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Soft Robotics

STATE-OF-THE-FIELD REVIEW

Challenges and Opportunities for Design, Simulation, and Fabrication of Soft Robots

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Abstract

This article describes new opportunities in soft robotics and some potential avenues to overcome challenges associated with the realization of these opportunities. New opportunities include new applications that exploit novel amorphous nonrigid dynamics, a new design space due to the elimination of traditional manufacturing constraints, more opportunities for modeling and mimicry of natural systems, and increased safety and mechanical compatibility with humans. Challenges include limited simulation and design automation tools, lack of soft actuation methods, and difficulty in manufacturing and component standardization. Both computational (e.g., evolutionary design tools) and mechanical (porous and jamming materials) approaches are proposed to alleviate these needs.

Introduction

The field of soft robotics is emerging as a new frontier of engineering, not only opening the door to many new possibilities, but also challenging traditional engineering thinking. Due to a confluence of technologies, ranging from new materials and manufacturing techniques, to new design and control tools, it is now becoming possible to create systems whose structure is composed almost entirely of soft materials. Soft robots are no longer merely rigid skeletal systems cloaked with a soft skin; these systems are composites of flexible materials that together give rise to entirely new modes of function and behavior, in many ways not unlike natural biology.

New Opportunities

The advent of soft robotics is creating opportunities in several areas. Opportunities are being created due to several key thrusts.

New applications exploit novel amorphous nonrigid kinematics and dynamics

Previously impossible tasks can be realized by taking advantage of continuous deformation—for example, robots with many degrees of freedom that can conform to objects, dampen or amplify vibrations by design, squeeze through gaps, and morph continuously to meet different tasks.

New designs are enabled through the elimination of traditional manufacturing constraints

The increased freedom associated with amorphous shapes and flexible motion opens up new degrees of freedom not previously available with rigid mechanics. These include robots with free-form shapes, new kinds of locomotion patterns, and manipulation. The advent of new manufacturing technologies, and specifically additive manufacturing technology that can handle soft materials and graded materials, greatly expands the space of possible designs far beyond what is possible with just rigid materials.

More opportunities exist for modeling and mimicry of natural systems

The robotics field in general serves two main purposes: the practical purpose of automation, and the intellectual purpose of modeling and understanding human and animal behavior and performance. Soft robotics greatly amplifies the ability of robotic systems to model and emulate natural systems for both purposes. Since many (if not most) biological materials are soft materials, soft machines can help understand and exploit natural concepts better.

Safety and mechanical compatibility with humans is increased

A major hurdle to adoption and use of robots that interact with humans both at home and at work is mechanical

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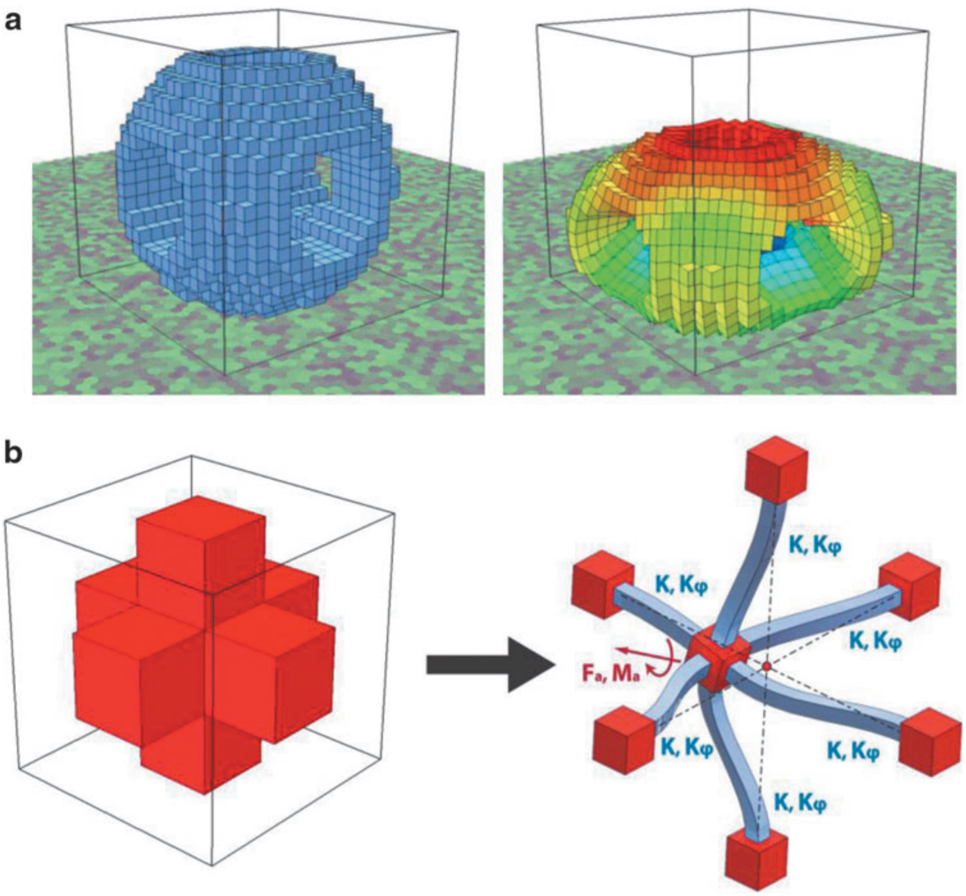

FIG. 1. Soft robot simulation using relaxation. **(a)** Soft structure under severe deformation due to gravity. **(b)** Relaxation solver simulates structure using a network of beams and masses. From Hiller et al.[1]

compatibility. Compatibility is critical both in terms of safety as well as in terms of comfort and perception by human users. Soft machines can help with all these challenges: soft robots offer better safety margins for collisions and more potential comfort in operation and may be perceived more warmly by nontechnical users. When robots need to operate inside or alongside a body, such as in medical or prosthetic applications, soft matter may also offer technical advantages.

New Challenges

The expanded opportunities are not without their cost. Several challenges are likely to dampen progress of the field, mostly stemming from the increased complexity of soft robotic systems and the lack of a structured disciplinary heritage.

Lack of simulation and analysis tools

Dynamics of soft materials are difficult and slow to simulate because of the many degrees of freedom and nonlinear material effects. The nonlinear effects imply that extensive computational processes need to be employed for correct simulation. Even if the simulation is correct, predictions are difficult to match to reality due to many empirical coefficients that need to be calibrated experimentally, for example, nonlinear elastic behavior and damping coefficients, interfaces between materials, and friction.

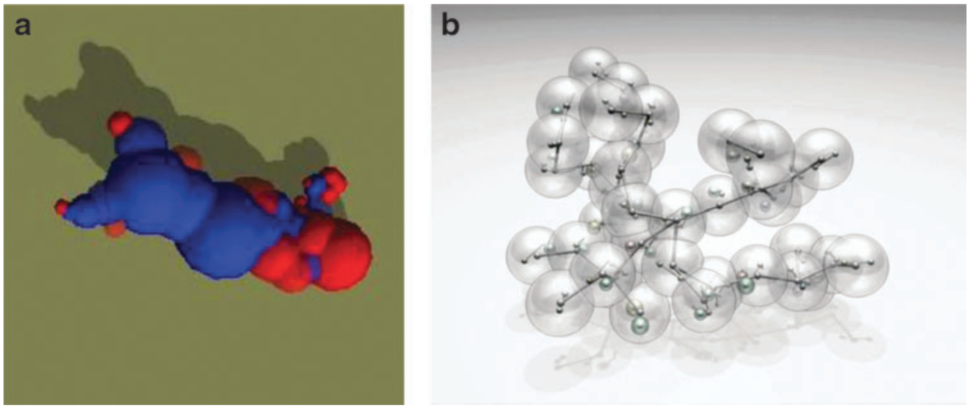

FIG. 2. Simulated flexible amorphous robot designs evolved using **(a)** CPPN representations and **(b)** ontogenetic development. Reproduced from Auerbach et al.[2] and Bongard.[3]

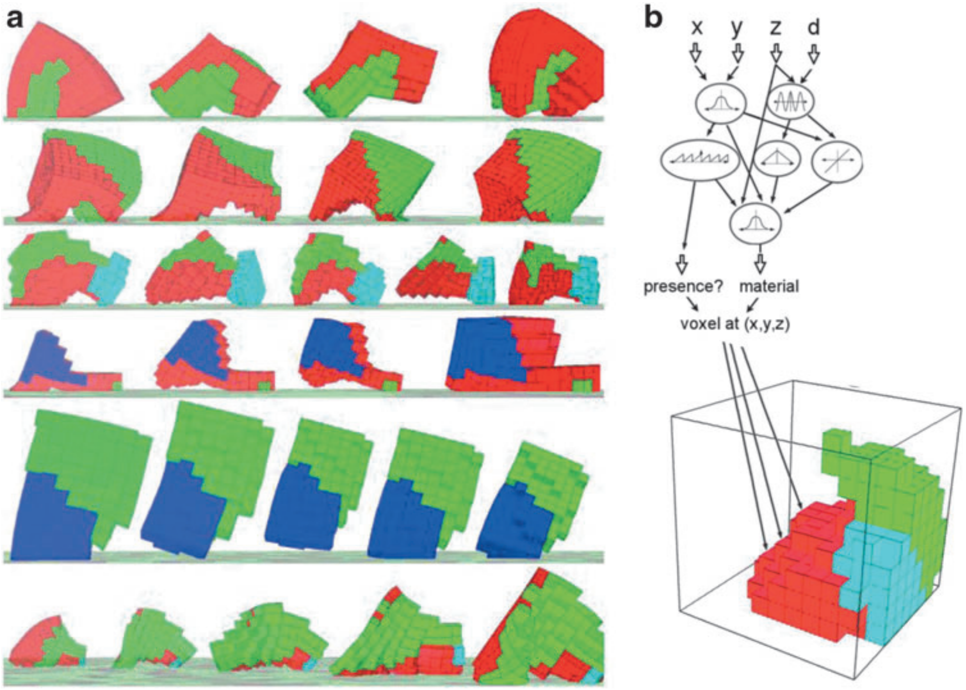

FIG. 3. Evolving soft robots **(a)** Examples of soft robots designed automatically using evolution with two volume-changing materials. Locomotion sequence from left to right. **(b)** Each candidate design is represented as a network of geometric transformations that determine which material goes in each position. Reproduced from Cheney et al.[4]

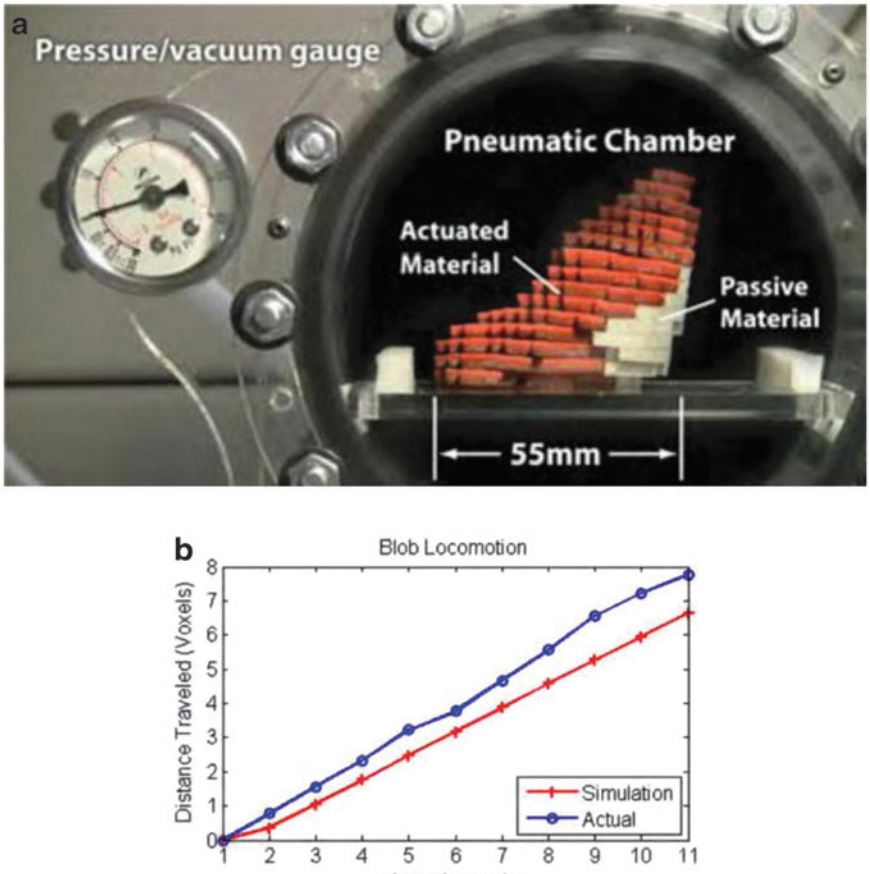

FIG. 4. Fabricated untethered evolved soft robot **(a)** Soft robot evolved using one actuation material, then fabricated using pressurized foam. **(b)** Kinematics closely match reality. Reproduced from Hiller et al.[1]

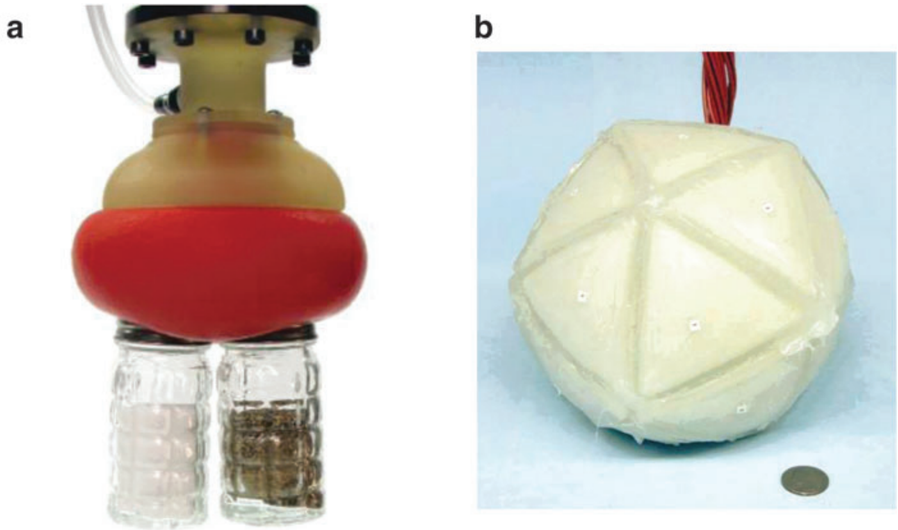

FIG. 5. Jamming phase change material transitions from soft to hard on command, opening new possibilities for **(a)** grasping and manipulation, and **(b)** locomotion using selective actuation. Reproduced from Amend et al.[6] and from Steltz et al.[7]

Lack of design automation tools

The complex nature of soft systems implies that human intuition into their behavior is limited, making design automation essential. Whereas many engineers guide their design efforts using intuition fed from daily mechanical experiences regarding behavior of rigid kinematics and dynamics, such intuition is poor and qualitative at best when it comes to soft materials. Intuition may improve as such systems become more common, but it is likely that ultimately design automation tools will be required to properly explore the design space and optimally meet high-level requirements. Design automation tools, however, require both new mathematical representations as well as accurate and fast simulators, both of which are mostly lacking.

Lack of soft actuation methods

Whereas soft materials for sensing and for structure are readily available, soft actuators are still relatively weak and inefficient. Electroactive polymers usually require very high voltages to operate, whereas lower voltage iconic polymer metal composites (IPMCs) are very inefficient, slow, and weak. Pneumatic actuation requires extensive additional pressure infrastructure, and shape-memory wires have severe power requirements. These actuation challenges make untethered soft robots difficult to realize.

Lack of control authority

Many robotic control schemes rely on precision actuation and control authority that is difficult to achieve in soft materials. Feedback control uses various estimation and correction mechanisms to adjust velocities and positions, often by assuming high structural impedance. As impedance is reduced by incorporating soft materials, lag times, deformations, and vibrations increase, making the control problem much harder, like controlling a marionette with rubber bands rather than with strings. Solutions may involve substantially more sensing and modeling, but ultimately new control methods and new design paradigms that are compatible with the new design space will need to be developed.

Primitive fabrication methods, modularity, and standards

Multimaterial fabrication methods for soft systems are still limited and expensive. Most rigid robots today are fabricated

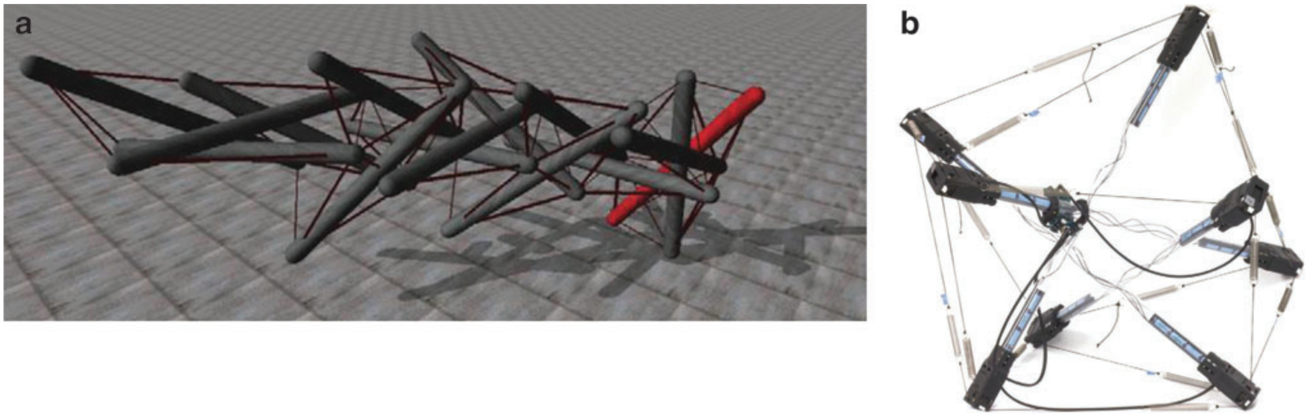

FIG. 6. Tensegrity robotics combine rigid struts and elastic cables to create soft structures. **(a)** Evolved design, and **(b)** fabricated robot. Reproduced from Rieffel et al.[8]

by combining standardized components and modules: standard motors and sensors, wheels, mechanical transmissions and linkages, grippers, and so on. These standardized components are not yet available for soft systems, requiring every soft robot project to start design and manufacturing essentially from scratch and making knowledge transfer difficult. Manufacturing technologies that have been honed for rigid systems are not yet fully optimized for soft materials: for example, there are relatively few soft materials for 3D printers, and their properties are not well characterized. Some standardization may emerge as soft systems become more popular, yet the amorphous nature of those systems may imply that the field may never become fully standardized.

Potential Approaches

Many of the challenges listed above are typical of any new field of engineering that involves new materials, new production processes, and new design goals. Some of the challenges may be alleviated as the field matures, yet other challenges may require fundamentally new engineering approaches.

Over the last decade, we have explored a number of potential new approaches for the simulation, design, fabrication, and actuation of soft robots. Often, these explorations initially attempted merely to solve a specific challenge, but eventually led to a deeper understanding of the opportunities of soft robotics.

Simulation of soft materials

Our initial attempts to simulate soft materials involved the use of standard nonlinear (iterative) finite element solvers. However, we quickly discovered that even nonlinear approaches are limited to relatively small deformations. When a material can experience very large deformations that cause it to fold and bend, and even change the boundary conditions by collapsing on itself, iterative linear methods do not suffice.

Instead, we developed an approach based on nonlinear relaxation and used it for kinematic simulation.[4,9] In nonlinear relaxation, the structure is represented as a network of simple elements such as springs, beams, and masses. The dynamics and kinematics of each element are well understood and can be simulated relative to the component's local environment. A network of elements is then simulated in parallel, each element in relation to its surrounding elements on a lattice, essentially performing a particle-based material simulation. The approach can simulate both large-scale deformations as well as physically correct dynamics of very soft materials (Fig. 1). As a validation, a dynamic simulation of a flexible beam matched the theoretical analytical solution for resonance frequencies.

The advantage of using a particle-based approach for simulating soft structures is the ability to easily incorporate new, nonlinear, and active elements such as actuators, contacts, and arbitrary reactive materials. Because of the decoupled nature of the simulation, each element can be controlled separately and have its own "local" behavior, leading to a rich simulation pallet. Material behaviors can be blended and merged to create new kinds of graded digital materials.

Having a physically correct simulator does not automatically imply that predictions of the simulator match physical reality. In order to match reality, various material parameters must be calibrated using experimental data. Depending on the complexity of the elements and the number of different element types in a model, extensive physical tests may be required to calibrate these parameters with confidence. Various machine-learning algorithms can also be used to "back out" optimal parameter settings to best match overall observed performance.

Voxelyze, a soft matter physics engine, and its matching graphical user interface, *VoxCAD*, have been released as open-source[10] and serve as the basis of several soft robotic systems described here.

Design automation

Design automation tools are necessary to augment human intuition and creativity when combining soft materials for a design goal. Since human intuition is relatively limited when it comes to predicting the behavior and interaction of soft materials, design automation tools can help explore the design space more efficiently, find entirely new solutions, or refine known designs.

Adequate physical simulation and analysis is a prerequisite to any design automation tools. Once physical simulation is in place, optimization tools can then be used to search for optimal shapes and multimaterial arrangements in order to achieve a desired design goal. For example, one can search for the optimal arrangement of hard and soft materials to achieve the most lightweight structure that can carry a given load. Starting with a solid block of hard material, the optimization algorithm can add, remove, and change material while continuously improving the performance criterion, gradually approaching the optimum.

In practice, the challenge in developing design automation tools lies in finding both the proper *representation* for the space of potential designs, as well as the *optimization* algorithm that can optimize those candidate designs. The representation, or encoding, is the language for describing the shape and composition of the robot. For example, a direct encoding could represent solutions simply as a 3D array of voxels, each voxel corresponding to a certain choice from a pallet of materials. One could then use a simple gradient descent algorithm that would start from a random arrangement of materials and gradually improve material choices voxel by voxel until no further improvement can be made. Direct representations, however, are inefficient and unlikely to discover uniform or periodical materials, and gradient optimizers are both slow and prone to getting "stuck" in local optima.

Over the years, the evolutionary robotics community has explored a variety of representations and global optimization algorithms for designing robotic systems. These representations ranged from simple direct encodings to sophisticated indirect encodings that describe the composition of materials as a spatial function that described how the material is arranged in space[2], or growth rules that describe how a seed develops into a final shape[3,11], such as those shown in Figure 2.

Some of the early experiments in using evolutionary methods for generating simulated[8] and physical[11] robots focused on systems with rigid components. Despite the use of increasingly sophisticated generative representations and nearly two decades of research, however, evolved robots remained relatively simple in their structure and behavior.[5,11]

The confluence of soft robot simulation and suitable design representation, however, may help unleash evolutionary creativity and bring it to a new level. A particularly successful method for representing spatial functions has been the compositional pattern producing network,[12] which can be used to describe robot morphologies by specifying the type of material as a function of spatial coordinates[2,4] (Fig. 3b). Using evolutionary techniques that involve gradual "complexification" combined with diversity maintenance, we were able to evolve a variety of robots. The shift from rigid to soft matter combined with improvements in morphology representations is finally beginning to yield diverse natural-looking morphologies (Fig. 3a).

Fabrication

Fabrication tools provide the final step into reality for any soft robot design. Some soft robot designs are manufactured manually from a single material using techniques such as casting or molding. However, realization of the full potential of soft robots will require longer-term manufacturing processes capable of forming multiple materials simultaneously into complex forms. Beyond shape complexity, fabrication of robotic structures also requires formulation of actuation materials. Most actuator materials today have power or performance specifications that are incompatible with untethered soft robots.

In order to explore actuation fabrication, we manufactured one of the evolved robots using foam actuation material. We deliberately used two types of foam—open-cell foam and closed-cell foam. When the ambient pressure changes, open-cell foam remains unaffected, but closed-cell foam shrinks or expands in proportion to the pressure change. We can use this volumetric effect as an arbitrary-shape actuation material.

A single-actuator robot was evolved and fabricated using a manual additive manufacturing process by laser-cutting and stacking adhesive-backed foam layers. We then placed the robot in a pressure chamber and cycled pressure. The final robot, shown in Figure 4, displayed the correct kinematics and crawled across the chamber's floor.

Foam-based actuation is one of several possible soft actuation materials that change their mechanical properties dramatically in response to environmental stimulus such as pressure change. An alternative set of soft material that changes mechanical properties exploits the jamming phase transition. Jamming material are essentially granular materials that, when packed, grains interlock to form a solid. As is familiar to anyone unsealing vacuum-packed coffee, when the pressure is released, the grains unlock and flow over each other like a soft material. This effect can be used to control mechanical properties of soft systems such as fabrication of robotic grippers (Fig. 5) or entire working robots.[13] These systems use material property change to enable or disable motion generated by a second actuator, creating a new form of robotic mechanism known as *selective actuation*.

Most soft robots, however, invariably have some rigid components. Such hybrid soft-rigid robot designs attempt to optimally incorporate a few stiff elements within a larger context of soft material. Such judicial use of rigid and soft structures may help alleviate some of the challenges of soft robotics, such as actuation and manufacturing, while retaining many of the advantages such as overall flexibility. A good example of hybrid soft-rigid robots are tensegrity robots,[14] inspired by the cytoskeletal structure of cells combining stiff fibers and a soft membrane to achieve optimal structural integrity and flexibility (Fig. 6).

Conclusions

The nascent field of soft robotics is unique in that it holds great potential but also challenges many of the assumptions, models, materials, tools, and techniques used in traditional robotics for decades. Traditional processes for design and manufacturing are brought to their limits as we seek to create machines with complexities and mechanical properties that imitate biology. New material concepts, new design processes, and new simulation algorithms, however, are beginning to lift some of these barriers, revealing a new world of robotic systems far richer and more promising than we can imagine.

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Author Disclosure Statement

No competing financial interests exist.

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