guiding rehabilitation movements of distal limbs. Wearable soft exoskeletons assist people with mobility impairments as they complete everyday tasks. Lastly, soft robotics technologies have been used to build biomimetic organs, such as heart models and larynx simulators, that serve as models to study pathologies or as prostheses to restore physiologic function.

As soft robotics have risen in prominence over the past few decades, advances in understanding and manipulating biology have triggered a concurrent convergence of and collaboration between life scientists and engineers.[4] This merge of disciplines created new fields such as controlled drug delivery, gene editing, cell therapy, and tissue engineering. While early applications of these biotechnologies were largely focused on drug development, many scientists now see the advantage of leveraging these tools for advancing human health by other means, ranging from sustainable agriculture to “biohybrid” soft robotics that integrate active biological components.

Biohybrid soft robots that leverage both biotic and abiotic components have spanned length scales from the molecular to the cellular to the tissue scale.[5,6] Understanding the mechanisms of molecular motors and nucleic acids has given rise to nanoscale tweezers and ratchet motors that could be deployed as stimuli-responsive biosensors and therapeutics in the body. At the microscale, single-cell-based machines have demonstrated that basic biological units can be manipulated for specific functional tasks, ranging from magnetically steerable bacteria for targeted drug delivery *in vivo* to controllable exoskeletons for mammalian spermatozoa that enable assisted reproduction.

Recent advances in our ability to build larger and more complicated assemblies of living cells, both via bottom-up assembly of organoids and top-down 3D printing of multicellular tissues, have also been promising for soft robotics. Over the past decade, several groups have developed machines that leverage cardiac and skeletal muscle contraction to swim, walk, grip, and pump.[7] While biohybrid soft robotics has centered around manufacturing and deploying biological actuators, machines that leverage electrically excitable cells to engineer tissue sensors and processors are also emerging as novel thrusts in this field. To date, however, tissue-scale biohybrid robots have primarily been used to model human physiology and pathology, and their robotic applications as autonomous wearable or implantable devices have yet to be fully unlocked.

Future

Current adoption of soft robotics technologies for building medical devices, like wearables or surgical tools, indicates the emergence of a trend we expect to grow rapidly in the coming years (Figure 2). We predict a progression of technology adoption in which wearing soft robots for rehabilitation and motor function recovery will be a viable and accessible treatment that is part of the clinical standard-of-care. Soft robotics adoption at this scale will likely open up more applications areas, including human life support and performance augmentation at home and at work, particularly in harsh environments such as underwater or outer space.

Beyond active wearables, we envision disruptive progress in the use of soft robotics technologies for mimicking natural organs or body parts. Realistic mimics of tissue mechanical properties and natural movements, coupled with personalized simulations that leverage individual health data, have the potential to produce physical-digital twins of the human body. Such twins would provide an unmatched tool for studying human physiological and pathological conditions, investigating the impact of medical interventions and simulating and predicting a range of potential outcomes that are personalized to individuals. Moreover, they would provide an innovative and immersive training tool for physicians and care providers. Ultimately, the very same soft robotics technologies used for building such human simulators could be adopted for artificial organs and body parts for replacement. Concurrently, we envisage a future extension toward other living species, within and beyond medical applications.

Autonomous soft machines, ranging from minimally invasive surgical tools to ingestible endoscopic capsules, will also play a role in assisting with medical procedures and showcase how robots can

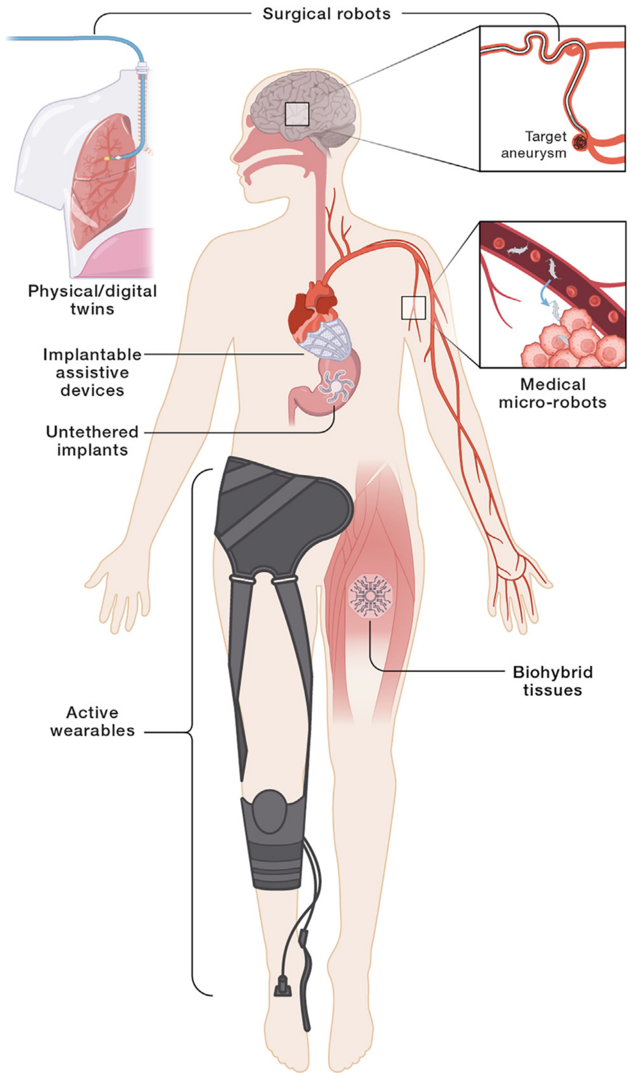

Figure 2. Future applications of soft robots in advancing human health, mobility, and quality of life

A whole body view of potential future applications of soft robotics in healthcare, including surgical robots, implantable assistive devices, untethered micro- and macro-scale robots, biohybrid tissues, and active wearables.

improve the safety and efficacy of clinical practice. We envision that future generations of machines deployed inside humans will be mostly or entirely soft, thus avoiding mechanical-mismatch-induced damage of surrounding tissues and enabling real-time sensing of physiologic environments and closed-loop control. Following early advances in integrating soft end effectors with surgical robots, we expect that the field will grow to incorporate a suite of soft machines that can be deployed *in vivo*, such as untethered micro- and macroscopic devices that navigate to tissues of interest and perform precise procedures including therapeutic cargo delivery, biopsies, ablations, and suturing. It is important to note that the degree of "softness" required of a robot will be highly dependent on its intended *in vivo* use, with machines deployed in highly sensitive, complex, and compliant environments like the brain imposing some of the most stringent design constraints.

Finally, we predict the rise of chronically implantable soft robots that integrate both living biological tissues and programmable abiotic materials as active functional components. In addition to designing and deploying replacement organs alongside tissue engineers, we anticipate that soft roboticists will leverage engineered tissues to power safe, energy-efficient, adaptable medical devices, such as drug delivery pumps or active shunts actuated by muscle actuators. By leveraging sugar as a primary energy source, such robots would avoid the negative impact of abiotic batteries typically used to power implantable devices, including overheating, reduced imaging compatibility, potential for toxic leakage, and non-renewable waste. If successful, we anticipate that biohybrid soft robots could directly interface with native tissue to personalize their therapeutic activity to the needs of a specific patient and adapt to changing needs throughout an individual's lifespan.

No technology exists in a vacuum. The future of soft robotics thus depends not only on scientific advances, but on the continued growth and evolution of a broader societal framework including considerations of sustainability, governmental regulation, and equitable access. To that end, we encourage soft robotics researchers to consider the environmental impacts of the robots they build throughout the lifetime of a machine, from manufacturing, to usage, to disposal. Additionally, we hope that roboticists engage in accessible science communication efforts, with the goal of enhancing public trust of and engagement with emerging technologies. We anticipate that broad adoption and trust will be critical to expanding regulatory pathways for medical soft robots, thus enabling translational impact on human health.

REFERENCES

1. Trivedi, D., Rahn, C.D., Kier, W.M., and Walker, I.D. (2008). Soft robotics: Biological inspiration, state of the art, and future research. Applied Bionics and Biomechanics *5*, 99–117. https://doi.org/10.1080/11762320802557865.

2. Laschi, C., Mazzolai, B., and Cianchetti, M. (2016). Soft robotics: Technologies and systems pushing the boundaries of robot abilities. Sci. Robot. *1*, eaah3690. https://doi.org/10.1126/scirobotics.aah3690.

3. Cianchetti, M., Laschi, C., Menciassi, A., and Dario, P. (2018). Biomedical applications of soft robotics. Nat. Rev. Mater. *3*, 143–153. https://doi.org/10.1038/s41578-018-0022-y.

4. Raman, R. (2021). Biofabrication (MIT Press).

5. Ricotti, L., Trimmer, B., Feinberg, A.W., Raman, R., Parker, K.K., Bashir, R., Sitti, M.,

Martel, S., Dario, P., and Menciassi, A. (2017). Biohybrid actuators for robotics : A review of devices actuated by living cells. Sci. Robot. *2*. eaaq0495. https://doi.org/10.1126/scirobotics.aaq0495.

6. Webster-Wood, V.A., Guix, M., Xu, N.W., Behkam, B., Sato, H., Sarkar, D., Sanchez, S., Shimizu, M., and Parker, K.K. (2022). Biohybrid robots: recent progress, challenges, and perspectives. Bioinspir. Biomim. *18*, 015001. https://doi.org/10.1088/1748-3190/ac9c3b.
7. Raman, R. (2024). Biofabrication of living actuators. Annu. Rev. Biomed. Eng. *26*. https://doi.org/10.1146/annurev-bioeng-110122-013805.

About the authors

Ritu Raman, PhD is the d'Arbeloff Assistant Professor of Mechanical Engineering at MIT. Her lab is centered on engineering adaptive living materials for applications in medicine and machines with a focus on tissue engineering neuromuscular bioactuators. She has received several recognitions for scientific innovation, including the NSF CAREER Award, the Army Research Office YIP Award, the Office of Naval Research YIP Award, and being named a Kavli Frontiers of Science Fellow by the National Academy of Sciences. She is passionate about science communication and has served as an AAAS IF/THEN ambassador and authored the MIT Press book *Biofabrication*.

Cecilia Laschi, PhD is Provost's Chair Professor at the National University of Singapore. She is co-director of CARTIN – Centre for Advanced Robotics Technology and Innovation. She is on leave from Scuola Superiore Sant'Anna, Italy, the BioRobotics Institute (Dept. of Excellence in Robotics & AI). Her Soft Robotics Lab investigates fundamental challenges for building robots with soft materials with a bioinspired approach and with applications underwater and in the biomedical field. She has editorial roles in top robotics journals and has received an Honorary Doctorate from the University of Southern Denmark, Odense and awards from the IEEE Robotics and Automation Society.