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SCIENCE ROBOTICS | VIEWPOINT

Subject: Soft robots

Title: Hard questions for soft robotics

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Abstract: The establishment of a new academic field is often characterized by a phase of rapid growth, as seen over the last decade in the field of soft robotics. However, such growth can be followed by an equally rapid decline if concerted efforts are not made by the community. Here we argue that for soft robotics to take root and have impact in the next decade, we must move beyond "soft for soft's sake," and ensure that each study makes a meaningful contribution to the field, and ideally, to robotics and engineering more broadly. We present a three-tiered categorization to help researchers and reviewers evaluate work and guide studies toward higher levels of contribution. We ground this categorization with historical examples of soft solutions outside of robotics that were transformative. We believe the proposed self-reflection is essential if soft robotics is to be an impactful field in the next decade, advancing robotics and engineering both within and beyond academia, and creating soft solutions that are quantitatively superior to the current state-of-the-art—soft, rigid, or otherwise.

Summary sentence: How can the field of soft robotics have impact in the next decade?

INTRODUCTION

Academic fields have life cycles, coming into existence, evolving over time, and sometimes becoming extinct (*1*, *2*). The beginning of a new field is often characterized by a long period of isolated developments before a phase of definition, exploration, and rapid growth (*3*). This pattern is well suited for describing a particular new field of engineering: soft robotics. After a new field's initial growth, some take root and have long-term impact, while others "fade into oblivion" (*1*). Accordingly, in this article, we explore how soft robotics might take the former path, thriving and having impact in the next decade. Although this article focuses on soft robotics, the implications apply to new fields across disciplines.

A Brief History of Soft Robotics

Soft robotics, as defined by Kim, Laschi, and Trimmer, is the study of "robots with…bioinspired capabilities that permit adaptive, flexible interactions with unpredictable environments" (*4*). These robots have bodies that are predominantly soft—either through modulus or geometry—

and can be made to move not only via fluidic actuation, but also a variety of other methods including electroactive polymers, shape memory alloys and polymers, motor-driven tendons, ferromagnetic elastomers, and biohybrid actuators. The basic concept of adding compliance to robotic systems grew slowly over many decades from seeds planted by various disparate efforts. For instance, McKibben created a soft artificial muscle-powered hand orthosis for his polio-paralyzed daughter in 1958 (Fig. 1A) (*5*), Leifer made the Orm, a pneumatic continuum arm, in 1966 (*6*) (Fig. 1B), Wilson introduced a soft pneumatic elephant trunk in 1984 (*7*) (Fig. 1C-E), and Suzumori designed a flexible microactuator in 1992 (*8*) (Fig. 1F-G). Later in the 1990s, the stage was further set for the soft robotics boom by another key innovation—series elastic actuation (*9*). The concept is to add an elastic element between the actuator and the robot joint. This innovation forfeits the precision of rigid joints but gains inherent safety and improved control of forces, allowing these robots to perform better in uncertain environments. In the 2000s, bio-inspired robotics became a pre-cursor to soft robotics, integrating principles from the natural world into the design of robots (*10*, *11*). Then, around 2011, we find a marked increase in the number of publications per year with the term "soft robot*" (Fig. 2), from approximately 10 per year for 2000-11 to nearly 100 per year for 2011-15. Various "contributing forces" (*12*) accelerated this growth: institutional funding such as the *DARPA Chembots* program in the US (*13*), OCTOPUS IP (*14*) and *A Coordination Action for Soft Robotics (RoboSoft)* (*15*) in the European Union, and later, Tri-Co Robot in China (*13*); enabling technologies such as the fused deposition modelling (FDM) patent entering the public domain (*16*); and related impactful publications (e.g., (*17–20*)).

This first decade of widespread research in soft robotics was characterized by defining, inspiring, and exploring. Several important Review articles (e.g., (*4*, *17*, *21–26*)) set out to answer the question: "what is soft robotics?" Further, these and other articles inspired the field (e.g., (*27–31*)), answering the question: "what can soft robots potentially do?*"* Trimmer wrote, "These robots will have numerous applications, including biomedical diagnosis or surgery, search-and-rescue in emergency situations and hazardous environments, space instrument repair, mine detection, and assistive machines in the home environment" (*29*). Finally, many articles explored what capabilities were possible when we incorporated soft materials into robots.

Impact in the Next Decade

For a new research field to take root, persist, and have impact, this growth phase of definition, inspiration, and exploration must give way to a more mature phase of research (*3*). As we enter the second decade of widespread research in soft robotics, we believe we are at an important point in the field's history (Fig. 2). We can either continue with the exploratory nature that characterized much of the work of the first decade and risk never establishing a long-term thriving field, or, with introspection and self-reflection, we can refocus our efforts and refine our course for the second decade.

Here we argue that for soft robotics to become a thriving, impactful field in the next decade, every study must make a meaningful contribution. Impact may be measured in various ways, such as the number of citations from outside the field, licensed patents, commercial successes, lives improved, or some other meaningful metric. Regardless of the metric, we believe impact will follow from work that clearly contributes to advance our field and ideally, advance robotics and engineering more broadly. How do we accomplish this? As a first step, we present a three-tiered categorization of future soft robotics work based on the levels of contribution they will have in the second decade, to which researchers and reviewers can refer for guidance in designing a study and crafting an article.

We note that within a given level, a contribution can range from fundamental (i.e., advancing the state-of-knowledge) to applied (i.e., advancing the state-of-the-art), as described in the "Material Advancement Progression (MAP) Scale" introduced by the journal *Matter* (Cell Press). We also note that certain papers do not seek to make a contribution to the field of soft robotics itself but instead use soft robotics to test or demonstrate a hypothesis in another field (e.g., biology, materials, haptics, education, etc.). Such papers are outside the scope of this article, and they are likely best suited for journals in their respective fields, for which their contribution can be judged.

LEVELS OF CONTRIBUTION

Level 0 (Minimal contribution, limited advancement to the field in the second decade). Level 0 studies will offer a minor contribution to the field in the context of the second decade. An article reporting such a study will often start with vague, boilerplate text that states why soft robots are important (they are "adaptable," "robust," and "reconfigurable"). Soft robots will often be compared to strawman versions of rigid robots, portrayed as clunky and useless, rather than to the actual state-of-the-art (e.g., academic and commercially available systems that can autonomously drive, fly, and even run through unstructured environments). The results of the study may demonstrate an ad-hoc implementation of a soft robot or component that moves, crawls, or grasps along with limited experimental characterization. However, these demonstrations will not show performance that exceeds what many others have done before. Instead, they typically will demonstrate similar or worse performance that is achieved in a different manner. Moreover, articles on these studies will provide no clear statements of how the work compares to or advances either: (i) the state-of-the-art of soft robotics via quantitative performance metrics, or (ii) the state-of-knowledge via scientific principles, theoretical models, design guidelines, or hypothesis-driven experiments that address unknowns in the field.

We note that we are categorizing future work in the context of moving the field of soft robotics forward in the second decade; we are not categorizing previous articles. At the beginning of the first decade, it was important to conduct rapid and broad exploration, often simply trying to see which robotic devices could be made soft. These early efforts helped the field search through the possible approaches for the design, actuation, and control of soft robots. Now, after ten years of exploration, these "soft for soft's sake" implementations are becoming increasingly less useful to the community. If such studies are the norm for the second decade, we risk stagnation and a field that does not take root in the broader scientific community.

Level 1 (Contribution within the field of soft robotics). Level 1 studies will advance soft robotics, but will have limited impact on other research fields or technology domains. Unlike the Level 0 studies described above, Level 1 studies will identify a gap in the state-of-the-art or knowledge in soft robotics, such as efficient locomotion, reliable grasping, large-scale bodies, untethered operation, accurate modeling, precise control, or actuation that is powerful, force-dense, and efficient. These studies will then advance the field of soft robotics by presenting unconventional solutions that help address the identified gap, and provide demonstrations with clear, quantitative performance improvements over the state-of-the-art in soft robotics. Alternatively, they may offer principles, models, or experiments that address a gap in the state-of-knowledge in soft robotics. Such contributions to the field of soft robotics may range from incremental to field-changing.

Although these are meaningful studies that will advance our field, we note a limitation here: advancing soft robotics given the sometimes arbitrary and minimally justified constraint of softness means that the broader applicability of the advance beyond soft robotics is often limited. That is, the results may show quantitative improvements over the state-of-the-art soft robot, yet at the same time show inferior performance compared to other non-soft solutions. For example, a study doubling the speed of soft, tethered, inchworm crawlers would offer a contribution within the field. However, without experimental results or theoretical predictions demonstrating a favorable comparison to state-of-the-art solutions outside of soft robotics, such work would remain in Level 1. We suggest that, whenever possible, we should strive to push beyond work that only contributes to our own field. Otherwise, the field risks becoming too inwardly focused. At the same time, we acknowledge the importance of Level 1 work; in some cases, new work in soft robotics will not immediately contribute to engineering more broadly, but could lay the groundwork for later studies that do.

Level 2 (Contribution to robotics and engineering more broadly). Level 2 studies will advance not only soft robotics but impact other scientific fields and application domains more broadly. Such studies may identify an open challenge in robotics or engineering, for instance those proposed in the *Science Robotics* "Grand Challenges" (*32*). They present technical solutions or scientific insights that advance engineering and robotics by leveraging the methodologies and design principles of soft robotics. Such studies will report quantitative performance improvements over the state-of-the-art (soft, rigid, or otherwise) and/or present principles, models, or experiments that advances our general understanding within engineering practice. That is, these studies employ the principles of soft robotics not as an artificial constraint, but instead use these principles to advance state-of-the-art technology and understanding across disciplines. For example, yet-to-be-imagined soft medical devices could leverage compliance to outperform current rigid solutions in terms of patient outcomes, or soft energy harvesters could exploit elastic instabilities to improve efficiencies beyond what is possible with rigid materials. Level 2 work will directly answer a key challenging question that is not directly answered by Level 0 or 1 articles: "Why soft?" Answering this question in each study is the key to promoting a field that has an impact in the next decade and beyond.

Inspiration from the Past

Although achieving Level 2 contributions for soft robotics is challenging, it is not impossible; indeed, there are readily available examples outside of robotics in which soft solutions not only outperformed but even displaced the state-of-the-art. For instance, over a century ago, the first practical pneumatic tire was introduced by Dunlop for bicycles (Fig. 3A-B), and within three years the major races around the world were being won using this new soft solution (*33*). The quantitative advantage was clear: speed was increased by over 10%. Pneumatic tires became the norm, and immediately were adopted for automobiles when these were invented. Over a hundred years later, we have yet to create something better than this soft solution. Likewise, successful soft solutions in the medical realm include balloon angioplasty for coronary disease (Fig. 3C-D) (*34*) and the Foley catheter for indwelling catheterization (Fig. E-F) (*35*), both introduced over 60 years ago. Balloon angioplasty utilizes many of the same materials and principles that have been adopted in soft robotics, and the technology has revolutionized vascular medicine and saved many lives, with close to 1M procedures each year in the US alone (*36*). Likewise, the Foley catheter has made tremendous impact in urology and represents a yearly market of over $1B (*37*). A final example of a successful soft technology is the polydimethylsiloxane (PDMS)-based microfluidic chip (Fig. 3G-H). Initially, the miniaturization of chemical analyses onto chips was attempted using technologies derived directly from semiconductor fabrication, but these technologies were tailored to the manufacture of rigid, solid-state systems and not well suited for integrating flow channels, pumps, valves, biological specimens, etc. Soft lithography (*38*) uses an elastomer as the primary device material, which conforms to contacting surfaces, enables simple approaches to replica molding and device sealing, reduces cost, and improves biocompatibility (*39*). Later work further took advantage of the soft PDMS substrate to embed pneumatic/hydraulic valves (*40*) and achieve large-scale integration analogous to electronic chips (*41*). PDMS-based devices hold the largest revenue share of microfluidic chips (33%), as compared to devices based primarily on other materials such as glass or silicon, in a global market evaluated to be worth $13.5B (*42*).

DISCUSSION

Considering the level of contribution of one’s work is by no means a unique concept. However, we hope that by formalizing a categorization of contribution for the field, this article helps advance soft robotics.

In addition to defining these categories, we also wish to briefly discuss a higher-level distinction between Level 0 and Level 1 or 2 work. Level 0 studies often focus on superficial methods rather than underlying principles. They may show a new method, but it is a rework of previous methods based on the same principle with no measurable improvement. This contrasts to Level 1 and 2 work, which make contributions to the principles themselves (Level 1 focuses on principles interesting to soft roboticists, and Level 2 focuses on principles of broader interest). Indeed, the benefits of focusing on principles rather than methods were recognized over one hundred years ago by Harrington Emerson, an American efficiency engineer, who himself contributed work elucidating principles of efficient management (*43*). Harrington stated, “As to methods there may be a million and then some, but principles are few. [One] who grasps principles can successfully select…methods. [One] who tries methods, ignoring principles, is sure to have trouble.”

A key to moving beyond Level 0 contributions in the second decade may be in the training of the next generation of soft roboticists. Courses, training, and even a textbook that clearly describe what principles have been uncovered by previous work in the field could help new researchers ask the right questions when formulating their studies. Indeed, answering questions is relatively easy when compared to finding the best question to answer.

CONCLUSION

The question examined herein—*how can soft robotics have an impact in the next decade?*—is hard, yet we believe that it is one which the field must ask itself. We believe that impact will follow when we take a critical look at how our research publications advance the state-of-the-art and the state-of-knowledge. These advances, both small and large, are needed to help the field make the transition into an established and thriving discipline in the coming years. Critically, we believe this thriving field will advance robotics and engineering broadly, and will lead to many new soft robotic solutions that are quantitatively superior to the state-of-the-art. These solutions will potentially have impact beyond academia, creating commercial successes, solving problems in industry, and even saving lives. Indeed, this was the vision early in the first decade; Trimmer wrote in 2013 that “soft robots will be capable of performing feats no current machines can accomplish” (*44*). Our thoughtful efforts can make this vision a reality in the next decade.

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FIGURES

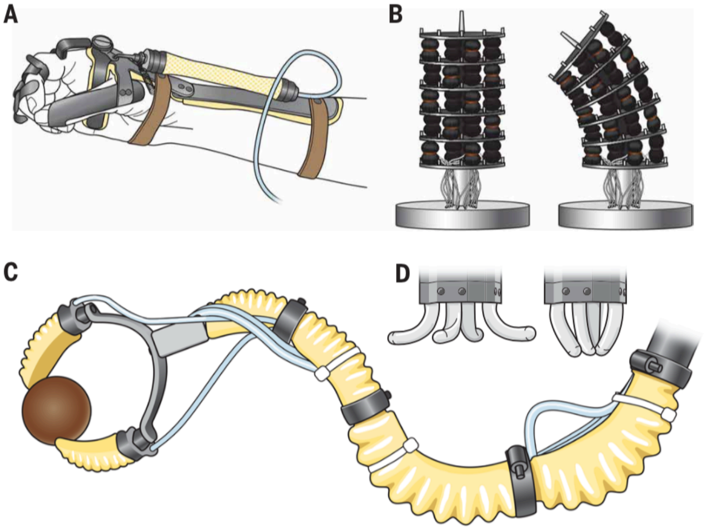

Fig. 1: **Early examples of the design principles of soft robotics that planted the seeds for the explosive growth in the last decade.** (**A**) The wearable exoskeleton powered by soft artificial muscles, made by Joseph McKibben in 1957 for his daughter with a paralyzed hand (*5*). (**B**) The ORM, a soft pneumatic continuum manipulator from 1966 (*6*). (**C**) A soft pneumatic elephant trunk-inspired manipulator from 1984 (*7*). (**D**) A flexible microactuator (12 mm diameter) from 1992 (*8*).

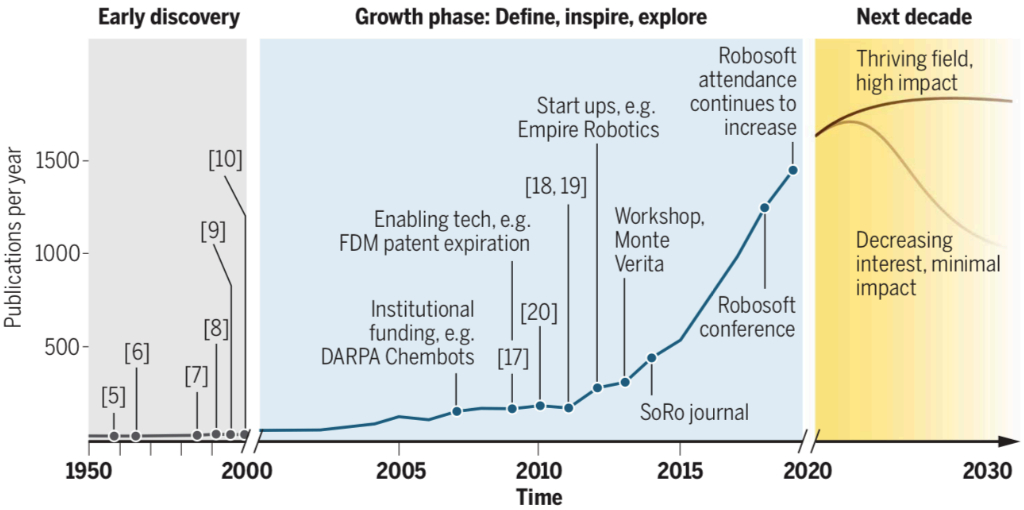

Figure 2: **The growth of soft robotics.** *Early Discovery*: Various disparate efforts demonstrate basic principles underlying soft robotics. *Growth Phase*: Publications per year (including the term "soft robot*") show a notable increase around the year 2011. Various contributing forces are shown. Source: Web of Science. *Next Decade*: We believe that we are at an important point in the history of the field, where a concerted effort will have strong influence on the future trajectory. We posit that critical self-reflection on the contribution of our work will allow the field to follow a thriving and impactful trajectory.

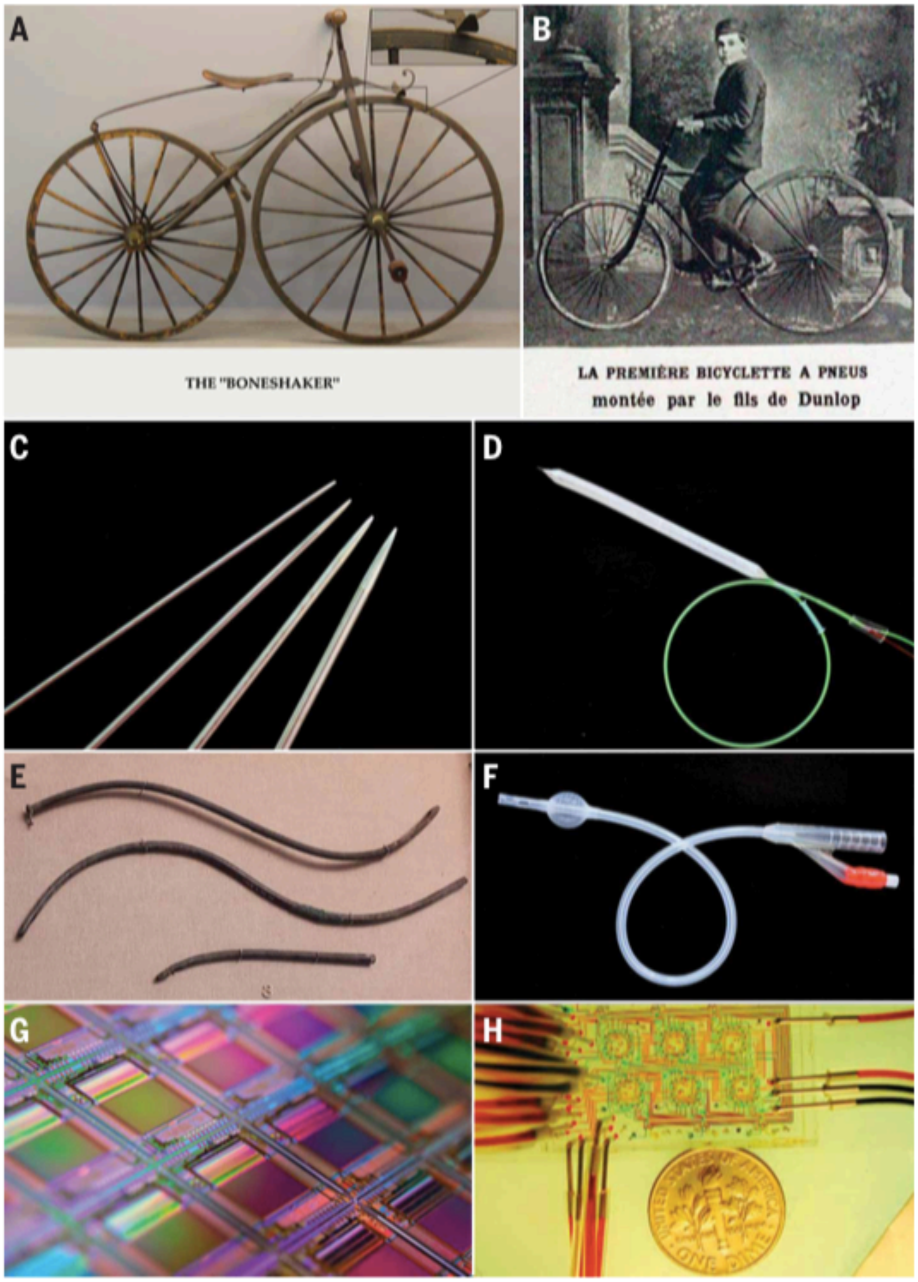

Figure 3: Inspirations from the past, showing soft technologies (right) that displaced the state-of-the-art (left). (**A**) The "boneshaker" bicycle from the second half of the 19th century with metal "tires." (**B**) The pneumatic tire promptly swept through the market after a practical implementation was introduced by Dunlop in 1882 (*33*). (**C**) The first recanalization of a blood vessel was done in the 1960s using rigid dilators, forced through the vessel one at a time with increasing diameter (*46*). (**D**) The soft balloon catheter has all but eliminated the previous method (*34*). (**E**) The rigid urinary catheter, such as these brass versions from the Roman Empire, date back to the first century A.D. (**F**) With the introduction of soft rubber catheters (*48*), a multi-thousand-year-old technology was rapidly replaced. (**G**) Microelectronic chips are generally fabricated using processes that are tailored to the manufacture of rigid, solid-state systems. (**H**) The softness (among other desirable properties) of PDMS has enabled new approaches to the fabrication and integration of microfluidic chips—referred to as *soft*

lithography—to achieve biological lab processes at the chip scale. [A: Courtesy of Geert Versleyen, yesterdays.nl. B: Originally printed in Le Miroir des Sports, January 5, 1922. E: Photo by Mikael Häggström, M.D., used with permission. G: Photo by Laura Ockel, used with permission. H: Reprinted with permission from (*49*).]

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