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Soft Robotics

PERSPECTIVE

Soft Robotics: A Perspective—Current Trends and Prospects for the Future

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Abstract

Soft robots are primarily composed of easily deformable matter such as fluids, gels, and elastomers that match the elastic and rheological properties of biological tissue and organs. Like an octopus squeezing through a narrow opening or a caterpillar rolling through uneven terrain, a soft robot must adapt its shape and locomotion strategy for a broad range of tasks, obstacles, and environmental conditions. This emerging class of elastically soft, versatile, and biologically inspired machines represents an exciting and highly interdisciplinary paradigm in engineering that could revolutionize the role of robotics in healthcare, field exploration, and cooperative human assistance.

Introduction

Conventional robots and machines are made of rigid materials that limit their ability to elastically deform and adapt their shape to external constraints and obstacles. Although they have the potential to be incredibly powerful and precise, these rigid robots tend to be highly specialized and rarely exhibit the rich multifunctionality of natural organisms. However, as the field of robotics continues to expand beyond manufacturing and industrial automation and into the domains of healthcare, field exploration, and cooperative human assistance, robots and machines must become increasingly less rigid and specialized and instead approach the mechanical compliance and versatility of materials and organisms found in nature. As with their natural counterparts, this next generation of robots must be elastically soft and capable of safely interacting with humans or navigating through tightly constrained environments. Just as a mouse or octopus can squeeze through a small hole, a soft robot must be elastically deformable and capable of maneuvering through confined spaces without inducing damaging internal pressures and stress concentrations.

In contrast to conventional machines and robots, soft robots contain little or no rigid material and are instead primarily composed of fluids, gels, soft polymers, and other easily deformable matter. These materials exhibit many of the same elastic and rheological properties of soft biological matter and allow the robot to remain operational even as it is stretched and squeezed. Because of the near absence of rigid materials and its similarities to natural organisms, soft robots may be considered a subdomain of the more general fields of soft-matter engineering or biologically inspired engineering. However, whereas these existing fields can be defined by their scientific foundations in soft-matter physics and biology, respectively, the emerging field of soft robotics remains open and free of dogmatic restrictions to any constrained set of methods, principles, or application domains. Instead, soft robotics represents an exciting new paradigm in engineering that challenges us to reexamine the materials and mechanisms that we use to make machines and robots so that they are more versatile, lifelike, and compatible for human interaction.

Compliance Matching

The promise of soft robots is perhaps best realized in environments and applications that require interaction with soft materials and organisms and/or the artificial replication of biological functionalities. For example, whereas industrial robots typically handle metals, hard plastics, semiconductors, and other rigid materials, medical robots will primarily interact with soft materials such as natural skin, muscle tissue, and delicate internal organs. Likewise, biologically inspired robots for field exploration and disaster relief will often encounter easily deformable surfaces like sand, mud, and soft soil. To prevent the robot from penetrating into the surface and causing damage or mechanical immobilization, the forces transferred between the robot and surface must be evenly distributed over a large contact area. This requires compliance

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matching—that is, the principle that contacting materials should share similar mechanical rigidity in order to evenly distribute internal load and minimize interfacial stress concentrations.

One measure of material rigidity is the modulus of elasticity, or Young's modulus—a quantity that scales with the ratio of force to percent elongation of a prismatic (i.e., uniform cross section) bar that is stretched along its principal axis (Fig. 1a).[1] Young's modulus is only defined for homogenous, prismatic bars that are subject to axial loading and small deformations (< 0.2% elongation for metals) and thus has limited relevance to soft robots and other soft-matter technologies that have irregular (nonprismatic) shape and undergo large elastic or inelastic deformations. Nonetheless, Young's modulus is a useful measure for comparing the rigidity of the materials that go into a soft robot. As shown in Figure 1b, most conventional robots are composed of materials such as metals and hard plastics that have a modulus of greater than 10^9 Pa = 10^9 N/m^2. In contrast, most of the materials in natural organisms, such as skin and muscle tissue, have a modulus on the order of 10^2–10^6 Pa. That is, the materials in natural organisms are 3–10 orders of magnitude less rigid than the materials in conventional robots. This dramatic mismatch in mechanical compliance is a big reason why rigid robots are often biologically incompatible and even dangerous for intimate human interaction and rarely exhibit the rich multifunctionality and elastic versatility of natural organisms.

To prevent injury or robot immobility, the surface of soft robots must be adequately soft and deformable in order to distribute forces over a large contact area and eliminate interfacial stress concentrations. For contact with human tissue or organs, stress concentrations may cause physical discomfort and even physical injury. For a hard robot in contact with a soft substrate, stress concentrations can cause the robot to puncture or "dig in" to the surface and become immobile. Compliance matching also has a critical role in areas such as medical implants and tissue growth. For joint replacements, cardiac stents, and other medical implants, compliance matching prevents stress concentrations and preserves the natural distribution of internal forces and pressure.[2] In tissue growth and engineering, the relative elasticity of contacting tissue can influence how tissue cells move, grow, and differentiate.[3] Mismatches in elastic compliance can lead to damaging stress concentrations, redistribute internal forces in a way that leads to disuse atrophy of bone or tissue, or introduce rigid kinematic constraints that interfere with natural motor function.

Compliance matching is particularly important in the subdomain of wearable technologies for human motor assistance. These soft robot technologies are wearable and contain artificial muscles that match the compliance of natural muscle and provide physical assistance to humans who have motor impairments or are engaged in strenuous tasks. As with natural muscle, these artificial muscles must not only be capable of reversible shape change but also reversible changes in elastic rigidity. For motor tasks that involve underactuated or passive dynamic motions, such as downhill walking, the assistive robot should be elastically soft and avoid interfering with the natural range of joint motion. For physically strenuous motor tasks, the artificial muscle must supply mechanical work and become rigid in order to support large forces. As with natural muscle, the artificial muscle used in wearable soft robots should stiffen in order to prevent injury during collisions, absorb impacts, or to catch fast-moving objects.

Potential Applications

Because they are composed of materials that match the compliance of biological matter, soft robots are mechanically biocompatible and capable of lifelike functionalities. These features will potentially lead to plenty of promising new technologies, from the aforementioned soft wearable robots

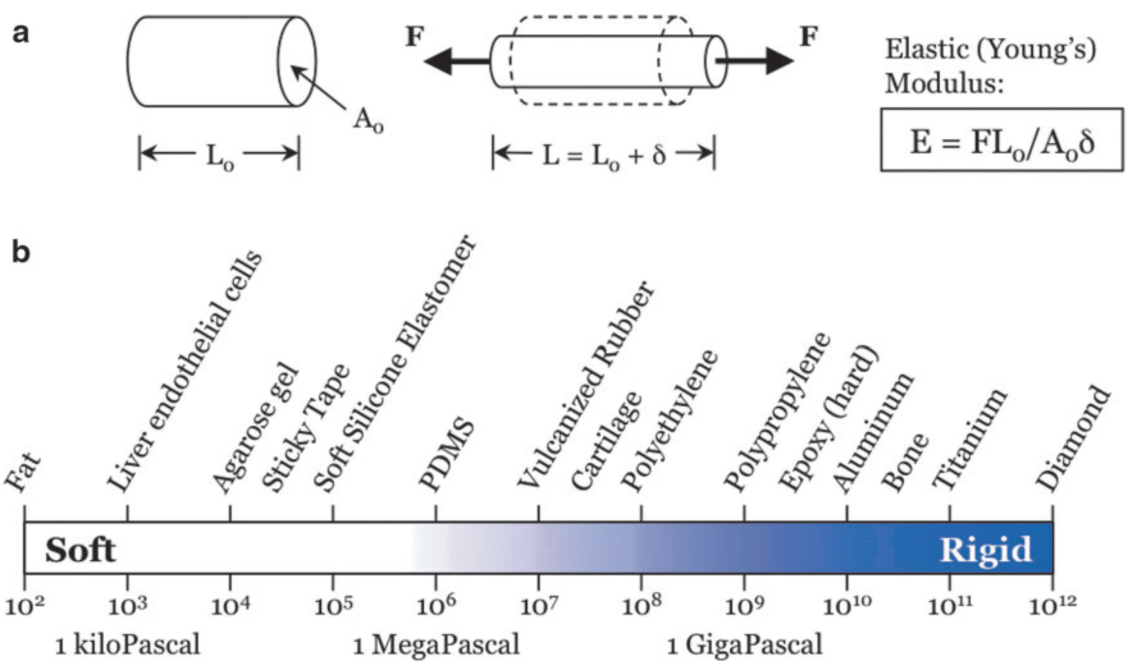

FIG. 1. **(a)** The elastic (Young's) modulus scales with the ratio of the force F to the extension δ of a prismatic bar with length L_0 and cross-sectional area A_0. **(b)** Young's modulus for various materials (adapted from Autumn et al.[23]).

for human motor assistance and biologically inspired field robots for autonomous exploration to soft and lightweight cooperative robots that safely interact with people (Fig. 2a). While these technological prospects are certainly exciting, how will soft robots specifically be used and what unique opportunities will they create for society and industry in the future?

Perhaps the most immediate application of emerging soft robot technologies will be in the domain of human motor assistance and *co-robotics*. For example, a soft active ankle foot orthotic (AFO) could help prevent foot dragging for patients that suffer gait abnormalities such as drop foot.[4] When active, the AFO would stiffen and supply mechanical work to the ankle to assist with lifting the foot. In its passive state, the AFO would remain soft and allow the ankle joint to freely rotate. Soft wearable robots could also assist with grasping and other fine motor tasks in patients who have suffered stroke or traumatic brain injury. As with the AFO, a soft hand orthotic would contain artificial muscles that reversibly change shape and elastic rigidity to alternately supply assistive mechanical work and accommodate passive motion in the fingers and wrist. In addition to matching the natural compliance of human skin and tissue, the hand orthotic must be thin, comfortable, and lightweight. Such assistive technologies will effectively function like a *second skin*[5] that compensates for missing or impaired motor function by cooperating with the body's healthy tissue (Fig. 2b). By minimizing dependency on a physical therapist, these second-skin soft technologies can give the patient greater physical independence and new opportunities to relearn or discover motor functions for grasping and gait.

Assistive robots that cooperate with human partners—also known as co-robots—will have an increasingly central role in a broad range of social, scientific, and industrial activities. As with the personal computer, the universal integration of co-robots into society and industry will depend on robust and multifunctional platforms that can be operated by nonspecialists. Because they will physically interact with humans, co-robots must be adequately soft and lightweight in order to prevent injuries during collisions. Soft robot features such as compliance matching and biocompatibility are especially important for applications in nursing and elderly care that require carrying, lifting, and other forms of intimate contact. With conventional machines and rigid robots, safe and comfortable human–machine interaction is possible but requires precision sensing, fine motor control, and advanced feedback systems. While tractable in specialized applications, feedback-based compliance can be challenging in general-purpose platforms, especially humanoid robots that must safely cooperate with humans in a broad range of medical, industrial, and domestic tasks. In order to minimize demands on sensing, motors, and computation, future generations of co-robot platforms should be primarily composed of materials and machinery that are elastically soft and naturally match the compliance of human tissue. This same condition also applies to soft prosthetics that are powered by artificial and natural muscle and controlled through cognitive commands, body gestures, and onboard sensing.

Instead of conventional electric motors and hydraulics, some existing soft human exoskeletons, robot arms, and humanoids use pneumatic air muscles. The pneumatic air muscle, also known as a McKibben actuator, is a type of artificial muscle composed of an inflating balloon encased in a braided shell of woven inextensible fibers. As compressed air is delivered to the balloon, the braided shell constrains the muscle to increase its diameter and shorten. In addition to shortening, the pressurized air muscle exhibits greater tensile rigidity—that is, more force is required to elongate the muscle by a prescribed amount. Pneumatic air muscles were originally introduced by A.H. Morin and later adapted by J.L. McKibben for applications in orthotics.[6]

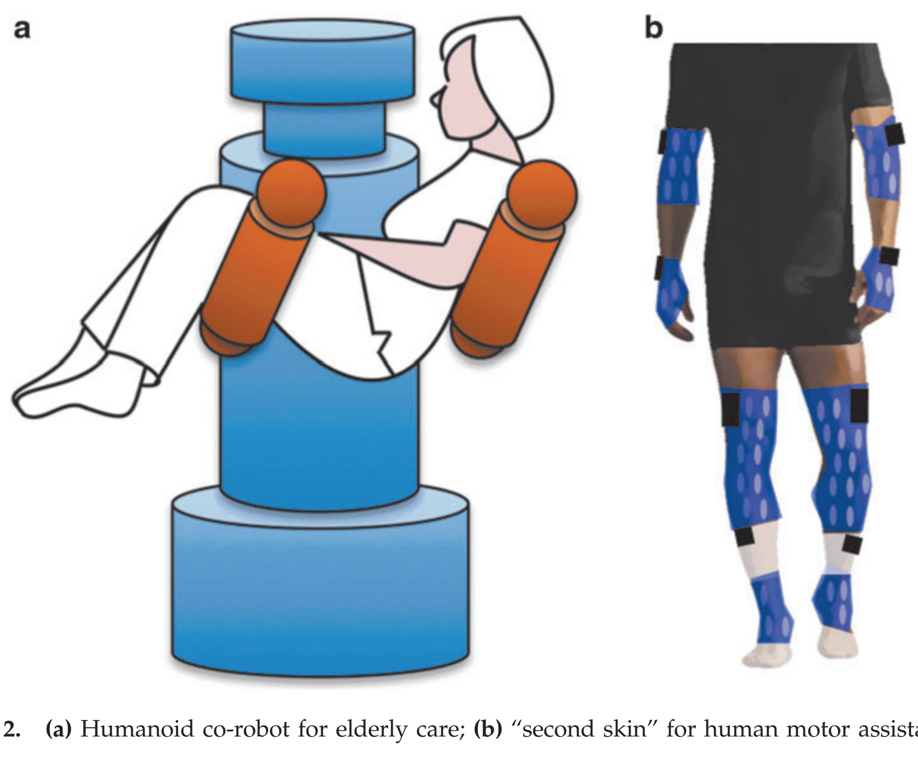

FIG. 2. **(a)** Humanoid co-robot for elderly care; **(b)** "second skin" for human motor assistance.

While promising, pneumatic air muscles rely on external pneumatic hardware such as valves, pumps, and compressors in order to control the delivery of pressurized air. For a robot to be completely soft and autonomous, these artificial muscles should be operated with soft or miniaturized pumps and valves that can be embedded in the robot without introducing elastic rigidity. Soft or miniaturized pneumatic hardware are also needed in recent bioinspired robots that use variations on the pneumatic air muscle. These include the pneu-Net[7] and Suzumori bending actuators for soft robot limb motion.[8] By making these soft robots completely autonomous, they will be capable of crawling and swimming through tightly confined spaces that are impossible to navigate with rigid or tethered robots. Specific applications include search operations for natural disaster relief, field operations for military reconnaissance, and pipe inspection for sewer maintenance (Fig. 3).

Of course, soft robots are not limited to pneumatically powered humanoids, orthoses, and prosthetics. As artificial muscle, skin, and nervous tissue technologies are further miniaturized, soft robots will eventually be scaled down to the size of small invertebrates, insects, and microorganisms. At these length scales, functionality will depend not only on soft elasticity but also on the complex rheology of fluids, gels, and other inelastic soft matter. Beyond their potential role as field robots for search missions and data collection, miniaturized soft robots may also eventually be used for drug delivery, minimally invasive surgery, and medical implants. Just as with wearable robots, they should match the compliance of internal organs and be capable of navigating through the body without damaging vascular walls and tissue. For applications such as biopsy and angioplasty, they should also be capable of grasping tissue or anchoring to vascular walls through mechanical interlocking or adhesion. Lastly, like a colony of ants or termites, a swarm of miniaturized soft robots could be used in manufacturing applications to rapidly assemble structures from granular matter, burrow through soil to survey and extract natural resources, or to transport hazardous material.

These proposed applications represent only a few of the myriad potential uses of soft robots. In general, soft robots have a unique role in any application that involves physical interaction with the human body or demands the levels of multifunctionality and elastic versatility observed in nature. However, just as conventional machines and robots are not always well suited for human–machine interaction, soft robots are fundamentally limited by their mechanical compliance and will not be appropriate for applications requiring high power or precision. For example, it is unlikely that soft machines composed entirely of fluids and elastomers would ever replace heavy-duty industrial robots. Likewise, on the small scale, machine precision often requires rigid parts that lock tightly in place and do not slacken or deform elastically when loaded with surface tractions. Also, while natural neural tissue is soft and capable of extraordinary computational power, microengineered electronics are presently constructed from rigid materials with precisely spaced submicron features. Until there is an elastically soft artificial brain, soft robots will require rigid microprocessors for signal processing and actuator control.

Beyond Robotics

Like its host platform, the artificial muscle, skin, and neural tissue used in soft and bioinspired robots will be elastically soft and remain functional when deformed. In addition to their potentially transformative role in robotics, these soft-matter technologies will also be used in personal electronics, artificial organs, wearable computing, and other applications that involve permanent or frequent contact with the human body. As the field of soft robotics grows, the supporting soft-matter technologies used in sensing, electronics, and actuation will continue to mature and will eventually appear in application domains. Likewise, the manufacturing methods used to produce soft robots will extend to other areas within the field of soft-matter engineering and lead to new paradigms in the rapid and high-volume production of rigidity-tuning actuators, soft microfluidic circuits, and stretchable microelectronics.

Stretchable microelectronics alone represents a cross-cutting and high-impact technology that readily translates

FIG. 3. Soft field robot for military reconnaissance, natural disaster relief, and pipe inspection.

into other applications. Just as electronic circuits and sensors must be capable of accommodating the elastic deformation of a soft robot host, they must also be able to accommodate the stretching and bending that arise in wearable computing and smart textiles. Current approaches to stretchable electronics include wavy circuits[9,10] and soft microfluidics with conductive liquids.[11] Wavy electronic circuits are typically composed of thin-film solid-state microelectronics bonded to a prestretched sheet of soft silicone elastomer, for example, polydimethylsiloxane (PDMS). When the elastic sheet relaxes to its original length, it causes the circuit to buckle into a wavy pattern. The waves flatten out as the circuit is stretched and allow for elongations that are well above the intrinsic strain limit of metals and semiconductors. In contrast, soft microfluidic electronics contain no intrinsically rigid materials and are instead composed of microfluidic channels of conductive liquid, typically a liquid-phase gallium–indium alloy, embedded in a silicone elastomer. As the surrounding elastomer is stretched, the fluidic microchannels remain intact and deform without losing conductivity. However, unlike wavy electronics, soft microfluidic electronics are presently restricted to liquid-phase metal alloys and electrolytic solutions that are conductive but do not have the semiconducting properties required for transistor-based logic.

In addition to stretchable electronic sensors and circuits, soft microfluidics have also been used in lab-on-a-chip technologies for applications such as biological cell sorting and diagnostic assay analysis.[12] Soft microfluidic circuits are currently produced with soft lithography fabrication methods based on nonphotolithographic techniques such as replica molding and microcontact printing.[13] Silicone elastomers such as PDMS are embedded with microchannels of fluid that flow under the influence of electrophoresis, electroosmotics, or peristalsis.[14] Progress in soft microfluidics and soft lithography microfabrication will lead to new families of valves, pumps, and relays to support the actuators and electronics used in soft robots. Likewise, soft robots will provide a new source of technological demands that will continue to drive the nascent field of soft-matter engineering.

Artificial muscles represent another cross-cutting domain of soft robotics that will allow machines to be more lightweight and elastically compatible with the human body. By reversibly tuning their shape and elastic rigidity, they can perform mechanical work and independently control the distribution of internal load. Also, in contrast to combustion engines and high-power electric motors, they can provide nonrepetitive and discontinuous actuation without sacrificing efficiency. In addition to pneumatic air muscles, current technologies include dielectric elastomer actuators, ionic polymer metal composites (IPMC), shape-memory alloys and polymers, and liquid-crystal elastomers.[15] Along with these existing classes of actuators, future artificial muscles will not only power soft robots and assistive wearable technologies but also control the valves, pumps, and relays in soft-matter microfluidics and be used in medical implants, minimally invasive surgical tools, and diagnostic systems.

Other potential spin-offs of soft robotics are technologies that use soft gels, colloidal substances, and rheologically complex fluids. In miniaturized soft robots, these materials may be used for pseudopod-like locomotion, adhesion, and grasping. In the case of magneto- and electrorheological fluids, which contain a high concentration of microparticles suspended in a carrier oil, such colloidal substances can also be used for control valves in microfluidics[16] or for rigidity-tunable artificial muscles.[17] As the field of soft robotics matures, it will have an increasingly central role in efforts to identify new classes of gels and colloidal suspensions that reversible changes their elastic, rheological, optical, and morphological properties in response to external stimuli. Imagine, for example, a wearable array of light-emitting gel diodes that is elastically compatible with natural skin and functions as a wearable display or diagnostic tool for individually stimulating photosensitive biological cells.

Commercial Prospects

To be commercially viable, unique applications and functionalities are not enough—soft-matter robots and technologies must also be inexpensive and mass-producible. Soft robots are currently produced with soft-lithography-manufacturing techniques that eliminate the need for slow and costly clean-room fabrication and instead rely on replica molding and transfer printing. Templates and masters are fabricated with photolithography or rapid prototyping tools

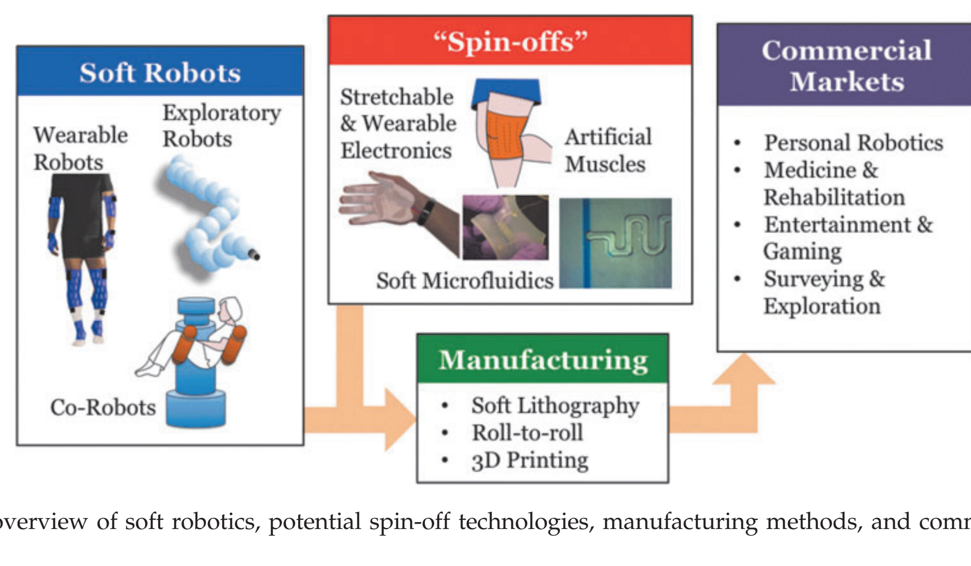

FIG. 4. An overview of soft robotics, potential spin-off technologies, manufacturing methods, and commercial markets.

such as laser micromachining, CNC milling, and 3D printing. These methods allow for inexpensive and easily customizable fabrication and enable the manufacturing costs of soft robots to be competitive with conventional robots produced from hard plastic. Moreover, the artificial muscles, skin, and nervous tissue that support robot functionality may eventually be produced with stencil lithography, roll-to-roll manufacturing, and direct ink-jet printing. For example, a millimeter-thin PDMS rubber embedded with a 0.1% volume fraction of microfluidic liquid gallium–indium channels will have a raw materials cost of approximately $100 per square meter, approximately the same order of magnitude as the sale price of flexible copper circuit on polyester.

Apart from cost and manufacturing scalability, commercial viability also strongly depends on immediate consumer interest. In the short-term, market demand will likely be driven by the medical robotics and gaming/entertainment industries (Fig. 4). Soft-matter sensors and electronics could be used in gloves and orthoses that monitor hand gestures and joint motion. In contrast to existing "dataglove" technologies,[18] these wearable electronics would be inexpensive and composed almost entirely of soft elastic material. In the longer term, soft wearable technologies may contain actuators and low-power electrodes for user feedback and muscle stimulation. Also, as co-robots enter the marketplace, the artificial muscles and skin used in wearable technologies for medicine and gaming could eventually replace the rigid motors and sensors in humanoids. ABI research predicts that the market for personal robots may grow to $6.5 billion by 2017,[19] a significant reduction from previous estimates but still a sizeable figure that could even be exceeded if robots are eventually designed to be more lightweight, cheap, and safe for human contact.

The 3D printing technology is another emerging market that is closely aligned with soft robotics. According to Lux Research, 3D printer sales may reach as high as $8.4 billion by 2025.[20] As with personal robotics, soft robotics may accelerate this growth by expanding the market to include nonspecialists. An inexpensive 3D printer capable of producing soft-matter electronics, machines, and robots would enable hobbyists, school robotics clubs, and artists to participate in the discovery of new soft robot functionalities and designs.

Living Robots?

If soft robots achieve their extraordinary multifunctionality with materials that match the elastic and rheological properties of biological matter, why not just directly build them from biological material? Hybridization of synthetic and biological materials with tissue engineering and synthetic biology represents another emerging trend that will eventually lead to technologies that are more biocompatible and life-like. When applied to soft robotics, tissue engineering and synthetic biology could result in bending actuators that are powered with natural muscle tissue[21] or soft-matter circuits composed of genes, protein, and bacteria.[22] As with other soft-matter technologies, these biohybrid soft robots would contain virtually no rigid materials and could be produced with soft lithography or 3D printing.

Like their engineering counterparts, natural muscles and biological circuits have their own fundamental limitations and will eventually be used to complement, rather than replace, nonbiological technologies. Nonetheless, for some applications, biohybridization can dramatically improve performance and overcome some of the fundamental barriers encountered with synthetic soft materials. Consider, for example, artificial muscles for reversible shape and rigidity control. Currently, most soft robots are electrically powered with shape-memory alloys, IPMCs, and dielectric elastomer actuators. For a robot to be untethered and autonomous, these actuators would require on-board electricity from an alkaline or lithium-ion battery. However, the energy density of batteries is 10–100 times less than that of the sugars and fats used to power natural muscle. Therefore, replacing battery-powered actuators and electronics with biohybrid materials that run on chemical fuel could lead to dramatically lighter and more autonomous soft robots.

Grand Challenges

In closing, soft-matter engineering represents an exciting new paradigm in robotics that has the potential to revolutionize its role in society and industry. In application domains such as medical and personal co-robotics, soft-matter machines and robots allow for safe and biomechanically compatible interactions with humans. For field exploration and disaster relief, soft robots can navigate challenging terrain and penetrate tightly confined spaces by adapting their shape and locomotion strategy in ways similar to natural organisms. At the small scale, miniature soft robots could function as artificial microorganisms in medical applications such as drug delivery, angioplasty, and biopsy.

As a field of academic research, soft robotics is highly interdisciplinary and introduces several grand challenges that demand further scientific exploration. One of these is to introduce new classes of electrically and chemically powered soft-matter actuators that exhibit the shape and rigidity-tunable properties of natural muscle tissue. Similarly, soft robotics requires artificial skin and neural tissue that are elastically soft and can be embedded without introducing kinematic constraints and rigidity. Also, as parallel efforts in synthetic biology and tissue engineering continue to advance, there will be an increasing need for biocompatible technologies that support living cells and tissue. Lastly, commercial success depends on new innovation in soft lithography, 3D printing, and other rapid prototyping technologies to mass produce soft-matter machines and robots that are inexpensive and satisfy market demand.

Author Disclosure Statement

No competing financial interests exist.

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