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Soft Robotics

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Objectives. This description of the developing field of soft robotics is not intended to be a conventional review, in the sense of a comprehensive technical summary of the field. Rather, its objective is to describe soft robotics as a *new* field—one that offers opportunities to chemists and materials scientists who like to make "things," and to work with macroscopic objects that move and exert force. It will give one (personal) view of what soft actuators and robots are, and how this class of soft devices fits into the more highly developed field of conventional "hard" robotics. It will also suggest how and why soft robotics is more than simply a minor technical "tweak" on hard robotics, and propose a unique role for chemistry, and materials science, in this field. Soft robotics is, at its core, intellectually and technologically different from hard robotics, both because it has different objectives and uses, and because it relies on the properties of materials to assume many of the roles played by sensors, actuators, and controllers in hard robotics.

Robotics is at a stage of technological development perhaps comparable to the very early internet (plausibly at the level of the transistor or simple chips). It's when machines, humans (and possibly animals and insects) begin to work together and/or to compete, and even fuse, that things change and get really interesting. Soft robotics will be an essential part of that change. Chemistry and materials science should not miss the opportunity to be a part of it.

Robotics and Jobs. Why is robotics an important field? The shortest and most immediate answer is "jobs." Robotics evolved to allow human- or animal-like functions to be carried out by machines. The original idea was to observe the architecture of a human worker or a working animal – body plan, skeleton, muscles, nerves – and mimic his/her/its useful functions, augmented with greater strength, speed, and accuracy, in a roughly human- or animal-shaped machine. (The idea of substituting machines for animals was, of course, not new: a farm tractor is, in a sense, an ox with wheels instead of legs, and an airplane is a reconsidered bird.)

The field of robotics is, however, much more than just a new way of providing useful work (even work that spares humans). It is a part of four very important subjects: i) jobs (and the economic capacity of nations), ii) non-human capabilities that come from biomorphic but inanimate forms, iii) physical compatibility or incompatibility of robots with humans, and the prospects of melding the two, and iv) the potential for (and perhaps inevitability of) fusing machines, humans, and artificial intelligence, and the consequences of that fusion.

The first of these is one important contributor to the sense of urgency that permeates economic considerations of robotics today.[1]Much of the conflict between nations and regions, and much of their economic welfare, is reflected in their competition for jobs, and in their efforts to match their workforce to the number of jobs their societies require.[2] Existing robots – from those on manufacturing assembly-lines, to driverless cars, autonomous drones, and semi-autonomous vacuum cleaners – constitute a remarkably rapidly developing set of machines that replace, complement, and/or augment human workers in many types of work.[3] Existing (hard) robots have, however, important shortcomings (sketched in the following sections in greater detail). *Soft* robots are important—more important than they might seem now, in their technological infancy—because they will circumvent some of the shortcomings of hard robots, and will solve problems hard robots cannot solve. Understanding the potential of this new field, and the opportunities that it is addressing, suggests some of the characteristics that successful soft robots will eventually possess, and thus indicates some of the features that must be embedded in their designs. Because so much of the function of soft robots will depend upon materials (as opposed to—or in many cases rather than—electronics, sensors and controllers, and mechanical systems), understanding their possible applications defines the materials that they will need (in part), and thus the role of chemistry.

An indication of the size of the problem that robotics addresses is given by a phrase that appears – in one or another form – in a number of analyses of robots: that is, " China's future is Japan's robots."[4] This startling statement is not, of course, literal, but it is based on demographic trends that will be hard to change. The population in China (and Japan, and much of the Western world) is aging, and the number of younger people available to fill jobs, and thus to support this aging population, is less than it must be for stable economic growth to continue.[5] In this sense, robotics is an essential part of China's future economic growth.[6] The same remark can be made for Japan, the United States, and Western Europe, where aging populations, and (often) negative population growth provide requirements for new strategies to use in operating industrialized societies. Robotics and intelligent machines is certainly one relevant new technology; computation and (AI) (whatever that becomes!) is another. A third might be changes in the societies themselves that make them more or less labor-intensive. Whether the robots that China uses are Japan's, or are those of some other region or society (including, of course, China itself), is now an open question. Japan was an early leader in robotics[7], but the United States, China, and Europe are all now important, with different regions having different strengths in areas of fabrication, operation and use, information technology, integration with the Industrial Internet of Things (IIoT), and other aspects of this technology.

The point of this discussion is not – obviously – to analyze regional demographic and economic trends, but rather to make the case that robots and intelligent machines will be a critical part of the future economic competence of countries and regions. I believe that soft robotics will provide important new capabilities for this broad area of technology. As a newcomer and a new technology, soft robots will not displace hard robots: soft robots will (at least initially) augment hard robots, supplement and extend them, and provide new capabilities that they cannot match. Soft robots (and, broadly, soft functional devices) are unusual in that they provide an exceptional opportunity for chemists and materials scientists to be a part of the core group founding a new field.

Hard Robots. Hard robots are fabricated, by definition, from rigid structural materials, and powered either using electrical actuators (motors and solenoids) or with pressurized fluids (pneumatically or hydraulically). Controlling the motion of hard robots is a very highly developed and technologically sophisticated field. They are used both in tethered form (that is, fixed to the floor of an assembly line, as in automobile manufacturing) or as mobile entities (e.g., in moving goods in warehouses, in household appliances, and in military applications). In both modes, they are more or less autonomous (e.g., capable of adapting to new tasks, and to changes in their environment, without human intervention and external control). They are often heavy, and inefficient in their use of energy. They are capable of amazingly complex motions, but at the cost of correspondingly complex motion-control systems.

Robots, Machines, and Actuators: What Is the Difference? The boundaries between these terms are blurry. An actuator is a device that supplies energy (usually in the form of motion, or the ability to do mechanical work) to another device. Electric motors, and pneumatic pistons, are actuators. A machine is a mechanical system – typically with multiple moving parts – that performs one or multiple tasks. A robot is a machine that replicates (or mimics) some features of (originally) humans or animals, and is capable of replicating useful human-like tasks such as walking or gripping (and, now, talking, and in the future, perhaps, understanding).

The overlaps between these informal definitions is obvious. Less obvious is the extension of the idea of complex, "human-mimetic" robots to organisms that are anatomically and functionally *less* complicated—starfish, worms, other "simple" animals—than people and horses, but nonetheless capable of very complex motions, and useful (especially for the organism) functions. These "simple" biological models have the potential to suggest useful new functions for robotics, and especially, since they are themselves soft, functions that might interact well with human needs. Mimicking their functions is also less difficult than those of higher organisms: "gripping" is easier to accomplish than "understanding," and even than "welding."

Soft robots are much earlier in their technological development than hard ones. Most of the current demonstrations of soft devices are in applications as actuators, or specialized functional components of complex robots or machines (grippers, lifters). In practice, most soft robotic systems are now used as components of hybrids integrating hard and soft components, and in which each component carries out the task for which it is best suited. In this perspective, we will typically talk of "actuators" when trying to be precise about a task, and "robots" for greater generality.

What is Missing in Hard Robots? Hard robotics is a hugely successful field, and robots are an indispensable component of many industrial functions. That said, hard robots—especially those intended for heavy industrial applications, have characteristics that can be severe limitations in other circumstances:

"Collaboration." The most important is that they are what is called "non-collaborative." They are often not able to work safely in close contact with (or proximity to) people, or other fragile objects. Because they are both heavy and hard, and are designed (in general) to move rapidly, to apply large forces, and to handle dangerous tools (e.g., tools for welding and cutting metal), they are too dangerous to be close to humans.[8] One important contribution of soft robots is the ability to allow robots to work safely with people, and to handle soft objects. (For example, soft grippers are attractive for handling food, or packages containing soft goods).

Simplicity and Lower Cost. Hard robots – like all hard machines – are built largely of noncompliant materials. As a result, they must be positioned accurately to perform their tasks, and they are generally not (nor are they designed to be) compliant, or able to adapt autonomously to different shapes and tasks. Soft robots, although much simpler in many ways, are much better adapted than hard robots for specific tasks in which the ability to conform autonomously to different shapes is useful. Rather than a "hand" requiring accurate positioning, sensors, and control loops for individual "fingers" (as in a hard robotic hand), soft robots can adapt to gripping and other tasks with minimal controls, by taking advantage of the compliance of the elastomeric materials from which they are made.[9] An important potential for soft robotics is to use the properties of the soft, elastomeric *materials* (perhaps combined with thin structures with high tensile moduli such as fabric, paper, or film) in a structure (e.g., a soft "hand") that might make unnecessary the much more complex systems of electronic controllers, actuators, and computers used in a hard "hand.".

With simplicity, of course, often comes lower cost, simpler operation, and greater durability. Further, since soft actuators are often fabricated from a single piece of flexible elastomer, and have no frictional surfaces at joints or bearings, maintenance and wear can be less than with hard robots. Although the relative cost of systems of hard and soft robotics competing for particular applications will depend upon the specifics of the application, there will be important applications for which soft robots are clearly more adaptable, better suited, and less expensive.

Other Characteristics: Light Weight, Thermodynamic Efficiency. Soft actuators are often lighter in weight than their hard analogues. (There are, of course, designs that maximize the ratio of strength-to-weight for both, but soft structures using pressurized thin walls can combine remarkably high stiffness with light weight.) The thermodynamic efficiencies of most soft systems has not been as carefully defined as have been those in hard ones, but hard robots are not, generally, thermodynamically very efficient, and may thus have high energy costs.

For Robots of All Kinds: *What will the future hold?* The integration of human workers with increasingly competent machines – whether hard or soft – seems inevitable. Particularly in the countries of the economically developed world with aging populations and a high standard of living, there are entire classes of jobs for which there are currently too few available human workers. Fruit picking, mining, food handling and preparation, house cleaning, military and police operations, eldercare, agricultural field work, garbage disposal, and a range of others: these jobs are sometimes difficult, unpleasant, or dangerous, and it might be better to have them done by machines than by people. Soft machines will be required, or preferred to people, for some of them.

The hope, of course, is that jobs that are transferred from humans to machines will allow the humans to take on other, more rewarding jobs. What will they be? The answer to this question is presently unknown. It is not impossible to make such replacements beneficial for all involved. Consider previous replacements of humans and animals by machines. The horse-drawn cart, locomotive, and automobile were all developed to replace the labor of humans or animals by machines. Washing machines and dishwashers freed (largely) women from these tasks, and allowed them tobecome teachers, managers, musicians, bankers, and other skilled professionals. The outcome of the redistribution of "work" among humans, animals, machines, and computers is impossible to predict in any detail now, but it is unquestionably one of the most important changes now facing society. Soft robotics will play a part.

What will be the result of fusion of robots, artificial intelligence (AI), and machine learning? How will humans be involved? The story of “future technology” is more complicated than just “humans,” “robots,” and the distribution of physical labor. There is also the enormously important role of future computer systems (the World Wide Web, mobile devices, artificial intelligence, autonomous systems, the Internet of Things (the IoT) and the Industrial IoT (the IIoT), and many other manifestations of “intelligent machines”). There is – at least in my opinion – a critical role for soft robots and actuators to act as intermediaries between humans (who are intrinsically soft, but involved both in physical tasks, and in using information), robots (which are highly competent machines, albeit with increasing sophistication in information processing) and computer systems (which, arguably, already “think,” and are moving—almost certainly—toward “understanding”). The form and function of these human/robotic/computer interactions, and of hybridized systems combining humans and machines, is presently unpredictable (but include—as physical manifestations—exoskeletons, prostheses, manipulators at very large or very small scales, brain-controlled machines, and sensors that augment human perception). To the extent that they will involve physical/mechanical contact between humans and machines, soft robotics and systems will be important.

What does the subject of Soft Robotics have to do with Chemistry? A major component of soft systems – from robotics to actuators—will be soft materials—elastomers, flexible sheets, fabrics, granules, foams, gels, liquid crystals, liquids, and other forms of matter. Reconfigurable soft robots incorporating harder structural components—such as those designed using the principles of origami and kirigami[10] —will also be important. As the field develops, certain soft systems will also require structurally rigid components (the equivalent of endo- and exoskeletons, intended to provide passive structural strength that soft materials may not intrinsically possess), but economics and materials compatibility will probably dictate that these materials are often also structural polymers rather than metals. Thus, soft robotics offers to material science, and thus to chemistry, an enormous range of opportunities to generate new types of function. The syntheses of super-soft elastomeric bottlebrush polymers by Sheiko,[11] super-elastic polymers by Suo et al.,[12] and self-healing polymers and structures by Bao[13] and Shepherd[14] are early examples. *Soft Robotics is, and will probably remain, a technology founded on soft, functional, materials, fabricated from molecular precursors, in polyfunctional designs.*

Background.

Hard Robotics is a mature field, and has been extensively reviewed.[15] We will not discuss it further. ***Soft Robotics*** has grown sufficiently rapidly that it is already described in many excellent, technologically focused, reviews.[16][17][18][19][20][21][22][23][24] Rather than trying to replicate or summarize them, we simply list them. We note only that (to paraphrase J.F. Kennedy, and many others before him) “Victory has many fathers,” and claims in these early reviews of who developed what technology first, are still to be adjudicated by history. Two historical efforts were particularly relevant to our own work. First, a class of pneumatic actuators based on mesh-constrained elastomeric bladders—a kind of semisoft actuator (McKibben Actuators)—were developed and commercialized in the 1950s.[25] These systems have been successful, but were intended primarily to be linear actuators. Second, Suzumori demonstrated simple, elastomer-based actuators in the 1980s.[26] These systems were, in fact, very similar to some of the soft devices that have emerged in the current explosion of work in "soft robotics," and Suzumori was perhaps the first to recognize a part of the potential for this kind of system.

My personal (and therefore, limited) perspective is that the field of soft robotics has been able to grow as rapidly as it has as a result of a confluence of six technologies developed independently for other purposes. These include: i) ***Poly(dimethyl siloxane) (PDMS) elastomers*** as structural materials that make fabrication convenient (and thus enable rapid prototyping), and possesses a number of useful properties (transparency, ease of sterilization, biocompatibility, etc.). ii) ***Soft Lithography and Microfluidics*** to form appropriate pneumatic and hydraulic channels. iii) ***Digital Fabrication***, especially to aid in making molds. iv) **Soft Composites**, to generate and control anisotropic motion on actuation. v) ***Computers, and Computer-based Systems,*** to serve functions from design and fabrication to control, and vi) ***Hard Robotics***. Hard robotics are particularly important, since they are highly developed, and provide a wide range of important capabilities (from positioning and motion control to visualization) that are also important for soft robotics, reliably and surprisingly affordably. Together, this set of technologies combine to provide: an elastomeric material with excellent properties, suitable both for prototyping and for production; fabrication methods taken from well-developed methodologies—soft lithography[27] and PDMS microfluidics;[28] a convenient, flexible method of making the molds required to fabricate the networks of pneumatic channels required in most designs; straightforward methods of controlling the anisotropy of strain by forming composites of PDMS with flexible but inextensible sheets (or other composite designs), and origami/kirigami-based structures[29]; design, control, and vision tools based on computers; and concepts from hard robotics, and more importantly, from existing, highly engineered hard robotic *systems*, for use in hard/soft hybrid systems. Which of these technologies persist as important parts of the field of soft devices as it develops depends on the characteristics of the applications being addressed.

Our Starting Point in Soft Robotics.

The Beginning: Biomimicry Based on Invertebrates and Higher (but Not Mammalian) Organismic Models: from Worms to Squid. The starting point for our work in this field was a series of discussions (largely carried out in the 1980s and 90s in a very stimulating working group – the DSRC, or "Defense Science Research Council" – a group focused heavily on materials science, and sponsored by DARPA). The possibility of approaches to robotics that provided capabilities beyond those of existing, largely industrial, hard robots was, of course, already a subject of active discussion, and one subject of discussion was always "are there other ways of doing it?" Most of robotics at that point was based on the idea of modeling humans or animals, or making other mechanical systems (e.g., aircraft or vehicles) more versatile and polyfunctional, in order to give them greater capability or autonomy.

Among our early interests in the subject of soft robots were the characteristics of animals lacking internal skeletons. All have countless interesting anatomical functions. Worms, for example, move with a sophistication that is still not easy to replicate; starfish provided the first models and inspirations for grippers. Squid and octopodes are inspiring examples of very intelligent animals using complex motions controlled using strategies quite different from the ones land-animals use. (For example, the tentacles of an octopus are at least partially controlled locally: each tentacle has its own complex set of local nerves as a controller.[30]) Insects do not have endoskeletons (or, generally, lungs), but they do have exoskeletons. These skeletons enable them to move efficiently without buoyant support from water, but they are limited in size by structural constraints, and by restrictions, *inter alia*, in rates of mass transport of oxygen from air into their tissue. Aspects of all of these functions are now visible in current soft actuators.

Discussions with DARPA program managers—originally Dr. Mitch Zakin, and later Dr. Gill Pratt—led to an initial, multi-team project: the "Chemical Robots", or "ChemBots" program. The objective of the program was to develop a soft system that would start by looking like a soft-drink can, autonomously unfold, move across the floor, find a door and crawl under it, and reconfigure into a something that looked like a soft-drink can on the other side. The ChemBots program did not, in fact, produce a working example of technology having this level of complexity, but it provided a number of successful component technologies, and was the very successful starting point for technical approaches to soft robotics. Probably as importantly, it nucleated the area, and provided initial support for a number of investigators—Rob Wood, Daniella Rus, Heinrich Jaeger, Peko Hosoi, Barry Trimmer, Mahadevan—and students/postdocs—Rob Shepherd, Carmen Majidi, Mike Tolley, Rebecca Kramer, Christoph Keplinger, and others—who have subsequently emerged as leaders of the field.

Although pneumatic inflation emerged from this program as the most immediately useful method of actuation (and certainly the simplest to implement), a number of other interesting approaches also emerged. For example, Jaeger's demonstration of pneumatics to accomplish granular jamming in loose particles, and thus to *freeze* shapes[31] is particularly interesting for its complementarity to pneumatic methods that cause large, *dynamic changes* in shape in soft elastomers, and will probably become an important part of the technology of the field in the future.

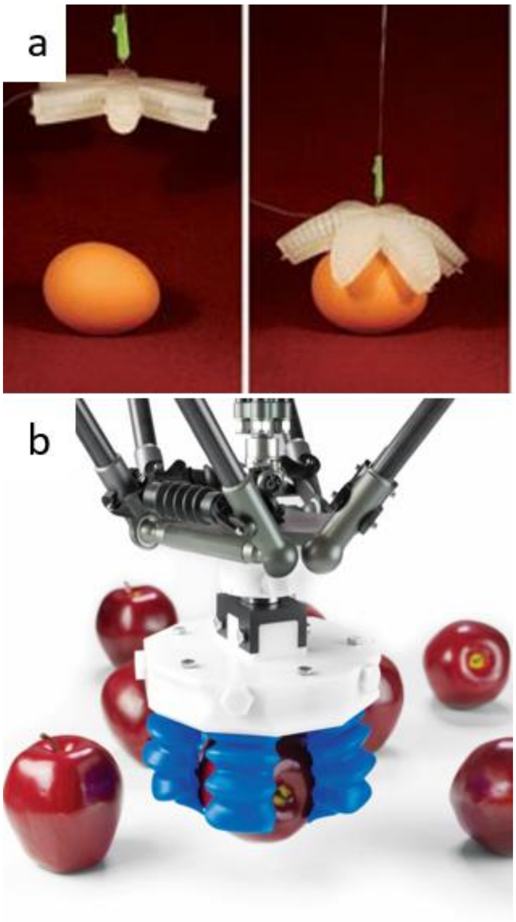

Figure 1. a. Soft gripper (a "starfish gripper") picking up an uncooked egg. Reproduced from Ref. [32] with permission. Copyright 2011, John Wiley & Sons. b. An industrialized adaptation of a gripper. The "fingers" are soft, and grip delicate objects (here, fruit) without damage. The "palm" of the gripper is hard, and attached to a commercial, hard, arm. (Soft Robotics, Inc.). Both rely on PneuNets and pneumatic actuation.

PneuNets: Initial Work on Soft Actuators. The initial work in my group was designed to provide the simplest solution we could find to the problem of actuation (Figure 1a). It used the expansion of a bladder (or balloon) constrained by its shape, and either by the anisotropic properties of the elastomeric materials (e.g., combinations of more and less flexible PDMS)[32], or by the incorporation of paper- or cloth-based structures into elastomeric composites to control anisotropy of motion on actuation.[33] To control the stress, and the distribution of stress, in these systems, we used a number of strategies. It was often useful to fabricate a network of small bladders (rather than a single large one) connected to a common source of pressure to engineer the distribution of strain, and thus shape, in the inflated soft device. Digital printing made it easy to make the molds required to form these microchannel systems (which we called "pneumatic networks," or PneuNets) in the PDMS.[34]

Sealing techniques developed in PDMS microfluidics could be used directly with these pneumatic systems; because we used pressures that were typically only 50 – 100 kPa (0.5 – 1 atm) relative to ambient pressure, high-strength seals were not required for prototyping. Figure 2 illustrates the process used originally; the same principles are still used, albeit with different designs for the bladders, and different methods of fabrication.

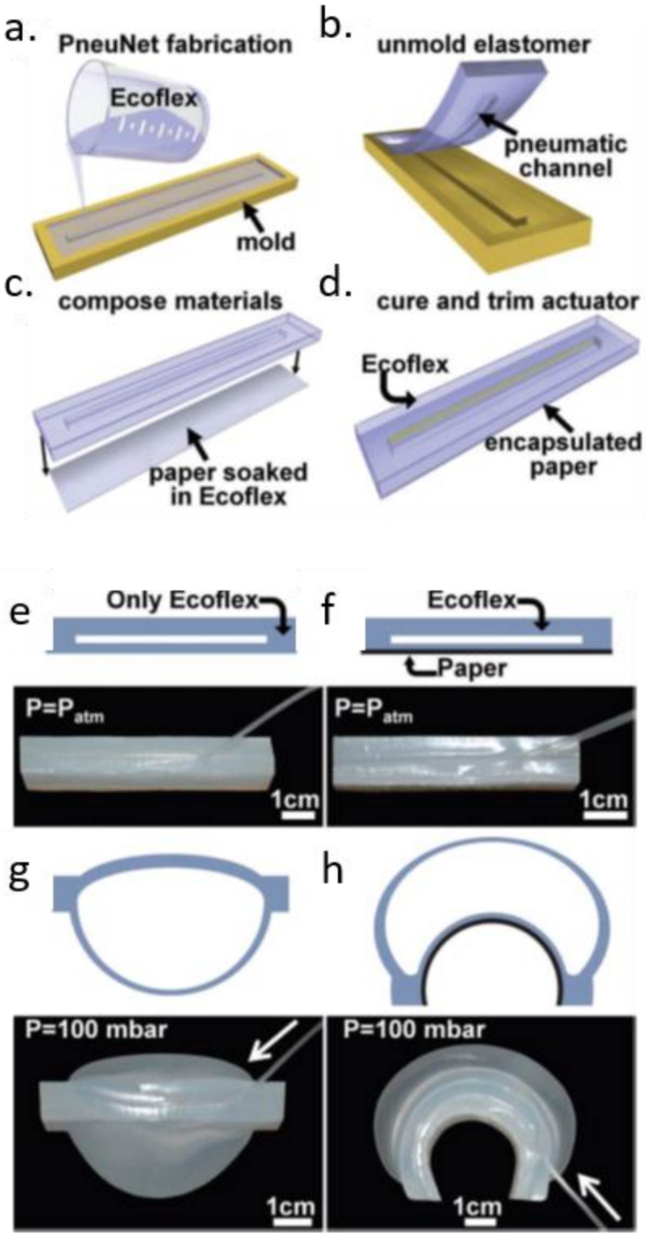

Figure 2. a-d. Schematic illustration of techniques used to mold and assemble a PDMS/paper composite. e-h. Cross-sections of PDMS ("Ecoflex") structures, both with and without a paper strain-limiting layer, (uninflated and inflated), together with photographs of these structures inflated and uninflated. Reproduced from Ref. [33] with permission. Copyright 2012, John Wiley & Sons.

The fact that relatively low pressures are involved in these actuators can seem surprising, but it is good to remember that net force scales with pressure and area (F = PA), and 1 atm of pressure over 20 in^2 (or 130 cm^2) is about 130 kg. Since actuation can result either from a positive or negative difference in pressure (that is, from either "applied pressure" or "applied vacuum") across appropriately designed PneuNets, the same forces can be generated with both. With appropriate materials and designs, it should be possible in the future to go to much larger pressures, and thus much higher applied forces (1 atm of pressure is ~ 1 kg-force cm^2).

These principles led quickly to a range of demonstrations of soft actuators with biomimetic functions.

"*Starfish Gripper.*" The first example of a useful soft device (published in *Angew. Chem.*[32] over the objection of the referees, on the grounds that it was "not chemistry") was a pentagonal gripper (Figure 1; shown picking up an uncooked egg).

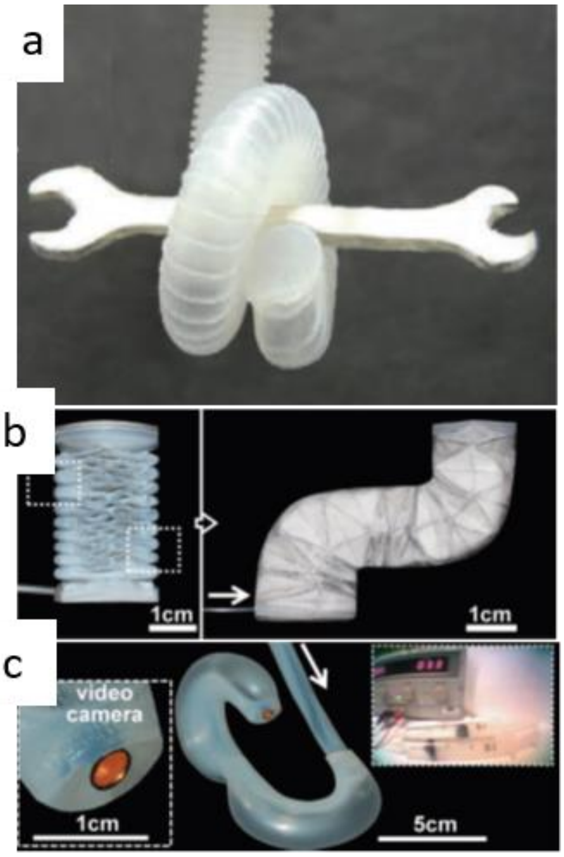

Figure 3. Examples of soft structures illustrating different functional modifications. a. A textured surface to improve gripping. Reproduced from Ref. [35b] with permission. Copyright 2013, John Wiley & Sons. b. A structure that includes an origami strain-limiting layer, with leaves glued together in specific points to control its bending. Reproduced from Ref. [33] with permission. Copyright 2012, John Wiley & Sons. c. A "tentacle" including a cell-phone camera and an optical link, with an image obtained with this system. Reproduced from Ref. [35b] with permission. Copyright 2013, John Wiley & Sons

Figure 4. Quadruped "walkers" using five pneumatically-controlled chambers: a. tethered to the pressure source through flexible tubes (length of walker ~ 20 cm); b. untethered, with compressor, valves, and other hard controllers riding on top of the soft walker (length ~ 0.5 m). Reproduced from Ref. [36b] with permission. Copyright 2014, Mary Ann Liebert, Inc.

Because grippers have proved so important practically, and because this class of actuator is relatively easy to make, many variants on the structures of grippers have already appeared (Figure 3). ***Tentacles***[35] have been designed and demonstrated in profusion, stimulated by the admirable dexterity of the octopus. (All of these demonstrations, and certainly including ours, fall far short of the capability of even the least capable cephalopods, and have essentially nothing to do with the anatomy, sensory system, and control with which they generate their extraordinary motions.) Simple ***Walkers***[36] proved easy to make, although not so far useful. They have, however, provided a useful test bed for the development of autonomous, mobile systems. Exploring other possibilities led to a number of interesting, if odd, functions. For example a ***"Chameleon's Tongue"***[37] demonstrated the ability of a soft actuator to move surprisingly rapidly (complete coiling of a tentacle[34] requires less than 200 msec.), and ***"Combustion-driven Jumpers"***[38] demonstrated that it would be possible to generate substantial pressure on-board (by filling the PneuNet with a methane-air mixture, and then igniting it with a spark).[39] Other methods of generating pressure internally – for example, the decomposition of hydrogen peroxide to oxygen and water[40]—have also been demonstrated, but have not so far proved practically useful. Perhaps (at least in the long term) a more interesting demonstration is that of the use of the microfluidic function built into soft devices for functions other than motion. For example, ***Fluidic Transport for Observation, Delivery, and Sampling***[35b] can transport reagents to an object or a test sample, examine its environment, and retrieve fluids from a test site, with almost no modification of the robot other than adding another small fluidic channel for transport of fluids.

The same type of microfluidic system provides the basis for a walker that capable of ***Camouflage***[41] (reflecting exchange of fluids in microchannel systems in the PDMS structure); this walker could show independent patterns in visible and IR spectral regions. (Camouflage has proved a subject of enduring interest in soft robotics, stimulated in part by the marvelous abilities of the octopus.) ***Non-Biological Functions.*** Similar uses of small channels in non-soft-robotic applications (e.g., microfluidics) had established the value of microchannels in fabricating optical waveguides and small dye lasers, flexible electrical conductors, and current carriers for generating magnetic fields using the same methods of fabrication[42]. Incorporation of a small camera (taken from a cell phone) on the tip of a tentacle, coupled to a computer either using a fiber optic or Bluetooth link, gave these simple systems "eyes."[35b, 36b]

Tethered vs. Non-Tethered Systems: Power. Most of these demonstrations have involved actuation by compressed gas from an external source, and thus require a gas-transfer line connecting the actuator to this source. Actuators that are connected to stationery, external power sources are called "tethered." It is still an unresolved and still contentious issue as to whether tethering is an important limitation of these systems or not. In practice, many existing hard robots—robots used on manufacturing lines, for example – are tethered. A smaller, but important set of robots—robots used for warehouse management, floor cleaning, and tasks requiring movement over large areas (airborne drones, autonomous vehicles) – are, and must be, untethered. Designing large, soft robots that are untethered and mobile, using PDMS and low pressures, is difficult, simply because it is not straightforward for the body of a soft robot to support its own weight, plus the weight of the power supply, compressor, valves, and control required for complete autonomy[36b]. The question of how important this limitation is, is still being actively discussed, but if it *is* important, it almost certainly can be solved using stronger elastomers and higher pressures. In practice (see below), most current applications of soft actuators are in systems in which they are combined with hard robots; hard robots can operate either in tethered or untethered mode, and – if needed – provide power for soft robots.

Biomimetic Function, but Not Biomimetic Mechanism. An important point of emphasis is the meaning of "biomimetic." These PneuNet-based systems (and others) were designed to mimic the *function* of biological systems: that is the ability to change shape, exert force, and do work. They were not designed to mimic the *mechanism* by which organisms accomplish these functions (using muscle, or specialized structures such as hydrostats.) Although the literature is replete with references to "artificial muscle," none of these structures-- although interestingly designed, and possibly useful-- mimic any of the biochemistry—the ATP dependent interaction of myosin and actin fibers—that underlies the contraction of muscle (Figure 5).

Figure 5. (left) Human arm showing the biceps muscle, and (right) a PneuNet structure that combines negative (sub-atmospheric) pressure and reversibly buckling elastomeric beams to mimic the function of this muscle[43]. Reproduced from Ref. [43] with permission. Copyright 2016, John Wiley & Sons.

Alternative Designs. PneuNets, actuated using positive and/or negative (sub-atmospheric) pressures, have provided a starting point for providing power to soft devices, and have illustrated some of the motions available to them. One of the features distinguishing soft and hard devices is, however, the nature of their response to actuation. Hard robots are generally designed to be linear in their response to their controllers. One of the interesting and differentiating features about soft materials, is that—especially when operated with minimal controls—their response to actuation is often non-linear. This characteristic is one basis for their adaptability, but can make them more difficult to control than linear systems. We consider non-linearity an *advantage* (although one requiring management) rather than a disadvantage, in that it allows the generation of very complex motions using very simple actuation (for example, Figure 6a). One example of a useful *class* of non-linear motions available in soft robotics is buckling.

Buckling and Other Non-Linearities of Materials.

For most hard materials, buckling is a mechanism of failure. As one increases the pressure on a concrete pillar, for example, its response (compressive strain) will be small, until it fails catastrophically. Soft beams also buckle (that is, at some pressure they show a large and nonlinear response), but this buckling is *reversible,* and hence a useful mechanism for actuation that is not available in hard materials (Figures 5, 6).

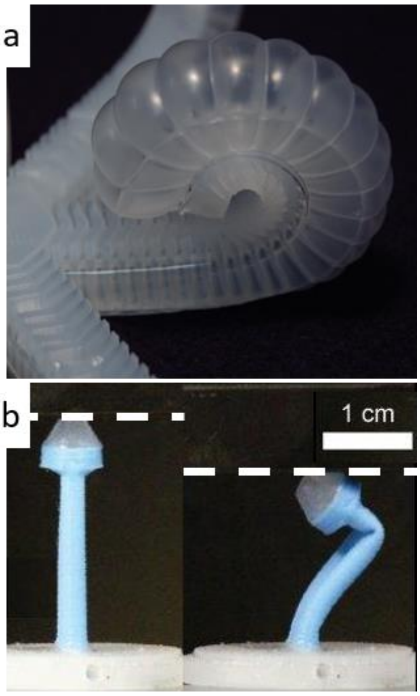

Figure 6. Two structures illustrating “snap-through” (a useful form of non-linearity in soft structures). a. An “arm” of a starfish gripper that—on uniform pneumatic actuation—curls non-uniformly, starting from the tip. Reproduced from Ref. [32] with permission. Copyright 2011, John Wiley & Sons. b. A hollow, elastomeric beam that—when compressed—buckles and crimps (thereby blocking the flow of air through the tube): this structure can serve as a soft valve

Buckling, and nonlinear properties of materials, have been extensively studied. Our work in soft materials has relied both on empirical observation of prototypes of soft devices, and (heavily) on beautiful studies by our colleagues Bertoldi[44], Suo[43], and Mahadevan[45]. Figures 5 and 6 provide examples of the application of buckling in actuation. The structure in Figures 5 particularly interesting: this structure contracts linearly on application of vacuum, and this motion results from the buckling of a series of internal elastomeric beams.[43, 46] It is—so far as we know—the structure that comes closest to mimicking the behavior and functional characteristics (but certainly not the *molecular* mechanism) of biological muscle.

Pneumatic Origami Structures, and Structures with "Semi-soft" Components. Another broadly useful class of structures are those in which the strength of soft materials is increased by adding flexible but non-elastic components. Figure 7 shows two examples.

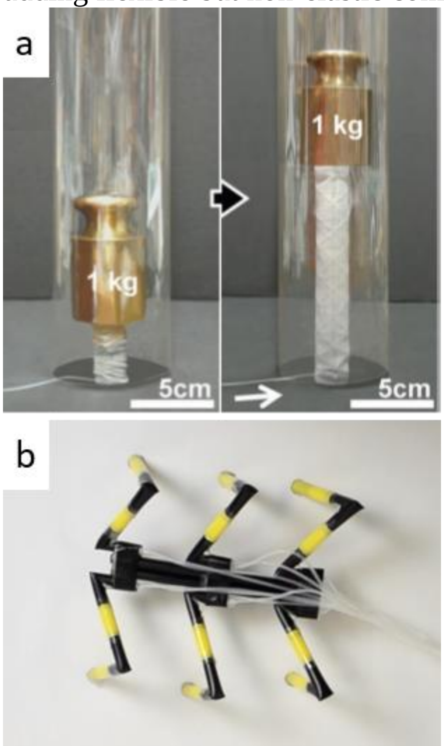

Figure 7. a. A PDMS tube, reinforced with a paper origami strain-limiting structure, lifts a heavy weight on pressurization. Reproduced from Ref. [33] with permission. Copyright 2012, John Wiley & Sons. b. An arthrobot, in which the combination of flexible but non-elastic tubes (polyolefin drinking straws) and PDMS balloons (inside these tubes) provides a joint that mimics functional aspects of the joints of a spider.

The upper figure shows a "lifter" that has an origami structure of folded paper embedded in a thin, circular PDMS membrane.[33] This type of structure provides sufficient compressive strength to lift a remarkably heavy weight (as a multiple of its own weight). Extensions of this principle have recently demonstrated grippers with potentially useful strength. Figure 7 also shows what we call an "arthrobot."[47] This walking structure is loosely modeled on arthropods, which have hard (chitin, for ants) or semi-hard (for spiders) exoskeletons. This particular structure has six legs (as does an ant) but joints whose mechanism of action is modeled on those of a spider (whose joints are, surprisingly—for such a complicated organism—among some of the simpler joints found in arthropods). The structural strength is provided by circular tubes (polypropylene drinking straws, chosen for their availability, light weight, high strength, and low cost).

The Materials Science of Soft Robots. Most of the initial work in soft robotics has been devoted to demonstrating elementary designs: of these, PneuNets,[34] and analogs of them, have so far proved the most broadly useful. For most of this work, commercial elastomers (especially PDMS, with occasional applications of elastomeric polyurethanes) have been the materials of choice. PDMS has been especially useful because its properties are "good enough" (and perhaps in some cases optimally good) for both academic prototypes and initial commercial products, and because it is particularly easy to mold and seal. Silicone elastomers also come in a very wide range of structures and properties; the family of siloxanes has the versatility required to solve many problems in soft materials science. The fabrication of PneuNets has also benefited from the fact that much of the technology needed for academic demonstrations of soft robotics has been able to exploit (often without modification) fabrication methods developed for PDMS-based microfluidic systems. Further, composite structures—structures fabricated with heterogeneous structures—typically incorporating elastomers with different mechanical properties and with flexible but inextensible sheet materials (paper, glass fiber, mesh, cloth)—have proved an integral part of soft robotics (Figure 8).

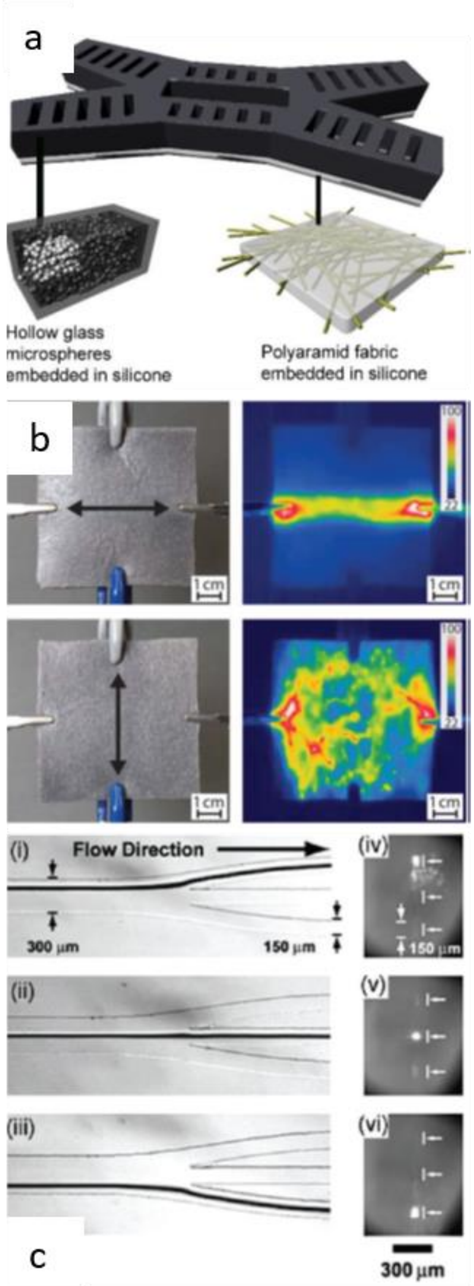

Figure 8. PDMS-based structures illustrating features that can be incorporated into soft robots. a. Glass microspheres (to decrease weight) and polyaramid fabric (for strength) in a walker (Figure 4). Reproduced from Ref. [36b] with permission Copyright 2014, Mary Ann Liebert, Inc. b. Anisotropic current flow (visualized in the IR as heat) in PDMS sheets containing steel wool on application of strain parallel (top) and perpendicular (bottom) to the orientation of the fiber, and the flow of current[48]. Reproduced from Ref. [48] with permission. Copyright 2015, John Wiley & Sons. c. Switchable fluidic optical light guide[49], visualized with an optical microscope (i-iii) from the top of the microfluidic channels and (iv-vi) from the ends of the microfluidic channels. Reproduced from Ref. [49] with permission. Copyright (2004) National Academy of Sciences, U.S.A.

Elastomeric composites are much less extensively explored than composites of hard materials (where they are, of course, at the heart of the design of materials-based structures). It is routine to embed flexible sheets into PDMS structures to limit and direct their strain under the stress of inflation. By using origami or kirigami sheets, fibers, or flexible beams, a wide range of interesting and useful behaviors can be achieved with minimal changes in methods of fabrication.

Although composite structures are central to materials science, *soft-matter* composites are relatively unexplored, and the broader opportunity for introduction of new types of soft, composite materials into soft robotics is enormous. Chemistry has produced a very wide range of elastomeric materials, ranging from very soft gels to very tough particle- and fiber-reinforced rubbers (e.g., for tires). Very little of this range has yet to be explored as materials of construction for soft, "ultra-soft" or "hard-soft" robotics. Design and preparation of elastomeric materials with useful electromagnetic and optical properties is also just beginning. Biomedical applications will require careful engineering of mechanics, surfaces, biocompatibility, and gas-transport properties.

The Material as the Controller: "Intelligent Materials." A concept that has emerged from initial work in soft robotics—one that differentiates it from hard robots—is that of "the material as the controller." Hard robots are almost entirely dependent upon systems of sensors and active controllers: for example, for a gripper, pressure sensors in the "fingers" sense pressure or force on the object being gripped, and use that information to compute appropriate forces supplied, often by electrical motors, to provide adequate—but not damaging—gripping.[9] Much of this complexity can be eliminated with soft robots, albeit at the cost of reduced multi-finger dexterity. Because soft fingers are compliant, they can, however, adapt to complex surfaces autonomously, and distribute pressure in a way that limits damage to the object being gripped (Figure 1). Allowing the material (and the design) to control the pressure exerted by the gripper also allows much simplified control (in fact, in some applications, control limited to the applied pneumatic pressure), and safe manipulation of complex and fragile objects.

Engineering Properties. Establishing the properties of engineered materials—and the required materials databases—required to develop commercial products is an arduous process in which useful information accumulates with increasing volumes of application. Although relevant development research is just beginning, there are a range of indicators-- both from current work, and from accumulated experience using elastomers in other applications-- to guide expectations. ***Cycle Lifetimes.*** How many times can an actuator bend before it begins to fail? Simple bending tests with PDMS fingers and tentacles suggest that millions of cycles are possible with only small changes in stress-strain relationships.[34, 46a] ***Damage Resistance***. PDMS-based structures are remarkably resistant to damage on blunt impact. For example, because they are so light, it is almost impossible to damage them by dropping, and it is possible to drive an automobile over a walker without damage. Elastomers can also be astonishingly tough: fiber- and particle-reinforced truck tires are among the most durable of human-engineered structures. By contrast, PDMS and soft hydrogels fracture easily when *cut* (especially under tension). New types of very tough gels—typically inter-penetrating polymer networks—are, however, now appearing.[12, 50]

Relatively little detailed information relevant to the engineering of properties relevant to specific applications in soft systems is yet available. Comparisons between hard and soft systems may be difficult, since their properties are so different. ***"Wear***" Is an example that suggests the difficulties of making comparisons. When a soft "finger" or tentacle bends, stress is stored as strain (reflecting changes in the conformation of the constituent polymer chains). Strain-induced changes in the elastomer may result in accelerated aging, and thus in changes in bending modulus. By contrast, when a hard "finger" bends, sliding friction between hard surfaces in joints or bearings can cause frictional wear, and perhaps require lubrication and cleaning. Correct comparison of hard and soft systems is thus, in practice, difficult, since their motions are so different. ***Other Properties.*** A wide variety of other properties are relevant to specific uses of soft robots and actuators: surface textures for grippers, ease of sterilization, resistance to temperature or chemical corrosion, permeability, weight, optical and electromagnetic properties, biocompatibility, cost, and many others must be considered on a case-by-case basis. It is, however, clear that in some applications—handling food, tissue, and humans, picking up soft objects of irregular shapes, fitting into small or irregular spaces, operation in the presence of corrosive agents, and others—soft systems may be successful in applications that would be very difficult for hard systems.

New Directions

New Actuators. Most of the work in soft robotics has used a limited set of elastomers as materials, and pressurized air, or vacuum, for power. There is certainly interest in alternatives, particularly those that would use electricity. Some of this interest is probably more based on familiarity, and the technological maturity of electrically- and combustion-actuated systems (electrical and IC motors, batteries, electrically controlled solenoids and valves), than on a careful comparison of the characteristics and applications of hard and soft robots. Suo[51], Keplinger[52], Bauer[53] and others have demonstrated effective methods of electrical actuation relevant to soft robotics using dielectric elastomers, and others will certainly be examined, but strict electromagnetic analogs of hard robots have been slow to develop. Perhaps more importantly, an electrically-driven soft robot may simply not be as useful as a soft, pneumatically-driven, adaptive one in broad classes of applications. Efforts to use chemistry (either in terms of molecules with high free energy, such as H_2O_2, or by combustion) have not, so far, proved practically useful in powering soft robots, although they work to a limited extent.[38-40, 54] Fuel cells compatible with soft structures provide an obvious, and largely unexplored approach to hybrids combining chemical fuels and electrical actuators/controllers, but would require hard components. Soft supercapacitors might also be useful. Other types of actuations—for example, strain release in tightly wound, pre-stressed fibers (a concept developed by Baughman[55]) may also be interesting for some specific applications. That said, pneumatic actuation has proved so simple to implement in prototypes that no better method has yet emerged, and the problem of providing (or at least testing) a broader range of options for activation of soft machines represents a largely-unexplored opportunity.

New Materials: Elastomers, Composites, Gels, Foams, Particles. The exploration of the chemistry and physics of soft matter—in the specific context of actuators and robots—is in its infancy. A few elastomers have been surveyed, but only siloxanes have been seriously developed. Liquid-crystal polymers, fiber- or particle-modified elastomers, elastomeric systems designed for high-pressure actuation, ultra-soft elastomers, very tough, stiff elastomers, and a wide variety of hybrid soft-hard systems are all potentially interesting. In addition, states of matter such as very soft gels, foams, fibers, particle beds, fabrics, granular matter, and others are all, in principle, useful in actuators. In one relevant example, Jaeger and colleagues have demonstrated remarkable characteristics for vacuum-jammed structures as grippers that are quite different from grippers based on PneuNets.[31, 56]

Components and Soft Controllers. Pneumatically-actuated soft robotics is limited by the availability of the obvious, standard components used to handle compressed gasses as soft structures. The most commonly used types of valves are conventional hard solenoid valves, located (usually) close to the source of gas rather than on the robot; easily integrated equivalents of the "Quake valves"[57] (so useful in microfluidics) do not yet exist (although initial steps are evident[58]), nor are there reliable functional analogs of the set of components (transistors, resistors, capacitors, and inductors) that form the elements of electrical circuits, and that might—in principle—form the basis for "all-soft" controllers.

Multiplexed Fluidic Systems with Optical and Magnetic Functions.*[42, 59]* Two areas to which soft materials have been applied that are similar to soft robotics in some ways, and in principle easily integrated with it, are microfluidics and optics. Initial demonstrations into other areas suggest much broader application. For example, we, Dickey, and others have demonstrated PDMS systems that also act, in conjunction with liquid metals (for example, the eutectic alloy of gallium and Indium, or EGaIn) as metallic electrical current conductors[60], or (with ionic liquids or gels) as transmitters of electrical potential[61]. There are initial demonstrations of microchannel systems as optical waveguides[49] and dye lasers[62], as magnetic field generators[42], in channel systems for transport of fluids, for sampling[63], and for delivery of materials as liquids or suspensions.[64] The integration of sensing, and delivery and analysis of chemicals, will probably be easier with soft components than with hard ones. The potential for soft structures to be integrated with many biomedical applications—applications in which the robotics structure must interact intimately with humans (human patients, human tissue, care providers)—is large.

Autonomous Systems. For soft systems to reach their full potential, it will probably ultimately be necessary to develop them to the point where they can be autonomous (that is, capable of independent adaption to task and environment, and perhaps to mobile and untethered operation, with little or no human intervention or control). Applications undersea (which are being explored by Wood and Rus)[65] are an obvious area in which autonomy would be useful, and in which soft robotics seems a natural fit since polymers have roughly the same neutral density as water, and mobile systems will not require structural strength to support their own weight. Maintaining neutral buoyancy becomes an issue for such systems, and probably favors the use of hydraulic, rather than pneumatic, actuation).

Demonstrations of untethered systems using PDMS "walkers" have outlined some of the problems that must be solved to make autonomy practical on land (Figure 4b).[36b] A useful question to answer in considering mobility in untethered, soft robots is: "why do octopodes not run on land?" One answer is that they are adapted for the ocean, but a more technical answer is that they are not designed structurally to support their own weight easily in a gravitational field, in the absence of the buoyancy provided by water. Soft robots would not necessarily suffer from the same limitation as octopoids, since, in principle, the use of stiffer elastomers, and higher pressures, would allow support of much heavier robotic structures. Also, as with insects, the use of stiff or semi-soft endo- or exo-skeletons would greatly increase the strength of soft robotic structures, albeit at the expense of susceptibility to damage and of possible limitations to flexibility. None of these options has been developed for autonomous systems on land.

The potential for soft robotics in certain kinds of applications in the air has also already been demonstrated. The most ingenious involve making structures that are essentially helium-filled balloons with built-in capability to move in complex ways (Figure 9).

Figure 9. Light-weight structures (essentially, structured helium-filled balloons). (left) A commercial children's toy (an "air swimmer"), and (right) a long, steerable arm (a Giacometti Arm with a 20-m balloon body). Suzumori Endo Lab, Tokyo Institute of Technology[66]

These systems do not, at present, have great strength, but large gas balloons (dirigibles) with good strength are highly developed, and the simplicity and ingenuity of design of these new systems suggests applications where high speed, limited environmental range (e.g., operations in still air) and resistance to damage are not important.

Thermodynamic Efficiency; Systems for Temporary Storage of Energy in Strained Materials. There is still relatively little experimental information on the thermodynamic efficiency of existing classes of soft robots.[38, 67] The few exceptions (measured using simple procedures: for example, a comparison of pressure-volume work with the work of lifting a weight) suggest un-optimized efficiencies of ~ 30%. One of the potential advantages and opportunities offered by soft robots is, however, the ability to store and recover energy from strained elastomers. The leg tendons of kangaroos provide an example from Nature of the value of this kind of "spring-like" (and, in principle, recoverable) energy stored in strained structures.

Biomedical Uses. A major reason for interest in soft robotics is their collaborativity—that is, ability to interact safely with humans. Given that characteristic, one of the most obvious potentials for applications lies in medicine (broadly defined to include eldercare, treatment and prevention of pressure ulcers, prostheses of many types, catheters, surgical aids, aids in rehabilitation, assistive devices for nurses and hospital workers, technology for emergency response, and many others) or in biological research (e.g., handling laboratory animals, organs, and tissue samples). These areas of research are only now beginning to develop, at least in part, because many of the problems to be solved in these applications are not *per se* robotic, but biological, clinical, economic, or regulatory. Biocompatibility is still a field in its infancy; any experimentation on animals or humans is cloaked with regulations; the needs in most areas of medicine (and certainly of nursing practice or eldercare) are unknown to materials scientists; research on "devices" is unpopular with government funding agencies. Initial experiments by Walsh in rehabilitation and soft components in exoskeletons[9, 68] do, however, demonstrate the interest of the field (Figure 10 gives an example).

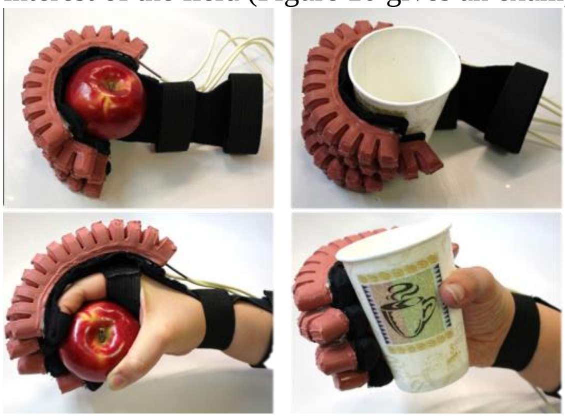

Figure 10. A grip-assist device, comprising a glove with pneumatically actuated elastomeric "fingers" that augment the grip of human fingers, or replace it. Reproduced from Ref. [68] with permission. Copyright 2013, IEEE Proceedings.

Toward large-Scale Reality

Initial Steps toward Commercial Technology ("Technology Transition"). Because the technology of soft robotics and actuators is intrinsically simple (although—as with all new technology—operationally sophisticated in fabrication and use), the movement of this area toward reality has been able to proceed rapidly. Our first paper—an academic demonstration—in this subject (the "starfish gripper") was published in 2011[32]. There are now (only seven years later) a number of startup and established companies (Soft Robotics, Right Hand, Empire Robotics, Festo, OtherLab/Roam, SuperRelease Robotics, Rethink Robotics, Disney Research, and others) have started programs in the area, and demonstrated opportunities and shortcomings in specific approaches to technology and market development. Most initial applications have involved integration of soft or semi-soft grippers with already-commercial hard robotic arms, controllers, and vision systems to address applications in areas such as food handling, eCommerce, and warehouse management.

What Limits the Transition of This Technology into Commercial Applications? The limiting factors now are probably less technological than matters of business: the most important is the availability of capital for applications research, product development, and manufacturing, for understanding the relationships between fabricators of existing, commoditized, hard robotic systems and these new (and perhaps complementary) soft technologies, and for developing economically successful businesses depending on soft robotics. Because the technology is new, there is also—inevitably—a first-developer and first-user premium for initial products. (The developer of any new technology assumes the risks of unanticipated technical problems, and in identifying and developing markets, and the users of the technology assume the risk of deploying an untested technology of unproven reliability and cost of use.) These types of issues make the first stages of commercializing soft robotics (as with all new technologies) challenging and intensely interesting. Comfortingly, the first generation of technology has already worked well in the hand of users. The problems that need to be solved now are problems in finance, market development, business model, and business operations.

The Role of Chemistry and Materials Science in Soft Robotics.

Expansion of the capabilities of soft robotics requires new functional materials; the central mission of materials science is function. *Materials science, in turn, is based on chemistry.* Soft robotics, therefore, offers many opportunities to chemists interested in functional materials. Structures able to exert very high force, biocompatible structures, materials and structures with built-in sensing and control functions, structures resistant to damage in environments in which electronics and conventional hard materials would fail (e.g., those with high radiation, temperature, and corrosion) are all obvious candidates. Materials that store and release energy efficiently during stress/strain cycles, materials with long-term, non-irritating contact with skin (as in prostheses) or internal tissues (as in surgical repair and reconstruction) are more complicated because they involve living organisms, but the successes of PDMS in cosmetic surgery are a good omen for future work. Materials that would autonomously transduce information (e.g., from strain to electrical potential, or from electrical potential to Young's modulus) would add new capabilities.

Biology also has an outsized role to play in the future of the field, both in terms of applications in biomedicine, and by providing countless examples of functional, soft structures on which to base new classes of robotic systems[69]. To take one example—feet—animals and insects use an enormous number of strategies to allow movement across surfaces[70] ranging from liquid water to ceilings; these strategies are normally based on the properties of soft biological structures. The list of interesting biological structures (feathers, scales, bone, blood vessels, eyes, muscles, nerves, tentacles, fluidic pumps and processors, and so on) is virtually endless, and almost none of these structures, or the functions that they generate, can presently be mimicked or replicated.

Although this area is a rich one for discovery and invention, it will require—for many chemists—an unfamiliar step: that is, moving from a sharp focus on molecular synthesis and structure, to a broader interest the design and preparation of materials with valuable functions, fabricated in forms and with economics that allow it to be useful. Taking that step opens many new opportunities, but it also requires collaborations with non-chemists, and learning significant parts of new fields.

Significance

Soft Robotics is a Vital Part of a Very Big New Thing: Robotics. Chemistry has developed as a field that—through extraordinary technical skill—was uniquely able to design and make new molecules. Capabilities in synthesis were critical for commodity chemistry, and for certain classes of specialty chemicals (explosives, dyes, adhesives, others) since the molecular entity—the chemical—*is* the product in these areas. For programs and products outside of commodities (e.g., pharmaceuticals, electronic materials, and agricultural chemicals) the *real* difficulties in developing concepts or products often begin *after* the molecular synthesis is complete. Synthesis is, for example, important in developing a successful drug, but the most difficult and challenging parts of drug development are not the complexities of multistep synthesis, but those in proving safety and efficacy, in running clinical trials, in interacting with the FDA, and in a myriad of other activities.

Where does soft robotics fit into chemistry, and how important is molecular design, as opposed to screening and development of existing organic materials? What, to me, is important, is that robotics is the basis of a technological shift in society, and that soft robotics will become a part of this shift (how important a part, only time will tell) with a very large component of materials and molecular design. Chemistry thus has an opportunity to play a major role in its development, through the invention, synthesis, and deployment of new functional chemicals, materials, and methods of fabrication. New, soft materials will also lead to new opportunities, although where is not yet clear. As an example, however: the exciting area of wearable electronics fits naturally into soft composite structures for soft robotics[71], and including electronically functional fabrics into elastomeric devices will allow the integration of sophisticated sensing, information processing, and motion, and integration of soft robotics and human healthcare requires development of technologies from biocompatibility and safety to ease of use *in vivo*, and from *in-vivo* sensing to non-contact communication and control.

Further, robotics, combined with artificial intelligence, is becoming a technology with the capability of generating "intelligent machines" that can compete with (or complement) humans for jobs and work (a so-called "peer competitor"). Soft robotics brings the "collaboration" necessary for smooth integration of biological, physical, and informatics systems. Robotics will span from bits and bytes to force and work, from simple generation of mechanical work to development of "machine intelligence," and from entirely non-human machines to fully humanoid systems (and to systems integrating humans and machines). Much of what happens will depend upon new functional materials.

Chemists have an opportunity to participate fully in the development of these materials, this field, and the world that robotics will create.

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Conflict of Interest. The author of this paper (GMW) owns equity in Soft Robotics, Inc., and is a member of its board of directors.

References

[1] a) S. J. DeCanio, *J. Macroecon.* **2016**, *49*, 280-291; b) J. Kaivo-oja, S. Roth, L. Westerlund, *Int. J. Technol. Manage.* **2017**, *73*, 176-205; c) L. Royakkers, R. van Est, *Int. J. Soc. Robot.* **2015**, *7*, 549-570; d) E. Brynjolfsson, A. Mcafee, Will Humans Go the Way of Horses? *Foreign Affairs*, July **2015**, *94*; e) I. R. Nourbakhsh, The Coming Robot Dystopia, *Foreign Affairs*, July **2015,** *94*; f) D. Rus, The Robots Are Coming, *Foreign Affairs*, July **2015**; g) M. Wolf, Same as It Ever Was, *Foreign Affairs*, July **2015**, *94*.

[2] a) N. G. Leigh, B. R. Kraft, *Reg. Stud.* **2017**, 1-13; b) China's Robot Revolution May Affect the Global Economy, *Bloomberg News*, August **2017**.

[3] a) D. Flynn, V. Robu, What robots mean for jobs, *World Economic Forum*, Augst **2017**; b) K. Stacey, A. Nicolaou, Stitched up by robots: the threat to emerging economies, *Financial Times*, July, **2017**.

[4] J. Quinlan, Investors should wake up to Japan's robotic future, *Financial Times*, September **2017**.

[5] G. Blair, Why Japan Will Profit The Most From Artificial Intelligence, *South China Morning Post*, August, **2017**.

[6] T. Orlik, China's Future, Reshaped by Robots, *Bloomberg*, August **2017**.

[7] N. Kumaresan, K. Miyazaki, *Research Policy* **1999**, *28*, 563-585.

[8] B. Matthias, S. Oberer-Treitz, H. Staab, E. Schuller, S. Peldschus, *Robotics, Int. Symp. on*, **2010**, 1-6.

[9] P. Polygerinos, Z. Wang, K. C. Galloway, R. J. Wood, C. J. Walsh, *Robot. Auton. Syst.* **2015**, *73*, 135-143.

[10] a) P. M. Reis, *J. Appl. Mech.* **2015**, *82*, 111001-111004; b) M. A. Dias, M. P. McCarron, D. Rayneau-Kirkhope, P. Z. Hanakata, D. K. Campbell, H. S. Park, D. P. Holmes, *Soft Matter* **2017**, *13*, 9087-9092

[11] W. F. M. Daniel, J. Burdyńska, M. Vatankhah-Varnoosfaderani, K. Matyjaszewski, J. Paturej, M. Rubinstein, A. V. Dobrynin, S. S. Sheiko, *Nat. Mater.* **2015**, *15*, 183.

[12] J.-Y. Sun, X. Zhao, W. R. K. Illeperuma, O. Chaudhuri, K. H. Oh, D. J. Mooney, J. J. Vlassak, Z. Suo, *Nature* **2012**, *489*, 133.

[13] C.-H. Li, C. Wang, C. Keplinger, J.-L. Zuo, L. Jin, Y. Sun, P. Zheng, Y. Cao, F. Lissel, C. Linder, X.-Z. You, Z. Bao, *Nature Chemistry* **2016**, *8*, 618.

[14] R. F. Shepherd, A. A. Stokes, R. M. D. Nunes, G. M. Whitesides, *Adv. Mater.* **2013**, *25*, 6709-6713.

[15] a) D. F. Louw, T. Fielding, P. B. McBeth, D. Gregoris, P. Newhook, G. R. Sutherland, *Neurosurgery* **2004**, *54*, 525-537; b) H. Yousef, M. Boukallel, K. Althoefer, *Sens. Actuators A Phys.* **2011**, *167*, 171-187; c) A. J. Ijspeert, *Neural Netw.* **2008**, *21*, 642-653; d) R. F. Gibson, *Compos. Struct.* **2010**, *92*, 2793-2810; e) A. Bicchi, V. Kumar, *IEEE Trans. Robot. Autom.* **2000**, *1*, 348-353; f) L.-W. Tsai, *Robot analysis: the mechanics of serial and parallel manipulators*, John Wiley & Sons, **1999**.

[16] C. Lee, M. Kim, Y. J. Kim, N. Hong, S. Ryu, H. J. Kim, S. Kim, *Int. J. Control Autom. Syst.* **2017**, *15*, 3-15.
[17] D. Rus, M. T. Tolley, *Nature* **2015**, *521*, 467.
[18] L. Hines, K. Petersen, G. Z. Lum, M. Sitti, *Adv. Mater.* **2017**, *29*, 1603483.
[19] S. Kim, C. Laschi, B. Trimmer, *Trends Biotechnol.* **2013**, *31*, 287-294.
[20] B. Mazzolai, L. Margheri, M. Cianchetti, P. Dario, C. Laschi, *Bioinspiration Biomim.* **2012**, *7*, 025005.
[21] C. Majidi, *Soft Robot.* **2013**, *1*, 5-11.
[22] P. Polygerinos, N. Correll, S. A. Morin, B. Mosadegh, C. D. Onal, K. Petersen, M. Cianchetti, M. T. Tolley, R. F. Shepherd, *Adv. Eng. Mater.* **2017**, *19*, 1700016.
[23] J. R. C. Laschi, F. Iida, M. Cianchetti, L. Margheri, *Soft Robotics: Trends, Applications and Challenges*, Springer International Publishing, Livorno, Italy **2016**.
[24] A. A.-S. Alexander Verl, Oliver Brock, Annika Raatz, *Soft Robotics: Transferring Theory to Application*, Springer-Verlag, Berlin, **2015**.
[25] a) V. L. Nickel, J. Perry, A. L. Garrett, *J. Bone. Joint Surg.* **1963**, *45*; b) H. Schulte, *Natl. Acad. Sci.–NRC.* **1961**, *874*, 94-115; c) M. M. Gavrilovic, Maric, M. R., *Med. Biol. Eng.* **1969**, *7*, 77-82.
[26] K. Suzumori, S. Iikura, H. Tanaka, *IEEE Control Systems*, **1992**, *12*, 21-27.
[27] X.-M. Zhao, Y. Xia, G. M. Whitesides, *J. Mater. Chem.* **1997**, *7*, 1069-1074.
[28] J. M. K. Ng, I. Gitlin, A. D. Stroock, G. M. Whitesides, *Electrophoresis* **2002**, *23*, 3461-3473.
[29] S. Li, D. M. Vogt, D. Rus, R. J. Wood, *Proc. Natl. Acad. Sci. U.S.A.* **2017**, *114*, 13132-13137.
[30] K. Rongjie, T. B. David, Z. Tianjiang, G. Emanuele, G. C. Darwin, *Bioinspiration Biomim.* **2013**, *8*, 036008.
[31] E. Brown, N. Rodenberg, J. Amend, A. Mozeika, E. Steltz, M. R. Zakin, H. Lipson, H. M. Jaeger, *Proc. Natl. Acad. Sci. U.S.A.* **2010**, *107*, 18809-18814.
[32] F. Ilievski, A. D. Mazzeo, R. F. Shepherd, X. Chen, G. M. Whitesides, *Angew. Chem. Int. Ed.* **2011**, *50*, 1890-1895; *Angew. Chem.* **2011**, *123*, 193-1935.
[33] R. V. Martinez, C. R. Fish, X. Chen, G. M. Whitesides, *Adv. Funct. Mater.* **2012**, *22*, 1376-1384.
[34] B. Mosadegh, P. Polygerinos, C. Keplinger, S. Wennstedt, R. F. Shepherd, U. Gupta, J. Shim, K. Bertoldi, C. J. Walsh, G. M. Whitesides, *Adv. Funct. Mater.* **2014**, *24*, 2163-2170.
[35] a) J. Paek, I. Cho, J. Kim, *Sci. Rep.* **2015**, *5*, 10768.; b) R. V. Martinez, J. L. Branch, C. R. Fish, L. Jin, R. F. Shepherd, R. M. D. Nunes, Z. Suo, G. M. Whitesides, *Adv. Mater.* **2013**, *25*, 205-212.
[36] a) R. F. Shepherd, F. Ilievski, W. Choi, S. A. Morin, A. A. Stokes, A. D. Mazzeo, X. Chen, M. Wang, G. M. Whitesides, *Proc. Natl. Acad. Sci. U.S.A.* **2011**, *108*, 20400-20403; b) M. T. Tolley, R. F. Shepherd, B. Mosadegh, K. C. Galloway, M. Wehner, M. Karpelson, R. J. Wood, G. M. Whitesides, *Soft Robot.* **2014**, *1*, 213-223.
[37] https://www.festo.com/group/ru/cms/10217.htm.
[38] R. F. Shepherd, A. A. Stokes, J. Freake, J. Barber, P. W. Snyder, A. D. Mazzeo, L. Cademartiri, S. A. Morin, G. M. Whitesides, *Angew. Chem. Int. Ed.* **2013**, *52*, 2892-2896; *Angew. Chem.* **2013**, *125*, 2964.

[39] a) M. Tolley, R. F. Shepherd, M. Karpelson, N. Bartlett, K. Galloway, M. Wehner, R. Nunes, G. M. Whitesides, R. J. Wood, *Intelligent Robots and Systems Proc. IEEE Int. Conf. on*, **2014**; b) N. W. Bartlett, M. T. Tolley, J. T. B. Overvelde, J. C. Weaver, B. Mosadegh, K. Bertoldi, G. M. Whitesides, R. J. Wood, *Science* **2015**, *349*, 161.
[40] a) M. Wehner, R. L. Truby, D. J. Fitzgerald, B. Mosadegh, G. M. Whitesides, J. A. Lewis, R. J. Wood, *Nature* **2016**, *536*, 451; b) P. M. M. Ventura, in *35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, American Institute of Aeronautics and Astronautics, Los Angeles, California, **1999**, pp. 99-2880; c) Y. Wang, R. M. Hernandez, D. J. Bartlett, J. M. Bingham, T. R. Kline, A. Sen, T. E. Mallouk, *Langmuir* **2006**, *22*, 10451-10456; d) F. Vitale, Accoto, D., Turchetti, L., Indini, S., Annesini, M.C., Guglielmelli, E., *Robotics and Automation*, *Proc. IEEE Int. Conf. on*, **2010**, pp. 2197–2202; e) M. Goldfarb, Barth, E.J., Gogola, M.A., Wehrmeyer, J.A., *IEEE/ASME Trans. Mechatronics* **2003**, *8*, 254-262; f) M. Wehner, M. T. Tolley, Y. Mengüç, Y.-L. Park, A. Mozeika, Y. Ding, C. Onal, R. F. Shepherd, G. M. Whitesides, R. J. Wood, *Soft Robot.* **2014**, *1*, 263-274.
[41] S. A. Morin, R. F. Shepherd, S. W. Kwok, A. A. Stokes, A. Nemiroski, G. M. Whitesides, *Science* **2012**, *337*, 828.
[42] A. C. Siegel, S. S. Shevkoplyas, D. B. Weibel, D. A. Bruzewicz, A. W. Martinez, G. M. Whitesides, *Angew. Chem. Int. Ed.* **2006**, *45*, 6877-6882; *Angew. Chem.* **2006**, *118*, 7031-7036.
[43] D. Yang, M. S. Verma, J.-H. So, B. Mosadegh, C. Keplinger, B. Lee, F. Khashai, E. Lossner, Z. Suo, G. M. Whitesides, *Adv. Mater. Technol.* **2016**, *1*, 1600055.
[44] S. Babaee, J. Shim, J. C. Weaver, E. R. Chen, N. Patel, K. Bertoldi, *Adv. Mater.* **2013**, *25*, 5044-5049.
[45] E. Cerda, L. Mahadevan, *Phys. Rev. Lett.* **1998**, *80*, 2358-2361.
[46] a) D. Yang, B. Mosadegh, A. Ainla, B. Lee, F. Khashai, Z. Suo, K. Bertoldi, G. M. Whitesides, *Adv. Mater.* **2015**, *27*, 6323-6327; b) D. Yang, M. S. Verma, E. Lossner, D. Stothers, G. M. Whitesides, *Adv. Mater. Technol.* **2017**, *2*, 1600164.
[47] A. Nemiroski, Y. Y. Shevchenko, A. A. Stokes, B. Unal, A. Ainla, S. Albert, G. Compton, E. MacDonald, Y. Schwab, C. Zellhofer, G. M. Whitesides, *Soft Robot.* **2017**, *4*, 183-190.
[48] J. Lessing, S. A. Morin, C. Keplinger, A. S. Tayi, G. M. Whitesides, *Adv. Funct. Mater.* **2015**, *25*, 1418-1425.
[49] D. B. Wolfe, R. S. Conroy, P. Garstecki, B. T. Mayers, M. A. Fischbach, K. E. Paul, M. Prentiss, G. M. Whitesides, *Proc. Natl. Acad. Sci. U.S.A.* **2004**, *101*, 12434-12438.
[50] a) J. Li, W. R. K. Illeperuma, Z. Suo, J. J. Vlassak, *ACS Macro Lett.* **2014**, *3*, 520-523; b) R. Bai, Q. Yang, J. Tang, X. P. Morelle, J. Vlassak, Z. Suo, *Extreme Mech. Lett.* **2017**, *15*, 91-96.
[51] Z. Suo, *Acta Mech. Solida Sin.* **2010**, *23*, 549-578.
[52] a) E. Acome, S. K. Mitchell, T. G. Morrissey, M. B. Emmett, C. Benjamin, M. King, M. Radakovitz, C. Keplinger, *Science* **2018**, *359*, 61; b) N. Kellaris, V. Gopaluni Venkata, G. M. Smith, S. K. Mitchell, C. Keplinger, *Science Robotics* **2018**, *3*.
[53] C. Keplinger, M. Kaltenbrunner, N. Arnold, S. Bauer, *Appl. Phys. Lett.* **2008**, *92*, 192903.
[54] C. D. Onal, X. Chen, G. M. Whitesides, D. Rus, in *Robotics Research, vol 100* (Eds.: H. I. Christensen, O. Khatib), Springer International Publishing, Cham, **2017**, pp. 525-540.
[55] T. Mirfakhrai, J. D. W. Madden, R. H. Baughman, *Mater. Today* **2007**, *10*, 30-38.

[56] a) H. M. Jaeger, *Soft Matter* **2015**, *11*, 12-27; b) I. R. Peters, S. Majumdar, H. M. Jaeger, *Nature* **2016**, *532*, 214.
[57] M. A. Unger, H.-P. Chou, T. Thorsen, A. Scherer, S. R. Quake, *Science* **2000**, *288*, 113.
[58] S. Russo, T. Ranzani, C. J. Walsh, R. J. Wood, *Adv. Mater. Technol.* **2017**, *2*, 1700135.
[59] A. C. Siegel, S. K. Y. Tang, C. A. Nijhuis, M. Hashimoto, S. T. Phillips, M. D. Dickey, G. M. Whitesides, *Acc. Chem. Res.* **2010**, *43*, 518-528.
[60] a) A. Fassler, C. Majidi, *Lab Chip* **2013**, *13*, 4442-4450; b) M. D. Dickey, R. C. Chiechi, R. J. Larsen, E. A. Weiss, D. A. Weitz, G. M. Whitesides, *Adv. Funct. Mater.* **2008**, *18*, 1097-1104; c) C. B. Cooper, K. Arutselvan, Y. Liu, D. Armstrong, Y. Lin, M. R. Khan, J. Genzer, M. D. Dickey, *Adv. Funct. Mater.* **2017**, *27*, 1605630; d) M. D. Dickey, *Adv. Mater.* **2017**, *29*, 1606425.
[61] C. Keplinger, J.-Y. Sun, C. C. Foo, P. Rothemund, G. M. Whitesides, Z. Suo, *Science* **2013**, *341*, 984.
[62] S. K. Y. Tang, Z. Li, A. R. Abate, J. J. Agresti, D. A. Weitz, D. Psaltis, G. M. Whitesides, *Lab Chip* **2009**, *9*, 2767-2771.
[63] Q. Fang, X.-T. Shi, W.-B. Du, Q.-H. He, H. Shen, Z.-L. Fang, *Trends Anal. Chem.* **2008**, *27*, 521-532.
[64] B. Zheng, L. S. Roach, R. F. Ismagilov, *J. Am. Chem. Soc.* **2003**, *125*, 11170-11171.
[65] F. Giorgio-Serchi, G. D. Weymouth, in *Soft Robotics: Trends, Applications and Challenges, vol 17* (Eds.: C. Laschi, J. Rossiter, F. Iida, M. Cianchetti, L. Margheri), Springer International Publishing, Cham, **2017**, pp. 37-46.
[66] K. Suzumori, in *The 6th International Conference on Manufacturing，Machine Design and Tribology*, **2015**, 4 - 5.
[67] a) D. Ross, M. P. Nemitz, A. A. Stokes, *Soft Robot.* **2016**, *3*, 170-176; b) A. A. Stokes, R. F. Shepherd, S. A. Morin, F. Ilievski, G. M. Whitesides, *Soft Robot.* **2013**, *1*, 70-74.
[68] P. Polygerinos, S. Lyne, Z. Wang, L. F. Nicolini, B. Mosadegh, G. M. Whitesides, C. J. Walsh, *IEEE/RSJ* **2013**, 1512–1517.
[69] a) V. Vogel, *Nat. Mater.* **2012**, *11*, 841; b) L. Chen, O. P. Andrew, W. H. Duncan, K. L. Han, S. F. Ronald, J. F. Robert, *Bioinspiration Biomim.* **2015**, *10*, 046003.
[70] T. Libby, A. M. Johnson, E. C. Siu. R. J. Full, D. E. Koditschek, *IEEE Trans. Robot.* **2016**, *32*, 1380-1398.
[71] a) J. Kim, M. Kim, M.-S. Lee, K. Kim, S. Ji, Y.-T. Kim, J. Park, K. Na, K.-H. Bae, H. Kyun Kim, F. Bien, C. Young Lee, J.-U. Park, *Nat. Commun.* **2017**, *8*, 14997; b) D.-H. Kim, N. Lu, R. Ma, Y.-S. Kim, R.-H. Kim, S. Wang, J. Wu, S. M. Won, H. Tao, A. Islam, K. J. Yu, T.-i. Kim, R. Chowdhury, M. Ying, L. Xu, M. Li, H.-J. Chung, H. Keum, M. McCormick, P. Liu, Y.-W. Zhang, F. G. Omenetto, Y. Huang, T. Coleman, J. A. Rogers, *Science* **2011**, *333*, 838; c) D. J. Lipomi, M. Vosgueritchian, B. C. K. Tee, S. L. Hellstrom, J. A. Lee, C. H. Fox, Z. Bao, *Nat. Nanotechnol.* **2011**, *6*, 788; d) S. Lee, A. Reuveny, J. Reeder, S. Lee, H. Jin, Q. Liu, T. Yokota, T. Sekitani, T. Isoyama, Y. Abe, Z. Suo, T. Someya, *Nat. Nanotechnol.* **2016**, *11*, 472; e) J. A. Rogers, *Nat. Nanotechnol.* **2017**, *12*, 839; f) K. J. Yu, Z. Yan, M. Han, J. A. Rogers, *npj Flexible Electron.* **2017**, *1*, 4; g) T. Lei, I. Pochorovski, Z. Bao, *Acc. Chem. Res.* **2017**, *50*, 1096-1104; h) D. J. Lipomi, Z. Bao, *MRS Bull.* **2017**, *42*, 93-97.