

A Data-Driven Review of Soft Robotics

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The past decade of soft robotics has delivered impactful and promising contributions to society and has seen exponentially increasing interest from scientists and engineers. This interest has resulted in growth of the number of researchers participating in the field and the quantity of their resulting contributions, stressing the community's ability to comprehend and build upon the literature. In this work, a data-driven review is presented that addresses the recent surge of research by providing a quantitative snapshot of the field. Relevant data are catalogued with three levels of analysis. First, publication-level analysis explores high-level trends in the field and bibliometric relationships across the more detailed analyses. Second, device-level analysis examines the tethering of robots and the incorporation of component types (actuators, sensors, controllers, power sources) into each robot. Finally, component-level analysis investigates the compliances, material compositions, and "function media" (energetic methods by which components operate) of each soft robotic component in the analyzed literature. The reported data indicate a significant reliance on elastomeric materials, electrical and fluidic media, and physical tethering; meanwhile, controllers and power sources remain underdeveloped relative to actuators and sensors. These gaps in the surveyed literature are elaborated upon, and promising future directions for the field of soft robotics are identified.

society long before the field of soft robotics was formally established. For example, painful silver catheters were replaced with more comfortable and safer elastomeric versions.^[1] Similarly, "bone-rattling" wooden bicycle wheels were eventually supplemented with air-filled rubber tires.^[2] The incorporation of soft materials in human-centric devices has, time and time again, increased safety and comfort for patients and users.

Beyond intrinsically soft materials, compliant geometric designs can enable soft devices from rigid materials. Self-adaptive mechanisms represent an early example of a compliant geometric design. First recorded in a five-century-old drawing by da Vinci of a design of a wing,^[3] self-adaptive mechanisms are also utilized in human grip via tendons and served as the foundation for Hirose's soft gripper proposed over 40 years ago.^[4,5] More recently, compliant geometries from the nanoscale to macroscale have been developed for modern technologies. Such compliant mechanisms formed from rigid

materials have enabled monolithic, nanoscale manufacturing of traditionally rigid materials in computer processors in nanoelectromechanical systems (NEMs);^[6] at larger scales, rigid machines employ flexible couplers, often through discs made of rigid material that are thin enough to flex or bushings made from soft materials to adapt misaligned shafts and to dampen vibrations.^[7] This adaptiveness for slight misalignments exemplifies the assistance that soft materials or compliant geometries can provide. Catheters can now adapt to the contours of the human body; bicycle tires can deform based on the terrain to provide a more comfortable ride; high-speed or high-torque rotating shafts are allowed a degree of tolerance with flexible discs or soft couplers.

While soft materials and compliant geometries have already produced many benefits to modern-day society, the field of soft robotics is facilitating the next step in the evolution of safety, comfort, and adaptiveness. Traditional robots have undoubtedly advanced society in their own regard and continue to do so, but rigid materials and complex control schemes may be unsuitable for certain applications involving dynamic, uncertain, or fragile environments. Just as nature's own design has epitomized adaptiveness, soft robots—often drawing inspiration from biology—are purpose-built to adapt to the struggle rigid robots face in situations involving close collaboration with humans, careful handling of other live species, and tasks in harsh environments, among other applications.


1. Introduction to Soft Robotics

Soft devices made from compliant materials represent the basis for modern research in soft robotics, yet soft devices and mechanisms were integral to the modernization of healthcare and

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Humans benefit from the inherent compliances offered by soft robots in a variety of situations. One of the most frequent use cases is medical technology:^[8] compliant materials that are bioabsorbable or biocompatible are often used in medicine for implantable or wearable devices.^[9] Navigation through complex and delicate organs can be achieved through continuum robots for catheters and stents or with wirelessly controlled microbots for drug delivery and removal of contaminants.^[10–14] External medical technology is also enabled by soft robots, especially pertaining to robotic systems that are used by and within close proximity to humans, as in human–robot interaction (HRI). Situations in which soft robotic HRI benefits humans range from assistance in medical therapy to industrial manufacturing settings.^[15,16] Furthermore, while soft robots in therapeutic assistance are often thought of as devices for physical therapy, recent research in soft robotics has explored use cases in psychotherapy. The resulting comfort-oriented soft robots have aided persons with autism,^[17] post-traumatic stress disorder,^[18] and dementia.^[19]

In addition to humans, many other species have also benefited from soft robots. Soft robots have become a tool to handle delicate crops across agricultural industries.^[20] Expanding beyond terrestrial applications to the sea, researchers have demonstrated soft grippers for gently handling marine life based on compliant materials and pressure-driven actuation—a benefit when operating in the high-pressure depths of the ocean. The inherent dexterity of soft-bodied underwater devices allows the traversal of delicate marine environments and the exploration of the ecosystems therein, minimizing distress among native species and enabling researchers to observe animals, plants, and habitats with few adverse effects.^[21–24]

Beyond using soft robots to interact with or learn more about biological creatures, biomimicry (or bioinspiration) has been a cornerstone in the design of soft robots themselves. By way of researchers building upon the iterative designs biology and evolution have spent millennia perfecting, bioinspiration has enabled the use of soft robots in a wider array of applications often ill-suited for rigid robots. Such applications include the use of robots in search and rescue,^[25] underwater and underground exploration,^[23,24,26] radioactive environments,^[27] tumultuous or unknown terrain,^[28] hot areas or areas currently aflame,^[29] and within medical equipment, including magnetic resonance imaging machines.^[30,31]

The use of soft robots in these situations and circumstances is facilitated through “embodied intelligence,”^[32–34] perhaps better described by the phrase, “the material is the controller.”^[32] The material acts as its own control scheme through its inherent motion- and force-limiting compliance. This simple control is achieved through the material conforming to its environment, with soft grippers being an important example. Grasping tasks are made trivial through wide tolerances of soft grippers in the location of an object to be grasped and the applied force or pressure relative to traditional rigid robots. As such, soft grippers often use a simple on–off open-loop control scheme. However, this underlying material intelligence also obscures the more intricate governing framework required for deliberate, explicit control. Following this notion, more complex control can result from the difficulty in decoding the nonlinear mechanics of the constituent soft material. In this more complex case, the unbounded degrees of freedom make precise control of soft

robots difficult, which is evident in positioning of end effectors and force control.^[35] These contrasting characteristics of compliant materials can therefore enable either simpler or more complex control depending on the desired functionality.

Moving forward, the difficulties arising from complex control of relatively simple systems are further hindered by the lack of availability and integration of soft robotic components required to emulate all of the capabilities of traditional robots.^[36] Here, we define a robotic component as any of the following four elements: 1) an actuator, 2) a sensor, 3) a controller, and 4) a power source. The limited soft versions of these robotic components illustrate that fully soft robots, while potentially useful in some applications, are not necessarily a current solution to all pressing problems faced by traditional robots. Soft robotics is a nascent, growing field with promising goals, but it certainly has pitfalls too. Accordingly, much research in soft robotics is built around one of the following two thrusts: 1) task-specific design of soft robots or robotic components for areas where they are intrinsically well suited and 2) improvement of performance metrics in the areas in which they are inherently limited.

The aforementioned use cases and benefits have drawn much attention to these two thrusts of soft robotics, both from researchers in previously unrelated fields and the general public. This influx of attention and research productivity has generated a surge in literature reviews and perspectives to compartmentalize and summarize the diverse subject areas within soft robotics. In contrast to these focused reviews, an all-encompassing view of the field may help inform future research by holistically and quantitatively showing what work has been done, what has been influential, and which gaps in research remain.

To fill this need, our work presents a data-driven analysis that describes the entire field of soft robotics, spanning across all sub-disciplines. We delineate three levels of analysis: publication-level, device-level, and component-level. The publication-level analysis pertains to bibliometric data, the trends of the field, and each publication’s type of contribution (i.e., whether the publication is considered a literature review, a primary research article, etc.). The device-level analysis examined each device, if presented in a given publication, for the number of component types (actuator, sensor, controller, or power source) contained within the device and its dependence on tethering (a physical tether, a nonphysical tether, or no tether). The component-level analysis was centered on three major considerations for each robotic component within each device: 1) the materials used, 2) any geometric design choices enabling compliance, and 3) the energetic method by which each robotic component operated, produced outputs, received inputs, or was powered (i.e., its “function medium”).

As we discuss more deeply in the following section, this data-driven review is distinct from the existing pool of available resources including authoritative perspectives, bibliometric reviews, and compartmentalized literature reviews. Specifically, this review analyzes and illustrates a representative data set that characterizes the collective output of the field of soft robotics. By dissecting and studying all the currently published research, we make the following contributions: 1) we present a view of the state of the art based on a consensus determined by the field itself in terms of citations; 2) we report progress on common and seminal methods of research; and 3) we provide insight

on both established and incipient research directions. While these contributions are not unique in and of themselves relative to existing literature reviews, the methodology and the resulting explicit, quantified data may provide a deeper and more intuitive perspective of the field of soft robotics than prior reviews that come to similar, yet subjective, conclusions. Understanding the current state of the art and using this information to predict where the future of soft robotics may lie will aid researchers in making educated decisions on which research directions to pursue next and how to do so.

2. Background and Motivation

Existing literature reviews and perspectives within soft robotics cover a wide range of topics, methodologies, and technologies. Here, we discuss the typical focus areas in which these literature reviews are conducted, divided into the following five categories: 1) holistic overviews including broad literature reviews or perspective pieces and 2) broad field-level bibliometric analyses, as well as reviews more focused in scope describing 3) the application of outside fields to soft robotics, 4) a specific soft robotic component type or the interaction between components of a soft robot, and 5) materials and fabrication methods. We note these styles of reviews are not mutually exclusive, and many reviews overlap in content.

Holistic reviews on soft robotics discuss recent breakthroughs in the developments of soft robots as an overall robotic device (typically with multiple component types) or provide a high-level field overview.^[28,37,38] Perspective pieces often provide similar overviews of soft robotics while ascertaining important technical questions to be addressed by the field and discussing potential future directions in pursuit of answering those questions.^[39–43] Perspective sections within reviews and entire perspective publications can provide insightful, yet subjective, conclusions. Moreover, while a holistic review is beneficial for readers external to the field and can offer a sufficient snapshot of where the field stands and where it could or should go, a broad overview can preclude many of the nuances in soft robotics research.

Bibliometric analysis is commonly used to correlate qualitative parameters, such as impact, reception, or quality of work, with quantitative data. This type of analysis typically relies on the quantification of citations or publications per year and can establish which topics are popular within a field based on these metrics.^[44,45] Such analyses can also highlight potential authors and groups that have performed (or are projected to perform) well, or a journal's performance in a field. Thus far, we have found that only one bibliometric analysis has been conducted for the field of soft robotics.^[46] While uncommon in soft robotics, researchers in other fields have used bibliometric analyses to gain insight on high-level trends and progression for their respective fields.^[47,48]

A third overarching focus area is directed at interdisciplinary research. Soft robotics is inherently a diverse field symbiotically relying on the expertise, insight, and application spaces introduced by outside perspectives. Reviews in this focus area stem from or are directed toward fields independent from soft robotics. Prime examples include soft robotics for chemists,^[49] textile research for soft roboticists,^[50] soft haptics for materials

scientists,^[51] and machine learning strategies employed for soft control schemes.^[52] More generally, some of the broad fields contributing to the theory, design, and fabrication of soft robots include chemistry,^[32,49] materials science,^[53–55] microfluidics,^[56] control engineering,^[35] and biomedical engineering.^[57–61] As the field grows and matures, we envision the interdisciplinarity will also expand to include even more fields of research.

Component-specific reviews, the fourth focus area, appear to represent the most common type of review. These narrow-scoped literature reviews discuss the state of the art regarding a single soft component type of the four main component types constituting robotic devices, i.e., actuators, sensors, controllers, or power sources. The vast majority of component-specific reviews that we encountered have an emphasis on soft actuators, soft sensors, or both.^[62–76] We found that fewer reviews exist on the less-frequently-studied (as evidenced by our data) soft controllers and soft power sources.^[77,78] We encountered only one review that examined three soft component types: actuators, sensors, and controllers.^[79] Another publication reviewed tethering of soft robotic devices.^[38]

Many of these component-specific reviews showcase soft robotic components that are the most prominent, recent, or have high potential, yet we did not discover any literature reviews that explicitly examined—in a general sense—the state of the art regarding the function media (i.e., the energetic method by which a component operates) of these soft robotic components. We found one review that examines fibers, yarns, and their resulting aggregations for not only the component types that constitute such materials but also their responses to various stimuli (e.g., function media), such as electricity, light (optical media), heat (thermal media), solvents (chemical media), pneumatic media, and magnetic media.^[80] Other literature reviews emphasized stimuli-responsive materials (specifically, polymers) and their function media.^[81–83] While these reviews discuss function media in detail for particular subsets of materials, their discussions are centered only on these subsets of materials.

The final focus area involves materials and fabrication, where authors explore compositions and manufacturing methods that are commonly used or are emerging in soft robotics. Occasionally, authors probe the philosophical question of “what is soft?” by attempting to delineate soft versus rigid materials.^[28,84,85] However, more often, these reviews tend to examine the actual material classes and compositions involved in soft robotics.^[54,71,74–76,86,87] Interesting material-specific reviews pertaining to incipient research have focused on textiles,^[50] as well as hydrogels and other stimuli-responsive materials.^[65,83,87,88] Associated with materials research, fabrication strategies for specific materials or fabrication strategies of devices made from certain materials are common review topics. In pursuit of such efforts, much recent work has been focused on fabrication and more specifically on 3D (or 4D) printing of material.^[89–95]

Looking beyond soft materials alone, soft roboticists harness the ability to create softness from rigid materials through patterning and structure, described as “geometric compliance.” Interestingly, we found no reviews on this topic as a whole, yet one review describes many (but not all) of the geometric compliances that our work details;^[96] this publication centers its discussion on the compliance of a particular class of materials: gels and elastomers. For more specific discussions on geometric

compliance for soft robots, we refer the reader to literature reviews on the 2D geometric compliance of origami in soft robots,^[97] auxetic materials,^[98] and the use of mechanical instabilities for the control, sensing, and actuation of soft robots.^[79] We later discuss how geometric design considerations can be advantageous in making rigid materials compliant as a form of soft robotics.

As corroborated by the wide range of focus areas and the literature therein, soft robotics has become an exciting entanglement of disciplines and literature. However, due to this expansion of information, established figureheads and newcomers alike may face difficulty maintaining an understanding of the state of the field or identifying upcoming technologies. The analyses and resulting data provided in this review introduce a fresh and unique approach to visualize the field and its state of the art. Our approach manifests the benefits of the focus areas described above and also contains alternative methods to assess and investigate the wide breadth of methodologies employed by researchers in soft robotics.

Hawkes et al. recently introduced the “hard questions for soft robotics” our field must address to ensure soft robotics not only persists but also grows to see continuous advancement and societal impact.^[99] Our data-driven review illuminates some quantified answers to methodologies that have (or have not) been realized, as well as the historical growth and trends within the field. We further identify new questions yet to be answered, such as why some technologies have not yet been impactful, how we evolve from a single high-impact publication to further collective investigation that expands on the topic, and what we as researchers can do to diversify technologies and methodologies to manifest the field’s perpetuity and relevance. In summary, this data-driven literature review explores the overarching and nuanced trends of soft robotics through systematic analyses with the intent of informing those within—and external to—the field of soft robotics with quantified data.

3. Methods of Analysis

Our methods detailed below allowed us to ascertain the common, uncommon, and formative methodologies conducted in soft robotics. Our methods can be divided into two main steps: 1) data collection and 2) data analysis.

3.1. Data Collection

Data collection utilized a search within Web of Science (WoS). We used WoS as our search engine because of its breadth of indices and databases, its advanced search options, and its ability to export identifiable information for each publication and its associated bibliometric data, namely citations per year (CPY). The query within WoS examined all titles, keywords, and abstracts that contained terms related to “soft device” or “soft robot” through a “topic search” (TS) as follows: TS = (“soft device*” OR “soft robot*”), where * is a wildcard character. The results were constrained to all databases within WoS, years 1900–2020, and filtered to include articles, proceedings, and review publications. This search query was performed on January 18, 2021, and resulted in 4609 results. These results were exported

and sorted according to each publication’s CPY, defined by the number of citations a publication has received divided by the number of years since the date that it was published.

The CPY metric was chosen as the sorting parameter for publications for four reasons. 1) Because this review pertains to content-based analyses as opposed to isolated high-level data, the use of author-based indices (e.g., h-index or m-quotient,^[100] g-index^[101]) or journal-based indices (e.g., Journal Impact Factor^[102,103]) would preclude the objective content- and publication-specific data we wish to present. 2) Citations, on the other hand, are well-documented as being an indicator of impact (although not necessarily an indicator of quality),^[45,104,105] and we found that a citation-based index was preferred for identifying impactful works within the field of soft robotics; additionally, a per-year metric normalizes relevancy for the age of a given publication, yielding a “fairer” consideration of more recent work. 3) The number of citations is determined by recognition from the authors within the field, so our data are derived from the field’s collective interpretation of works that authors have deemed influential. 4) Finally, the WoS citation report’s output of a standard CPY metric is not only useful for this work but is easily recreated in WoS or other databases for others to access, observe, and interpret, therefore allowing independent and repeatable analysis. Thus, our use of CPY facilitates a coupling of bibliometric data with low-level, granular analyses, represents an easy-to-obtain metric normalized for age, and indicates the impact and influence of work as determined by the field itself.

3.1.1. Limitations of Data Collection

We emphasize that applying a quantitative metric (e.g., CPY) to intrinsically qualitative characteristics (e.g., quality or promise) has shortcomings. We intend to summarize well-performing research and to identify where, and why, gaps exist in the data for various research subjects within soft robotics. Discussed more deeply in the following section, our data are based on a threshold of the top 10% of works based on CPY. Citation-based metrics are indicators of impact, but not necessarily quality, and this metric for impact or influence is subject to the biases of the contributors of the field. As such, removing the subjective selection of works and instead relying on the field’s determination of what is deemed “impactful” can also result in unintended consequences. More explicitly, when those within a field are biased towards citing particular authors, groups, or topics of said field,^[106–108] certain research may be excluded from reaching the top 10% threshold within an “expected” timeframe, or perhaps ever. Moreover, new and exciting research directions may lie in the margins far from the popular trends of the field (for at least some amount of time) and will not benefit from an “inertia of citations” as the popular trends or authors would.^[109] In recognition of this shortcoming, we have included many references to recent and noteworthy research that escaped our CPY threshold. These works that have thus far escaped the purview of the field are recognized for their exciting contributions to the respective sections under which they are cited.

We also note that there are general limitations in examining only 10% of any population. Increasing the percentage of examined works could paint a more accurate picture of the field, but

we note that this, too, could have limitations: 1) the marginal inclusion of publications near the bottom of a CPY-based ranking may not accurately represent the exciting and diverse work that defines and embodies the field of soft robotics and could even dilute the conclusions of a data-driven analysis; and 2) a larger sample size would either require a larger cost in terms of time (during which publication of new results would inherently reduce the relevance of any conclusions) or more participants contributing to the analysis (which inhibits consistency and quality control). Thus, if sample size is expanded in future work, perhaps this undertaking should be relegated to more automatic methods of data collection and analysis, such as text-based searching supplemented by machine learning (which would also entail its own biases).

3.2. Data Analysis

Using the collected data, we performed a detailed data analysis focusing on two aspects of the literature: bibliometrics and content. The former strictly used data from WoS, whereas the latter used analyses derived from careful and detailed characterization of individual publications. All determinations and categories related to the analysis are introduced in this section; the categories are further defined and expanded upon in Section 4.

3.2.1. Bibliometric Analysis

Bibliometric analysis was conducted for all 4609 publications resulting from the initial search query. The data collected include CPY, year published, country of origin, and university of origin. Further analysis was relegated to the top 10% of publications based on CPY. This 10% was compared with the remaining 90% of publications and was further examined through the pairing and comparison of the content contained within the top 10%.

Separation of the top 10% based on CPY was established through an ad hoc power law calculation. When analyzing the percent of cumulative CPY held by a certain percent of the publications, the heuristic Pareto power law becomes apparent (Figure 1a). The Pareto power law, more commonly known as the 80–20 rule,^[110] states that 80% of all outcomes stem from 20% of the causes. Following the same analysis, a value of 10% would account for 73% of the outcomes. Our results from WoS similarly indicate that the top 20% of publications in soft robotics, sorted by individual CPY, account for 75% of the total CPY; the top 10% of publications in soft robotics are responsible for 59% of the impact or influence within the field. In addition to describing soft robotics, we note that the Pareto power law seemingly holds true for other fields and citation metrics.^[111] Thus, our separation methods to filter for influential works with few diminishing returns could likely be used in future analyses regardless of field.

3.2.2. Content Analysis

Based on the observed accordance with the Pareto principle, we conducted a content analysis for the top 10% of publications at the 1) publication level, 2) device level, and 3) component level.

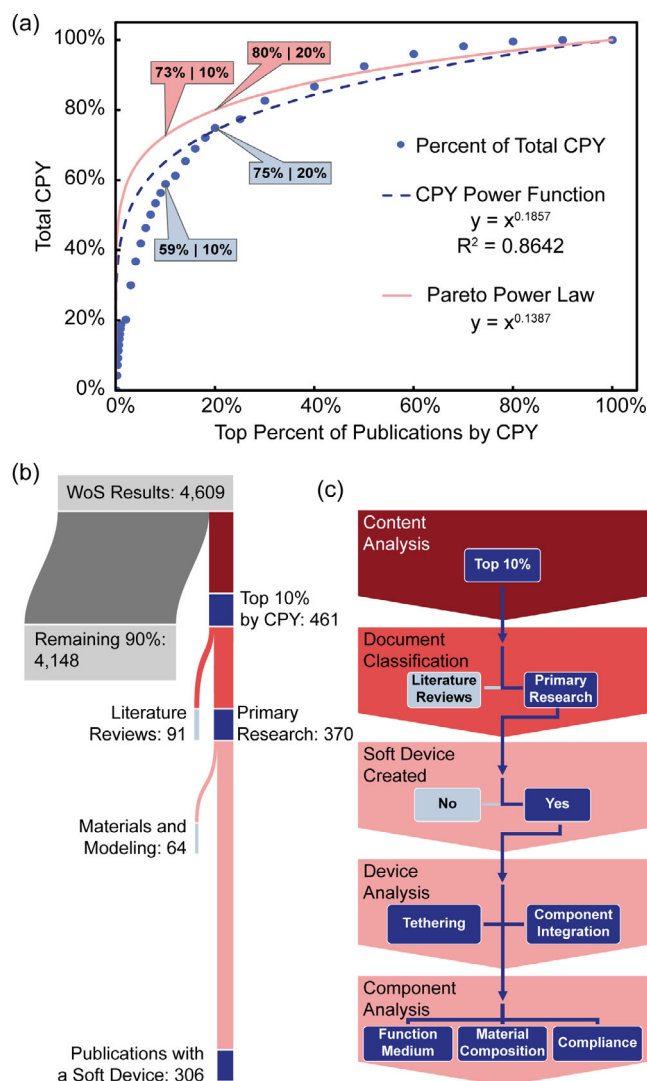


Figure 1. Methods of analysis. a) Pareto power law shown relative to the power function in cumulative citations per year (CPY) based on top publications. b) Sankey diagram showing proportional breakdown of analyzed, high-level results. c) Flowchart of the analysis process.

The analyses contained therein were determined through careful and detailed characterization of the publications (Figure 1b,c).

Publication-Level Analysis: Publication-level analysis consisted of bibliometrics, document classification, and determining if a soft device was presented. Bibliometrics were used to interrelate the categories contained within device-level and component-level analyses. The bibliometrics used in content analysis are the same as the bibliometric analysis from WoS for the 4609 publications with an additional metric: average citations per year (aCPY). In contrast to CPY, aCPY is a calculated mean of the CPY for all publications within a given category or level of analysis.

Document classification pertains to the nature of the work involved in the publication. If a publication was a literature review, it was classified as such.^[112–163] If the publication instead presented original empirical or analytical contributions for the

field of soft robotics, the publication was classified as primary research.

If a publication documented primary research relating directly to soft robotics, it was then assessed based on whether a soft device was presented. To be considered a soft device publication (which includes soft robots), at least one soft robotic component type had to be introduced (i.e., an actuator, sensor, controller, or power source). Otherwise, if no explicit soft robotic components were presented, the publication was categorized under “materials and modeling” of soft devices.^[164–227]

Device-Level Analysis: Device-level analysis assessed publications that contained a soft device.^[228–478] Publications were analyzed to determine the number of robotic component types used in each publication and to assess how the device described in the publication was tethered.

We counted the number of unique robotic component types contained within each device. These component types include actuators, sensors, controllers, power sources, and body. We excluded the body component in the postanalysis to simplify the presented data to only robotic components that employed a function medium (fluidic, electrical, thermal, magnetic, optical, and chemical media). Accordingly, a soft device could have one to four active robotic component types. A soft device with zero active components (e.g., a body or structural material alone, hence the “material” aspect of material and modeling publications) was excluded from the soft device publications and thus also from the device-level analysis.

Tethering, our second category at the device level, is defined as an attachment method employed by the soft device to a specified location. We delineated between three modes of tethering: physical tethering, nonphysical tethering, and no tether. Physically tethered devices are bound by some tangible restraint to a defined location; nonphysically tethered devices are not bound by a physical restraint but instead by the limits of any form of required wireless transmission of signals or power; untethered devices are not spatially constrained by any means during operation. If multiple modes of tethering were successfully demonstrated in a particular device, the least tethered option was selected.

Component-Level Analysis: Component-level analysis examined component-specific data for each component type in a publication. Component types include the four active robotic components: actuators, sensors, controllers, and power sources. These component types are independent of each other. The four component types were chosen based on previous literature and preliminary analysis.^[56] An actuator is defined as a transducer of an input medium into mechanical motion or action, whether intended as a manipulator, gripper, or locomotive device. Sensors detect or measure a physical phenomenon and have an output medium to be read or deciphered by a user or controller. Controllers regulate, compute, or conduct decisions or logical operations based on inputs and provide outputs determined by their defined operation. Power sources supply energy upon which other robotic component types rely to function.

For each component type in a publication, material analysis was conducted. The seven material categories considered here are elastomers, metals, carbon materials, shape-memory materials, biological materials, textiles, and plastics. While some of these materials overlap in purist definitions, the most apt and

accurate material was used to describe each component type based on the publication’s explanation of the material composition. Detailed descriptions of these materials are included in the following section.

As shown in our results, many soft robots do not strictly employ inherently soft or compliant materials. In addition, while some materials are intrinsically soft (e.g., elastomers), other materials can be either hard or soft under standard operating conditions depending on their composition and environment (e.g., liquid vs solid metals and rigid vs soft biological material). This realization leads to our next category of component-level analysis: material and geometric compliance. Soft materials were categorized based on the approximate moduli of biological organisms, i.e., less than 10^9 Pa; rigid materials were determined based on estimated moduli greater than 10^9 Pa.^[28] Additionally, composite materials with both rigid and soft materials were recorded in the literature and were separately classified as “composite.” Beyond the composition of a material, the geometric design can influence the compliance of a robotic component. We explored this notion and determined that robotic components could be made compliant using 1D, 2D, or 3D methods, none of which are mutually exclusive.

The final component-specific analysis investigated the function medium of each reported robotic component type. Function medium is defined as the method by which power or signals were transferred within or between robotic components. Actuators were categorized by their input function medium, as all their outputs were mechanical. Sensors were reported according to the function medium of their output because the purpose of a sensor (from the perspective of the robot) is reporting or outputting information to the robot. Controllers were based on their operational function medium, i.e., the way in which they conducted computation or embodied logic. Power source function media were recorded following the method by which they generated power, which was not necessarily the same as the medium delivered to other robotic components.

Of the 415 robotic components recorded in the 306 soft device publications, 342 robotic components were compliant or soft. While some publications presented multiple robotic components of a single component type, our analysis was conducted on the most prevalent robotic component for each component-type category, as described by each publication. Each component type was individually assessed and classified based on the categories described above. In other words, an actuator could have a different material than a sensor (and would be recorded as such) even if both were within the same device.

4. Results

4.1. Publication-Level Analysis

Analogized by the Pareto power law, our citation limit includes the top 10% of publications, which account for 59% of the cumulative CPY (Figure 1a). The citations required to remain above the cutoff for analysis increases with publication age, resulting in a downward sloping line in Figure 2a. The top 10% of publications also exhibit a larger variance and spread above this cutoff

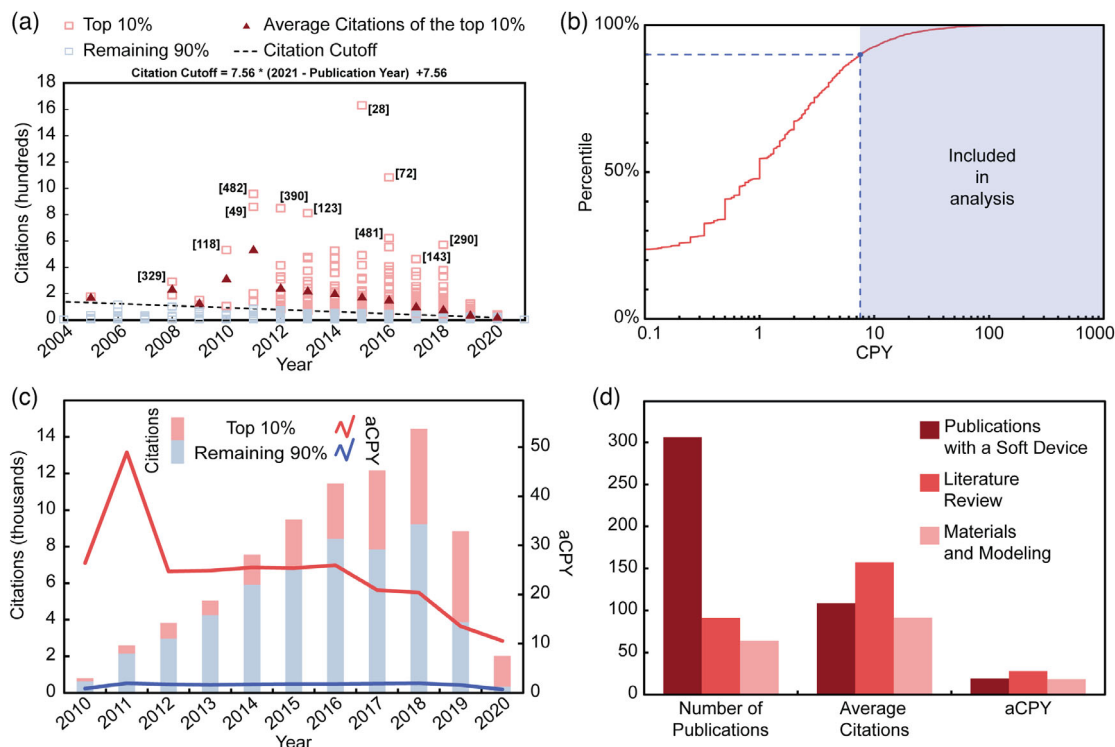


Figure 2. High-level filtering of publications from the field of soft robotics. a) Publications shown with the average amount of citations for that year for the analyzed publications. b) Percentile graph showing the average citations per year (aCPY) threshold at which a publication was analyzed. c) Citations for all publications in soft robotics for a given year. d) Cumulative number of publications, aCPY, and average citations for all analyzed publications.

threshold. The average citation count of the analyzed publications is plotted (where subsequent use of “analyzed” entails content analysis specifically and refers to the top 10% of publications). Outliers in terms of impact can also be observed above the cutoff threshold. The references for these high-performing outliers are indicated in the plot.

An alternative method of viewing analyzed publications is plotted on a semilog graph in Figure 2b. The cutoff number of annual citations required for inclusion was 7.56 CPY. This plot is based on a percentile ranking formula and shows the performance of “impact” between the top 10% and remaining 90%. Vertical climbs in the curve correspond to a number of citations that is commonly divisible by age (in years) to result in a simple fraction, such as 1/3, 1/2, 2/3, 1, etc.

Figure 2c compares in aggregate the top 10% and remaining 90% relative to each other. There is a decline in aCPY for the top 10% but an overall increase in the citations. Additionally, the citation trend is approximately linear. The recent exponential growth in the number of publications outpaces the linear growth in the number of citations, indicating that the large number of works is becoming insurmountable in authors’ efforts to digest and build upon prior studies with future work—a problem alleviated by this data-driven review. Another trait visible in Figure 2c is the notable peak in citations ≈ 2 years prior to 2020. This phenomenon appears throughout our analyses in later sections. This behavior is likely explained by an optimum age at which a publication has had enough time to gain recognition among the field while remaining relevant enough to continue being

cited. After about two years of age, the pertinence of research may decline. Prior to this age, a typical publication may not have had enough time to have been fully seen, appreciated, or iteratively improved upon—and consequently cited—by the field of soft robotics. In acknowledgment of this incubation time to reach peak impact, we have cited many recent and notable works that explore new topics in the field yet escaped our data collection threshold of the top 10% by CPY.

There is a notable bibliometric discrepancy between the top 10% and all other publications. A likely explanation is a barrier to entry. Established laboratories and principal investigators garnered the majority of the recognition throughout the early years of the field of soft robotics. As the field gains more interdisciplinarians, fresh academics, and a wider reach within society, the influence of these neophytes may continue to grow.

Our final publication-level evaluation initiates our more in-depth analyses. The top 10% consisted of 461 publications. 306 of these publications contained a soft device; this number is more than three times greater than the quantity (91) of literature reviews and nearly five times the quantity (64) of materials and modeling publications (Figure 2d) included in the top 10%. Unsurprisingly, while representing only a fraction of the total publications analyzed, literature reviews claim the largest number of citations and aCPY due to their ability to be invoked in many publications in soft robotics. Notably, publications presenting new and original work had similar impact regardless of whether a physical soft device was shown or the publication presented only materials and modeling for soft robotics.

4.2. Component and Device Analysis

Here, we present data regarding only soft robotic components or devices. Rigid robotic components were excluded in the main text but included in Table S1–S7, Supporting Information. The soft robotic component data are exclusively shown to emphasize the foundational progress and methodologies that make soft robots compliant. A robotic component was considered soft if it employed either an intrinsically soft material or a compliant geometric design.

4.2.1. Materials

While multimaterial robotic components were often documented, only one material per robotic component type was recorded. The determination of material was based on the most highly emphasized material for a given robotic component's function.

Special considerations were made for two specific materials. First, paper-based materials, while containing fibrous material, are predominantly nonarrayed. Thus, paper is designated as textile but not considered to also have 1D geometry as woven or knitted textiles (composed of long 1D yarns) do. Second, a single publication reported using leather, and the corresponding component was classified as a biological material.^[479] This

categorization represents the closest material category, despite the fact that leather is no longer a living material.

Elastomers have been implemented far more than any other material (**Figure 3**). Elastomers comprise any rubber-like polymeric material, per the International Union of Pure and Applied Chemistry (IUPAC) definition.^[480] Elastomeric material was the only material invariably considered soft. The inherent compliance, low cost, and ease of manufacturing lend to this material's persistent incorporation. The Octobot and multigait soft robot exemplify elastomeric actuators, where pressure-driven fluid fills and expands elastomeric chambers to cause motion.^[481,482] Another well-received example is an optical luminescent dielectric sensor harnessing ionic hydrogel electrodes to emit differing levels of luminescence based on strain and consequent capacitance.^[483] An alternative capacitive hydrogel sensor is demonstrated to be self-healing and applicable for wearable applications on dexterous body parts.^[484] Liquid crystal elastomers have been shown to actuate in the presence of light and were presented in the form of an artificial, mimetic flytrap.^[485]

Recent publications following our data collection have described progress in the 3D printing of elastomers for streamlined fabrication,^[486,487] and further development has occurred in self-healing elastomers that are combined with liquid metals or adhesives.^[487,488] Cui et al. even crafted garments made from bulk elastomeric material for thermoregulation of an individual to reduce environmental impacts.^[489] A widely adopted category,

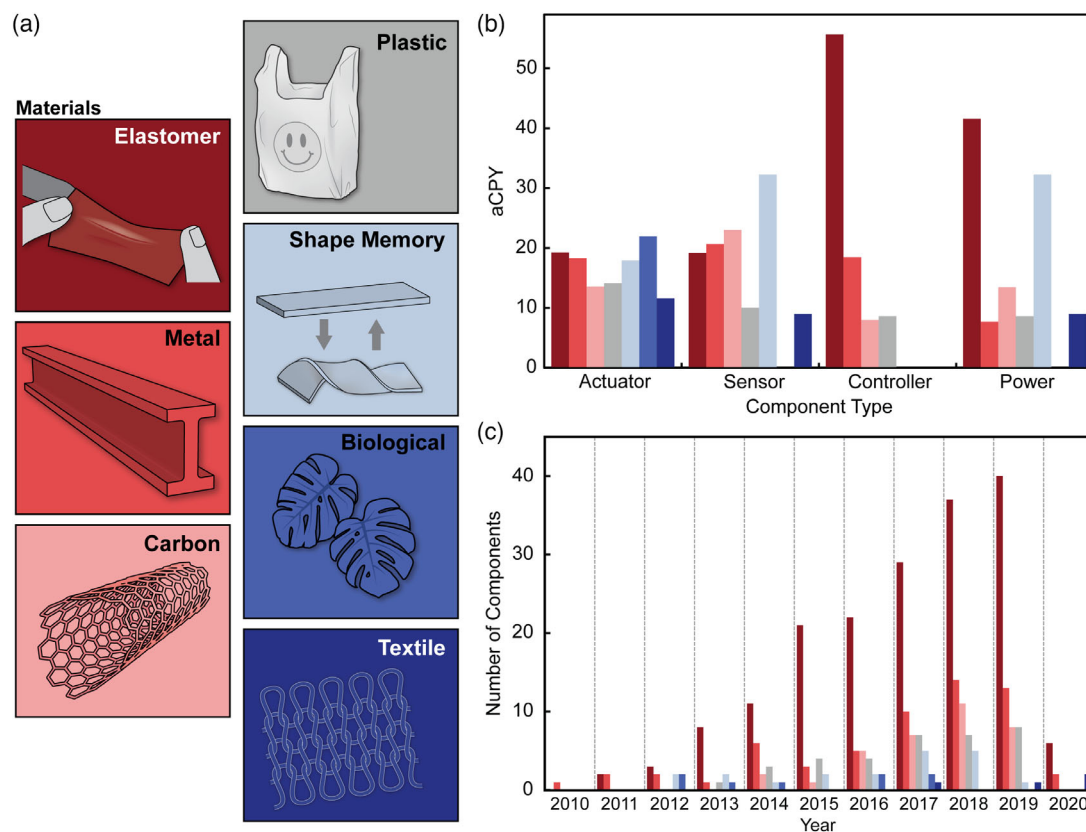


Figure 3. Material analysis for the top 10% of publications by average citations per year (aCPY). a) Material category examples and legend. b) Number of robotic components using a given material in each year. c) aCPY based on the material used for a given robotic component.

elastomers show great diversity in chemical makeup, application, and function media.

Metals were often utilized in hard and soft formats. Their frequency can be attributed to the benefits facilitated by their wide range of alloying options, low electrical resistance, and multiple geometric possibilities facilitated by their well-established and diverse methods of fabrication. Liquid metals (predominantly as eutectic alloys) allowed for the metal to be considered a soft material.^[490] Ferrous metals aided in magnetic applications.^[491] The electrical conductivity of metals was integral to many soft devices using electricity as a function medium,^[492] and their geometry varied from using 1D wires (e.g., flexible cables)^[493,494] to embedded nanoparticles in a paste or elastomeric composite matrix.^[490] Lately, researchers have expanded the theory of modeling for ionic polymer–metal composites and concocted a method of regulating bubble formation in liquid metals for modulation of the liquid’s surface to create a display for logic arrays or to alter electrical characteristics.^[495,496]

Carbon, a material with a multitude of benefits similar to metals, can be more electrically conductive than most metals, is the most thermally conductive element, is lightweight, and can be fabricated in many different forms. For our purposes, this material group excludes carbon-based life forms but includes a variety of 1D carbon materials and graphite grease for use in soft electronic systems. A common form of carbon in soft robotics is in carbon nanotubes (CNTs), particularly as electrodes and in composite structures for thermal or electrical conduction. CNTs have been used as electrodes in dielectric elastomeric actuators and in a variety of electrical sensors.^[77,497,498] Triboelectric nanogenerators have made use of graphite grease in electrodes to transfer electricity.^[499] Based on thermal expansion, CNT bilayer composites have enabled “flicking” locomotion.^[500] These publications (and other recent works)^[501–503] represent just a glimpse of the wide range of research harnessing the spectrum of properties and conformations that carbon enables.

A ubiquitous material in traditional robotic components, but less common in soft devices, is rigid plastic. Another polymeric compound like elastomers, plastic is defined here as an inelastic material. However, when integrated in a flexible sheet conformation,^[504] it would be considered compliant. More commonly, it is restricted to rigid bodies, often in the form of protective structures for shielding delicate internal components.^[505] Perhaps the most common controller in everyday life is a printed circuit board,^[506] made mainly from a composite matrix of rigid plastic. Nascent research has focused on making use of the rigidity of plastics for the grounding of torques in wearable exosuits,^[507] developing computational inverse designs of surface topologies for the aforementioned inflatable flexible sheets,^[508] and incorporating an array of kirigami-based grippers for manipulating delicate objects.^[509] The appeal of plastics generally comes from low-cost fabrication, availability, electrically insulating characteristics, and a breadth of structural properties.

As a relatively nascent material class, shape-memory materials have an inherent “intelligence” that is more distinctive than the typical embodied intelligence. These materials can revert back to a trained shape when triggered by an external stimulus, most often a change in temperature. Shape-memory alloys (SMAs) and shape-memory polymers (SMPs) were placed into this category and have primarily found use in actuation (Table S1,

Supporting Information). For example, an SMP taking advantage of origami-like designs produced reversible shape change based on photo- and thermoactivation.^[510] SMPs can also be 3D printed for facile fabrication of soft robotic components.^[511] SMAs have been used to mimic muscular hydrostats in octopuses by producing a 20% contraction in the radial direction of a bioinspired octopus tendril.^[512] Another SMA coil made from nickel titanium helped locomote a “meshworm” through peristaltic motion.^[513] These works represent common uses seen in the analyzed publications, and new recipes and applications of various shape-memory materials are still being explored.^[514–516]

Biological materials are rarely used in soft robots, a consequence of comprising living, organic cells that inherently require more maintenance and care than nonliving material. Combatting this drawback, the intrinsic organic properties of biological materials facilitate many benefits, including biocompatibility and biodegradability. Researchers taking advantage of millennia of evolution provide prominent stepping stones in the development of soft robots. Common forms of exploited biological materials include muscle cells and bacteria. Park et al. presented a soft robotic version of a batoidea, commonly known as a ray, which incorporated engineered tissue from rat cardiomyocytes that incur muscle activation when exposed to light, allowing it to swim.^[517] Harnessing motile bacteria for locomotion, “micro-swimmers” have been developed for modes of drug and cargo delivery within the human body.^[518] Tackling the difficulties in assembly of such delicate living materials, another progression leveraged new additive manufacturing strategies; skeletal muscle cells (as opposed to cardiac muscle cells) have been 3D printed to create functional bio-bots that more accurately represent animalistic actuations.^[519] An alternative method not analyzed in this review is the parasitic control of an organism, for instance an electronically controlled cockroach or Venus fly trap.^[520,521] While not technically a biological material, Yan et al. recently demonstrated a more “sustainable” SMP that incorporates a biomass-derived carbon nanomaterial.^[516]

The final material designation is for robotic components made of textiles. Textiles are diverse in both their constituent materials as well as their structuring processes, which can be tuned for strength or compliance. The adaptability of textiles enables a wide array of use cases for soft robotics, especially in use with humans or in wearable technologies. Woven and knitted fabrics coated in conductive polymers allow for amplification of strain and an increase in mechanical stability and can be electrically actuated akin to skeletal muscle.^[522] Jia et al. developed assembled hygroscopic silk actuators that actuate upon water absorption, showing a 70% contraction with a 60% increase in relative humidity of the surrounding air.^[523] Thermoplastic elastomer (TPE) coated fabrics can be hermetically sealed together with heat and pressure to create bellows and channels for actuators, akin to a pneumatic network (pneu-net).^[524] More recently, seamless pneumatic actuators have been developed, made possible through computerized machine knitting,^[525] other researchers are demonstrating that heat-sealable fabrics can be used to create a soft wearable rehabilitative or assistive device for individuals.^[526] Textiles need not be actuators and can instead perform structural duties; fabrics embedded in an elastomeric matrix can increase structural integrity,^[29] and braided constraints can be used for strain-limiting layers in elastomeric actuators to direct

motion.^[21] New work that pertains to the fabrication and tailoring of garments has shown a shape-changing robotic mannequin for customized fitting of garments to individuals—a helpful development if these textile-based devices are to provide wearable benefits.^[527]

Figure 3b shows the aCPY for aggregated component types, according to material class. There is no apparent trend within actuators, yet this popular component type offers a fair reference point by which we can compare the other three component types. Interestingly, with low sample sizes, controllers and power sources tend to have a lower aCPY. However, the singular elastomeric controller exceedingly outperformed all others,^[481] followed by elastomeric power (which resulted largely from the same publication as the elastomeric controller). The few shape-memory sensors and power sources also show promise,^[528] yet their uncommon usage likely stems from other more common material counterparts often being sufficient enough to integrate into soft devices. However, if more fully explored, these materials can vastly expand our tools to use in soft robotics. As such, these works were rewarded with significant recognition in the field.

Material use over time reveals the increasing diversity of materials used in recent years, yet there remains a stark contrast between the diversity in available materials and the overwhelming reliance on elastomers (Figure 3c). This naturally compliant material seems like an obvious tool for developing soft devices, but evolution of the field will only truly occur through the adoption of more materials and their capabilities. Compliant metals are a distant runner up in occurrence. Dependent on the year, compliant plastics and carbon materials compete for the third most used material. As the field grows, so does the number of robotic components employing each of these materials. The increasing diversification is promising, but high-potential and relatively simplistic materials, like textiles and shape-memory materials, should see increased use and development if we intend to implement soft robotic features into human-centric devices, such as wearable robots.

4.2.2. Compliance Methodologies

As mentioned earlier, a compliant device or robotic component does not require an inherently soft material. The design and use of composite soft and rigid materials or specific geometric designs, e.g., 1D, 2D, or 3D compliances, enables a diverse spectrum of soft-bodied devices. Not only is compliance between component types not mutually exclusive (nor are any other robotic component analyses at this level), but geometric compliances are not mutually exclusive from material compliances either; in other words, a component's material, material compliance, and geometric compliance are not dependent upon each other. While the dimensional designations are not mutually exclusive, the specified categories within each dimension are (i.e., a robotic component could not have multiple 1D geometric compliances but could simultaneously have 1D and 2D compliances). An interesting example reveals itself in the case of textiles. Woven fabric constitutes 1D fibers arrayed into a 2D flexible sheet. These flexible sheets can then be formed to create 3D pouches and channels through which fluid flows.

The resulting designation for such a device would take advantage of all three (1D, 2D, and 3D) geometric compliances.

3D geometry indicates geometric designs that are similarly significant in all three dimensions (i.e., length, $L \approx$ width, $W \approx$ height, H). The most common use of 3D compliance was seen in pouch or inflatable chamber designs. Some notable literature using these can be seen in the following examples. Elastomeric pneumatic networks are the quintessential representation of bellow- or chamber-based designs.^[49,529,530] More recently, textile pouches have come to fruition as a sealed system to allow fluidic flow.^[524,531] Building off of the aforementioned examples, harnessing combustion enables a fluidic power supply for chambered pouches to be self-contained within a soft robot. This tactic was used in a soft robot that employs elastomeric chambers that rapidly expand and cause a jumping motion when a combustion reaction produces pressurized fluid.^[505] Inflatable pouches almost always used some form of elastomeric material; however, even a compliant material can be made even more so with the introduction of this geometric design. The combination of elasticity and impermeability facilitates easy incorporation for such 3D pouch designs. More immediate efforts have focused on haptics, where sealable sheets can be inflated to provide tactile cues when worn by a user and scaled-down elastomeric pouches can be actuated via combustion to create a microfluidic tactile Braille display.^[532,533]

An alternative 3D geometry was designated for porous or spongy materials. Porous media could comprise soft or rigid material as the thin walls of each pore or cell allowed for more compliance than the bulk material would alone. In this implementation, Ding et al. created a piezoresistive conductive sponge for pressure sensing,^[74] and Wang et al. demonstrated a similar bimodal sensor from a carbon sponge.^[534] The use of porous geometries shown in these examples reduces weight and also allows dynamic electrical properties as the cell walls gain additional electrical contact points or reduced spacing between contacts upon compression. Porous media are now being researched to manifest not just a bending actuator, but one that can facilitate decomposition back into the earth once it is no longer needed.^[535] At a smaller lengthscale, a recent review summarizes the dual porosities of metal–organic cages and gels.^[536]

2D compliance is enabled by flexible sheet-based designs. Such designs have two significant dimensions (e.g., $L \gg H$ and $W \gg H$). Researchers have used this design consideration on its own within textiles and fabrics coated with TPE.^[524] Additional elastomeric sheets or beam geometries are considered in this designation as well.^[485,500,537] Generic flexible sheet conformations do not need a soft or elastic material; instead, the thinness of the material improves compliance by reducing both bending stiffness and minimum radius of curvature before failure. In pursuit of harnessing inextensible yet inflatable sheets, Panetta et al. have made progress in the computational inverse design of programmable topologies of 2D materials.^[508] A gripper made from thermoplastics with tunable adhesion and stiffness was also recently shown to have promise in a variety of use cases.^[538]

Within the 2D compliance category, a more specific designation was made for devices using origami.^[510,539–541] Origami enables preferential bending for predetermined shapes based on articulation at a folded or prestrained area. A fresh push has been

made by multiple groups toward developing a breadth of origami structures, whether through quickly deployable shelters,^[542] as stretchable and magnetically actuated grippers,^[543] or in an actuator with a variable effective length.^[544] Kirigami is also considered within this category and has been implemented in soft robotics work,^[509,545,546] but this 2D category was not seen in the analyzed publications because none of the existing work exceeded the CPY threshold for the top 10%. Similar to origami, kirigami instead uses cuts in the material to facilitate predetermined, designed articulation. A notable paper published after data collection includes the use of kirigami for simple fabrication of a gripper or an array of grippers for the delicate handling of fragile objects.^[509] Another interesting example of kirigami, albeit not explicitly related to soft robotics, is seen in the design of grooves and cuts in pasta to enable flatter and more efficient packing.^[547]

1D compliance is a method in which the geometric scale is significant in only one dimension (e.g., $L \gg W$ and $L \gg H$). These 1D compliances could then be arrayed with each other to form textiles in a flexible sheet-like manner,^[522] which would also be considered 2D. Alternatively, a 1D material could be wound in a coil to produce a spring—allowing rigid materials such as steel or other metals to become compliant.^[548,549] A final common use of a 1D geometric design entails flexible cable systems.^[494,550–552] Often referred to as Bowden or tendon cables, a drawn wire (or multistranded cable) can be routed around and next to moving or oddly shaped environments to permit structural integrity in the axial direction while maintaining compliance in other directions. Recent advances harnessing 1D materials vary widely, but works include the use of SMA coils or twisted polymer fibers.^[489,525,553–556] A particular work of interest pertains to the demonstration of a biomimetic canine tongue that can move both solids and liquids.^[515]

Figure 4 presents the variety of compliance methods employed by the soft robotics field. In correlation with the rising interest in soft robotics, we observe an increasing trend with each compliance method as time has progressed. At first glance, it is unsurprising that intrinsically soft material is the most common strategy to achieve a compliant device. However, not far behind is the use of 2D compliant geometries, such as flexible sheets or (less commonly) origami conformations. Moreover, while the most common material is elastomer, which one might associate with the use of fluidic function media, 3D compliant geometries (such as pouches and chambers) are hardly employed relative to the top two methodologies. This fact implies that elastomers are diverse in their use and are not relegated to strictly fluidic functions.

While the use of each compliance method has grown with time, there is no obvious difference in the reception of publications that employ different geometries (Figure 4c). However, it is worth noting that the aCPY of any given geometric compliance is near the average when compared with other publications in the top 10%. Incorporation of geometric design may facilitate emergence into the upper tier of influence and impact in soft robotics.

We also notice that actuators most often use two specific geometries: pouch and flexible sheet. The overwhelming majority use intrinsically soft materials (Figure 4d). These occurrences most likely stem from the prevalent use of pneumatic network actuators, more commonly known as pneu-nets, whether due to their introduction over a decade ago or the further

development in their applications and control more recently. Of the sensors seen in our analysis, nearly two-thirds use the flexible sheet method of geometric compliance. Sensor materials, however, are more varied (Figure 3, Table S1, Supporting Information). A greater diversity of geometric designs for sensors might be worth exploring should the field want increased integration of this component type into more soft devices. Controllers and power sources hardly employ any geometric advantage, but when these component types do, it is often through a flexible sheet conformation. The materials seen in controllers and power sources are nearly always rigid as well.

We note differing trends between controllers and power sources when examining the performance of each component type based on its compliance. The average soft controller received 24.5 aCPY, while rigid controllers received a lesser 20.9 aCPY. Noting that the average top 10% publication received 20.7 aCPY, rigid controllers may help publications breach into the top 10% but remain approximately average within this tier. Conversely, soft controllers have been recognized as a beneficial addition to the field with their higher-than-average aCPY. In contrast to controllers, soft power sources received 19.8 aCPY, while rigid ones obtained 24 aCPY. A difference of over 4 CPY between the two types of power sources makes it seem then that soft power sources are possibly more difficult to implement well or that rigid power sources are not a concern or limiting factor in soft robotics.

Our final analysis of compliance examines how the number of component types correlates with a given robotic component's compliance (Figure 4e). No single-component devices are shown as rigid here because rigid robotic components were excluded from this level of analysis. We see an increased reliance on rigid robotic components as the number of component types increases. A likely explanation for this increase is that, as more component types are integrated into one device, it becomes more difficult to maintain compliance across the entire device. This notion might come from the increased complexity arising from the integration of multiple component types together, whether that be from incompatible function media, incompatible materials, or generally a narrow array of compliant component types.

4.2.3. Function Media

A function medium is the energetic method by which an active robotic component is powered, operated, delivers outputs, or receives inputs. Six categories encompass all energized robotic components: fluidic, electrical, thermal, magnetic, optical, and chemical media. Mechanical movement may seem like an omission, but here we consider that mechanical motion is simply used for transmission of forces or torques. For instance, a flexible cable actuator in an exosuit may appear to exhibit mechanical operation, but this method often uses an electric motor to drive the cable retraction.^[551] Thus, the actuator would be considered electrical.

Fluidic actuators represent a plurality for every component type and function medium combination (Figure 5b). A pneu-net is the archetypical representation of soft robotics.^[49] A less frequent—but still effective—implementation of fluidic media includes hygroscopic or hygromorphic components that swell

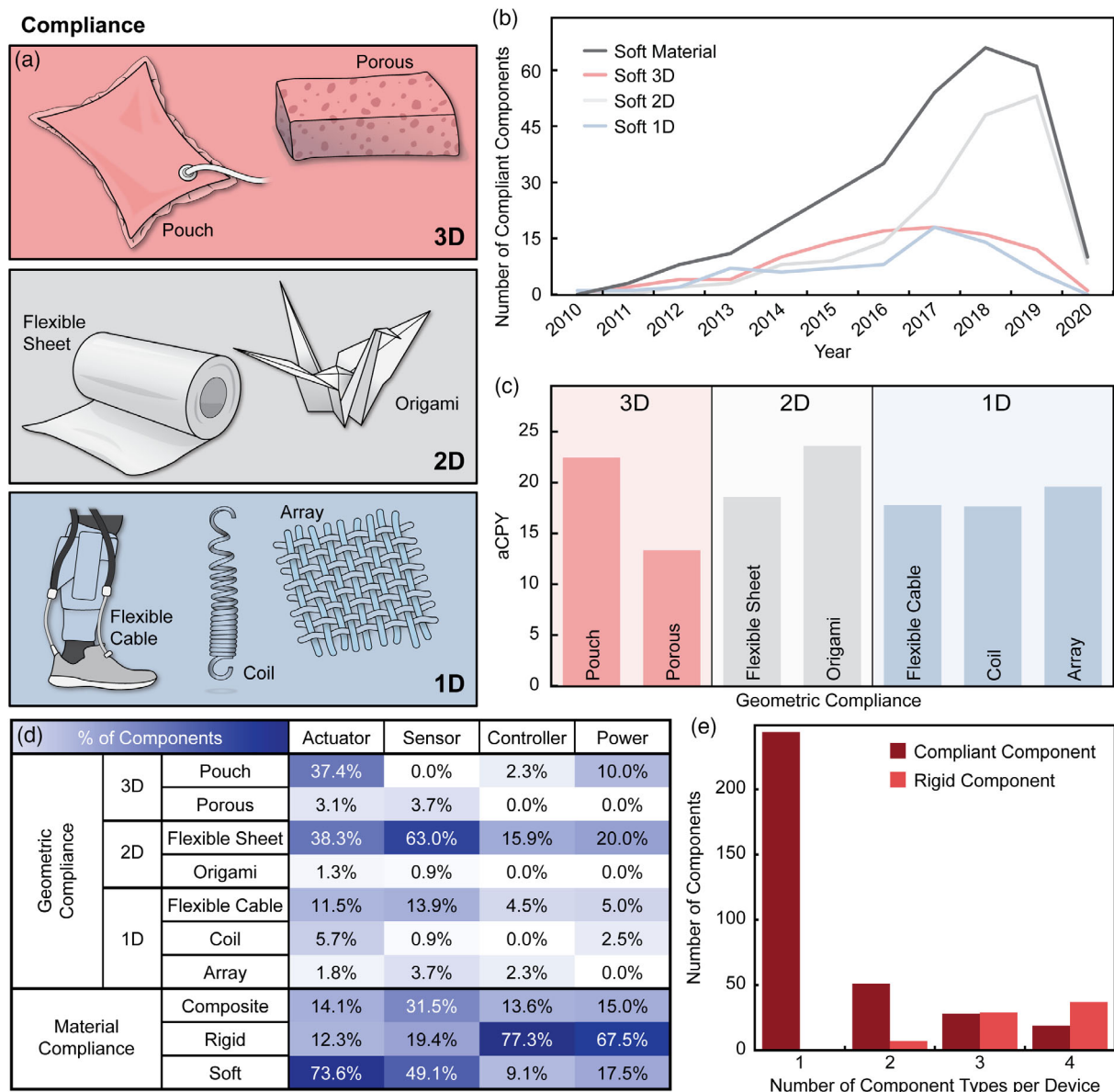


Figure 4. Geometric compliance and material compliance analysis. a) Compliance category and examples. b) Occurrence of compliance methods for each year. c) Average citations per year (aCPY) for a given geometric compliance. d) Compliant and rigid robotic components in a device relative to the number of component types for a given device. e) Heat map showing the proportions of different geometric compliances and material compliances for a given component type.

with the absorption of a liquid.^[523,557] Fluidic devices are now showing great promise for haptics and the thermoregulation of individuals.^[489,532,533,558] Other recent work has demonstrated low-cost, wood- and paper-based hygroscopic actuators for use in educational settings to teach more intuitively about soft robotics and botany.^[559] Another notable publication details a modular fluidic engine for soft actuators.^[560]

While the fluidic medium seems to be representative of the field, the electrical medium is the most commonly utilized overall. This medium accounts for the vast majority of soft robotic components, especially in sensors, controllers, and power schemes (actuators are more diverse). Untethered electric power

components often use batteries (electrochemical but designated here as electrical) that can be carried by the device or user.^[492] Most stationary (i.e., tethered) devices draw electrical power from power supplies, computers, or typical AC voltage from a wall outlet.^[551,561] Electric motors are often applied to actuate soft robots.^[494,550] Computers, data acquisition units, and printed circuit boards are typical electric controllers.^[505,551] Haptics appear yet again in recent work with a review on electrically driven soft haptic actuators.^[562] Researchers have also shown that alternating a conductive fluid with an insulating fluid within a flow constrained in a tube can encode the transported fluid with data that can be interpreted as electronic signals.^[563] Another noteworthy

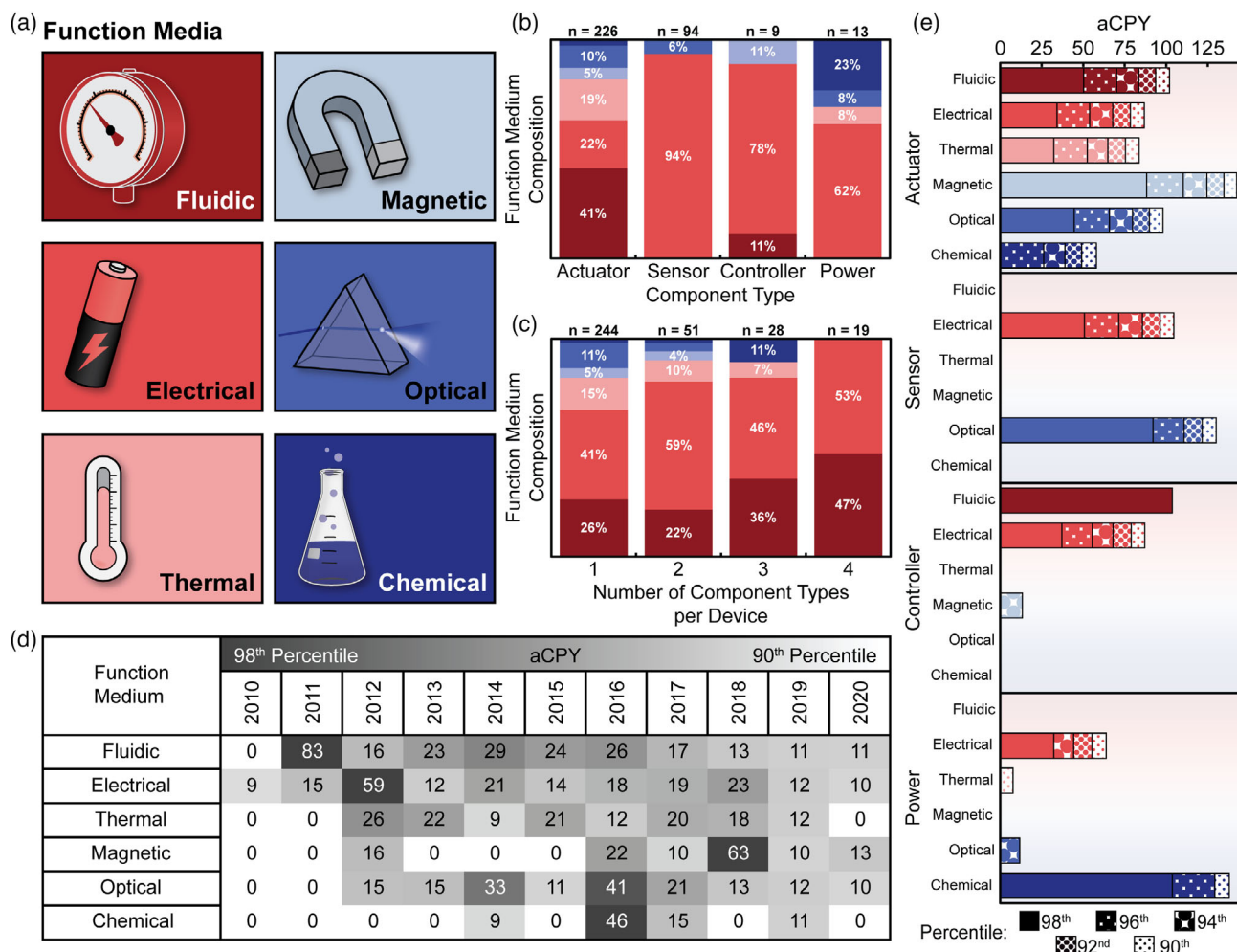


Figure 5. Function media analysis. a) Function media category examples and legend. b) Proportions of a given component type using a certain function medium. c) Proportions of devices using a certain function medium relative to number of component types in each device. d) Heatmap showing the average citations per year (aCPY) of function media for a given year. e) aCPY for each function medium within a robotic component separated by percentile.

liquid-metal-based design led to demonstration of adhesion control for soft robots in slippery and underwater environments.^[564]

Often derived from electricity through Joule heating in soft robotics,^[500] the thermal medium was selected for a robotic component regardless of the origin of the change in temperature, as long as the researchers characterized the performance of their robotic component relative to temperature. In another example beyond Joule heating, heat from sunlight could be described as an optical medium,^[500] but we classified this work as a thermal medium based on the original researchers' characterization of absorption to generate heat. Frequently used in a coil geometry, SMAs and SMPs are regular employers of thermal stimuli for actuation.^[510–513] More recent work details the integration of a liquid metal with shape-memory composites for self-healing and circuit-enabling purposes,^[514] while other researchers are investigating the use of thermal energy to enable soft devices based on liquid–vapor phase change.^[565]

Optical and magnetic components were some of the least frequently recorded items. The infrequency of magnetic

components likely stems from an intrinsic reliance on ferrous metal, a non-compliant material in bulk form. Some researchers were able to circumvent this issue by embedding small ferrous particles within a soft-bodied matrix as composites.^[490,566,567] Exciting recent work examined the use of magnetorheological fluids in soft robots for magnetic control and operation,^[568,569] while other researchers demonstrated the transportation of fluids and solids across a “soft magnetic carpet.”^[570]

Optical media were only seen in 23 actuators and five sensors, a small quantity relative to the 342 soft robotic components recorded. A typical example of optical media includes ultraviolet radiation.^[571] Other common inducers of optical actuation are lasers and lights for photoresponsive liquid crystal elastomers and SMPs.^[485,511] While not an optical sensor (due to the optical signal being an intermediate medium transduced to an electrical output), fiber optics have been reported as a method to measure shape changes based on the wavelength change induced by the instantaneous curvature of the cable.^[561] Azobenzene photo-mechanical polymers, a category of polymers that have optically

induced motion, are standard for soft optical actuators.^[53] As sensors were categorized by their output medium, the optical sensors recorded here would have a visible (e.g., chromatic) change in response to some (typically mechanical, e.g., strain) input.^[483,572–575] This use case is the only deviation from electric sensors. Chromatically changing actuators,^[503] microsphere expansion inducing volumetric changes,^[576] and a self-oscillating locomotor are examples of the subjects of just a few of the recent publications that describe optically driven soft devices.^[577]

The last function medium regards chemical operation. This medium was the least often recorded. Soft power sources commonly employ chemical reactions. Chemical media typically generate some form of thrust or propulsion through the use of compactly stored reagents or from the surrounding environment (e.g., stored in a surrounding chemical solution). Combustion reactions can drive fluidic actuation;^[505,578] gas evolution from catalytic decomposition is an alternative method of generating pressurized fluid flow for actuation.^[481,579] Surrounding pH levels can affect certain stimuli-responsive hydrogels for sensing or hygroscopic actuation.^[580,581] Metallic reactions also facilitate the use of chemical media as a mode of locomotion in liquid metals.^[582,583] Chemical-driven processes, such as combustion,^[533,584] have been explored more deeply since we initially conducted our analysis. Another exciting new publication discusses the Marangoni effect as a propulsion mechanism utilizing a surface tension gradient generated by the release of alcohol into the water on which a robot locomotes.^[585]

We note that many function media not only originate from alternate media (as in the case of Joule heating for thermal media and seen in fluidic actuation from a combustion reaction) but also can be inseparable from each other in the case of photothermal, electrothermal, or electromagnetic media. We restricted our data analysis for each robotic component to single data points of each category. This constraint allows for more succinct and digestible data. In the cases of combined media, especially those just mentioned, we delineated according to the researchers' method of quantifying their results (e.g., a Joule heating device that was measured in temperature as opposed to electrical current would be considered a component using a thermal medium).

When observing function media relative to component types, an obvious disparity arises, where actuators are again quite diverse, but the same cannot be said for any other components (Figure 5b). The variety of actuator media could certainly be due to the fact that actuators are the most researched component type. Adding to the variety of function media for robotic components can better enable the combination and integration of more component types in a single device, as some devices may be more easily realized if all robotic components function on a singular function medium. We anticipate exciting work as the field works to address the gaps in alternative function media in all component types.

The reliance on electric components remains consistently around 40–60% for all soft robotic components, regardless of the number of component types in a particular device, seen in Figure 5c. Interestingly, the rate at which researchers use fluidic components generally increases as the number of component types increases. The increased use of fluidic media and persistence of electrical media indicates a diminished diversity in function media as a particular device becomes more evolved with a

higher number of component types. A reliance on these two function media indicates that either fluidic and electrical components are inherently the most compatible within and across media or that the frequent occurrence of these function media leads to a more developed toolbox of robotic components from which researchers can choose.

The latter explanation for a reliance on fluidic and electrical media is further corroborated by Figure 5d, where their aCPY peaked in 2011 and 2012, respectively. The temporal data indicate that these media were developed earlier for soft robotics and consequently have had the most time to be finely tuned for specific device or use-case needs. Chemical and optical media peaked in impact at around the same time frame as each other, but chemical media began to impact the field two years after optical media. Further, chemical's peak in 2016 can be attributed to the Octobot holding three-quarters of the cumulative CPY for chemical media in that year.^[481] Both media appear to be exciting prospective methodologies to pursue as indicated by the fact that optical sensors and chemical power sources are well above the average aCPY across all component types and media (Figure 5e).

Actuators serve as a reference point to which other component types can be compared in terms of aCPY. Aggregate actuators are all relatively comparable in reception among the field, integrate all function media, and have a plentiful sample size (approximately a 20:10:1:1 ratio of actuators to sensors, controllers, and power sources, respectively). Acknowledging actuators as a point of reference (Figure 5e), we see optical sensors deviate from actuators in aCPY, yet it seems any integration of a soft sensor beneficially affects impact. Similarly, chemical power sources achieve the second most aCPY, but all other power sources fall short. Perhaps difficulty in the inclusion of alternative power schemes supersedes the capabilities soft power sources can bring to a soft device, or the fact that chemical systems are already well-proven as power generators negates the impact other media can have on this component type.

Magnetic media were used the least proportionally, which may be due to the recent emergence of this methodology. As noted in the Publication-Level Analysis subsection, the most recent two years are likely underrepresented, so magnetic media may currently have an upward trend. Even so, magnetic actuators appear to be the most impactful, reaching higher aCPY than any other combination of function medium and robotic component. An alternative explanation could simply be from the increasingly growing number of incoming researchers investigating the current "hot topic" of the field. If this is the case, any recently booming topic within soft robotics could be subject to a large influx of publications (and resulting citations to recent publications) on said topic.

Thermal media, however, may have a less fortunate explanation of absence than magnetic media. Shown by Figure 3, shape-memory materials, and especially those that rely strictly on temperature, have not been prominent in use over the past two years. Furthermore, temperature as a medium has hardly been implemented in any of the component types, except actuators, in which they have been perceived as less than average in impact. This near-nonexistence could mean that there is a significant gap in attempting to integrate this medium into soft robotics, or perhaps that there are performance characteristics limiting its use—for example, temperature media are typically slow relative to other media.^[510,531,586,587] Optical, magnetic, and electrical

media can respond at rates on the order of the speed of light; chemical reactions, while varied, may be expected to be implemented with high rates of reaction, such as combustion;^[223] fluidic media can operate at the speed of sound in their constituent fluid and yet may still be chastised for many orders of magnitude slower response times relative to the speed of light. Temperature, however, is commonly relegated to slower response times than even fluidic media. Fast changes in temperature rely on large differences in temperature and low heat capacities, parameters that can be difficult to implement in human-centric soft robots given our species' limited tolerable range of temperatures and the limited selection of available conformal materials. Inherently, these energetic rates are inferior to other function media, so unless thermal media is otherwise a design requirement, the explicit pursuit of further integrating thermal media into soft robotics may be a challenging path.

While researchers have most often implemented actuators—and with a spectrum of function media—other robotic component types have notable gaps in media beyond thermal media. The data indicate that the field has relegated sensors to be strictly electronic or optical, yet Hughes et al. demonstrated (after our data collection) a fluidic sensor.^[588] We have not identified a reason why the output of soft sensors could not take the form of other function media, just as the fluidic tactile sensor has done. As for controllers, of the nine soft controllers that we observed in the literature, seven are electric; one is fluidic,^[481] and one is magnetic.^[491] A noteworthy point is that the lone fluidic controller quantified here obtained around 100 CPY. If soft roboticists desire further evolution of soft robots, integration of soft robotic components other than actuators and sensors should be pursued. Because current three- and four-component devices overwhelmingly employ electric and fluidic components, further development of electric and fluidic controllers seems attractive, and soft fluidic controllers offer perhaps the most enticing pathway towards the evolution of soft robots. Soft controllers, as evidenced earlier, achieved an aCPY increase as opposed to soft power sources' aCPY decrease over their respective rigid counterparts. Other soft fluidic controllers have been pursued recently and provide helpful starting points upon which soft roboticists can build.^[36,589–593]

Power schemes should also be developed to facilitate the untethering of soft robots. Chemical media offer a fruitful methodology to do so through electrochemistry and gas evolution reactions (e.g., combustion) as a transduction of chemical energy to electrical or fluidic media. In furthering electrical and fluidic media across all component types, we can then achieve the next significant advancement in soft robotic devices through reduced tethering, longer working durations, and more on-board capabilities for other robotic components. However, perhaps new technologies using other function media will be the key to progress as opposed to developing the currently more established fluidic or electrical media, such as involving the emerging magnetic media or resolving the high latency involved with thermal media.

4.2.4. Tethering

We delineate three tiers of a device's tethering: physically tethered, nonphysically tethered, and untethered. In the case of

Figure 6b, the device data are shown relative to robotic component data, but Figure 6c,d show the same device data relative to the overall devices. In other words, the former is filtered for soft robotic components only (as previous analyses were), but the latter two are filtered for entirely soft devices as opposed to soft robotic components.

A physical tether necessitates a tangible connection transmitting inputs, outputs, power, or some form of a function medium between the device and an immobile or less-mobile system. A key example includes using a permanently stationed supply (e.g., a wall outlet or compressed air from a building).^[589] A relatively stationary supply was also defined as a physical tether; a “mobile” cart or laptop computer are instances of this physical tether designation.^[551,594] A stationary base that anchors to a static location precluded a system's ability to be mobile.^[552]

Nonphysical tethering includes both “wireless” and “environmental” tethering. Wireless tethering includes anything in the electromagnetic spectrum as a method of delivery, such as electromagnetic solenoid interactions,^[587] lasers,^[485] and directed light.^[511] Solenoid interactions required close quarters of operation as their range is relatively limited. Lasers and lights, depending on the required concentration of such media, are typically more conducive to larger ranges of operation. Environmental tethering, on the other hand, entails a triggering mechanism that is ambient or within the bulk of the surrounding environment of the device's workspace. Some examples include pH levels in a solution,^[580,581] sunlight,^[511] and humidity.^[523] These environmental tethers were less stringent in terms of their workspace, as these ambient conditions could often be found or created beyond the laboratory. Wireless and environmental tethering are combined into the category of a “nonphysical” tether due to the overlap, ambiguity, and resulting subjectivity in delineating between the two categories. Two notable implementations of a nonphysical tether have been shown recently in publications on thermally driven soft devices, one harnessing light from a lamp (a directed medium) and the other relying on sunlight (a more ambient medium).^[577,595]

The third tethering type, untethered, describes self-sufficient devices without any external connections. Untethered devices were able to support the payload of their power supply or connected locally to a person who carried the power supply in a wearable or portable method (e.g., as part of a wearable robot).^[492,505,530,596,597] These devices are entirely mobile and have effectively zero dependencies outside of their encompassed device or user. As such, untethered devices were not relegated to a particular operating location or range and were entirely portable. A notable exception could occur if the device requires a form of tethered charging (e.g., a mobile device charging wirelessly or charging via a cord), but this qualification did not preclude an untethered categorization. As discussed below, untethered devices appear to be much more achievable with an onboard power source. Recent research exemplifies this notion with three different approaches: a combustion-driven jumping robot that chemically creates its own hydrogen fuel from liquid metal,^[584] a battery that can stretch and also bend at a radius of curvature of 10 mm,^[598] and a soft robot that traverses the surface of water propelled by a surface tension gradient via alcohol released from an onboard porous medium.^[585]

(a) **Tethering**

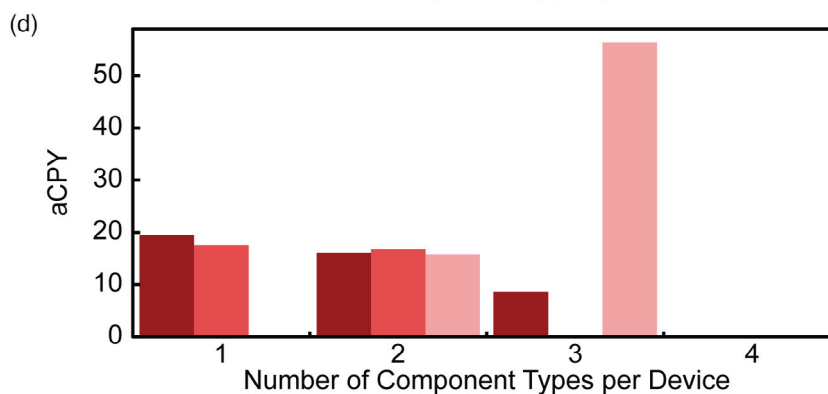
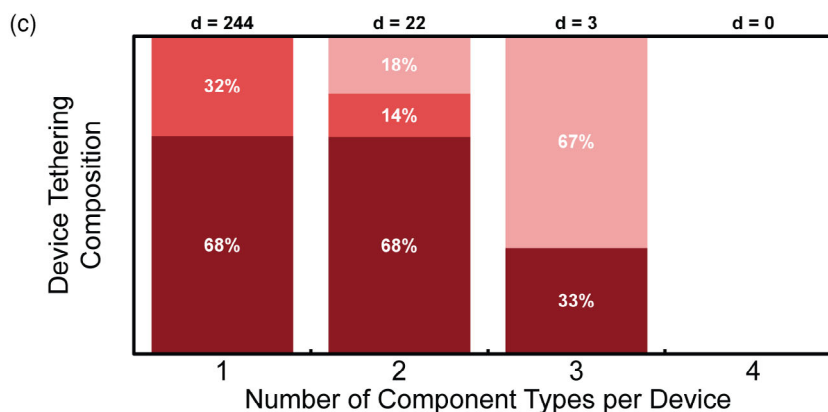
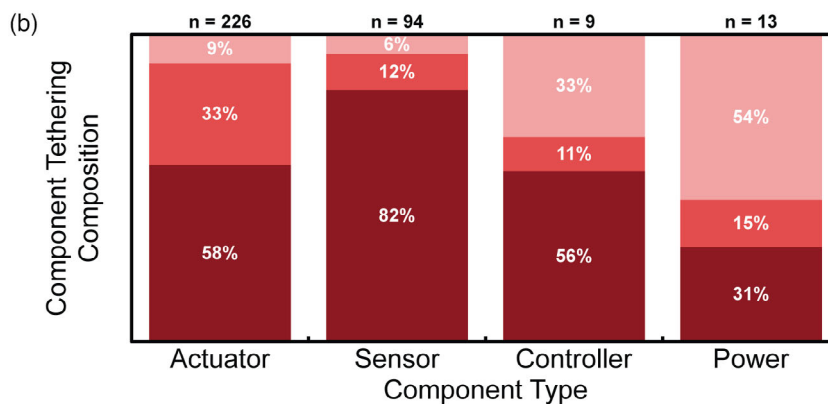
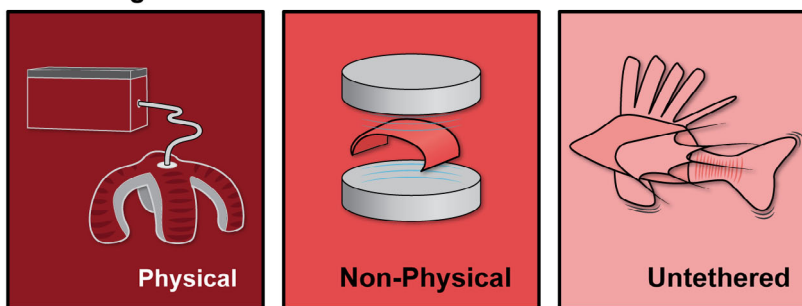


Figure 6. Device-level analysis. a) Tethering category examples and legend. b) Device tethering shown relative to the number of component types a given device contained. c) Device tethering shown relative to the type of component(s) found in a given device. d) Average citations per year (aCPY) for a device shown relative to the extent of tethering and corresponding number of component types.

Figure 6b shows a majority of physical tethering for all component types except a power-providing robotic component. This apparent anomaly is sensible when considering that the main limiting factor in tethering is the ability to produce or contain power to deliver to all other robotic components on the device. Once the device is powered and has media upon which robotic components can function, integrating other component types faces a reduced dependence on tethered external hardware or control.

Sensors show a significant dependence on physical tethering. This dependence can likely be attributed to a reliance on electricity as a function medium. The ability to read, decipher, and output meaningful information from electrical signals often requires more complex componentry than most soft robots support. Soft actuators share a similar fate with reliance on power delivery coming from large or rigid components (e.g., high voltages from power supplies required for dielectric elastomeric actuators, high pressures for fluidic functions delivered by compressors or accumulators, or high concentrations of other function media to cause macroscopic mechanical movements). Controllers, while similarly proportioned to actuators for physical tethering, exhibit a dramatic increase in their ability to be untethered relative to actuators. This increased share of untethered devices with controllers could be explained by addition of computational intelligence to a device that already has embodied intelligence. This added ability surely increases independence, but we note less of an increase than the addition of power sources. However, this plot again demonstrates the benefits soft robots would reap if researchers thoroughly investigate soft controllers and soft power sources in future work.

When looking at the device-level data in Figure 6c,d, there is a remarkable phenomenon: zero fully soft robots contained all four types of robotic components. More specifically, no four-component devices had more than two soft robotic components, and only three soft devices with three robotic components were entirely soft.^[481,599,600] Furthermore, zero one-component devices were untethered. The ability for a device to reduce its tether increases with the integration of more component types. The increase in component types enables better independence, but as the number of soft component types increases, researchers

seemingly have greater difficulties creating a fully soft device, as evidenced by the steep decline in number of devices, *d*. We acknowledge that untethered, fully soft robots could have eluded our data-selection algorithm due to either a lack of citations (perhaps due to the theorized difficulty in others creating and building upon such a device, manifesting in a citation rate below our cutoff value) or in the case that they were so recent that the publications had not gained enough recognition in terms of citations in subsequent work prior to our analysis; however, to the best of our knowledge, untethered, fully soft robots with all four component types have not been demonstrated to date.

Two of the three fully soft devices with three component types, those which were untethered, averaged a remarkable aCPY relative to all other fully soft devices (Figure 6d). Regardless of the number of component types, nearly all fully soft devices averaged a similar aCPY. An obvious exception is in the aforementioned three-component devices that are untethered. The data indicate that the integration of a fully soft device does not necessarily correlate with reception among researchers in the field beyond being in the top 10%, but when combined with a reduction in tethering, the impact could be substantial.

Our last content-based analysis combines the previously discussed function media and tethering analyses. We emphasize that the data shown in this data-driven review are not exhaustive, all-telling, or presented in the only way they could be visualized. In recognition of these points, we present an alternative method of visualizing our analyses through interrelating tethering of a component type to the same component type's function medium. **Figure 7** demonstrates the proportions of each analysis relative to a component type. There is an increasingly equal division of component types as tethering is reduced (from physically to non-physically to untethered). On the right side of the plot, electrical media visually dominate all other media, but fluidic media predominate actuators, while the remaining media are almost exclusively used with actuators.

4.3. Bibliometric Analysis

The final analysis presented in our data-driven review regards an overarching bibliometric analysis of the field from a top-down

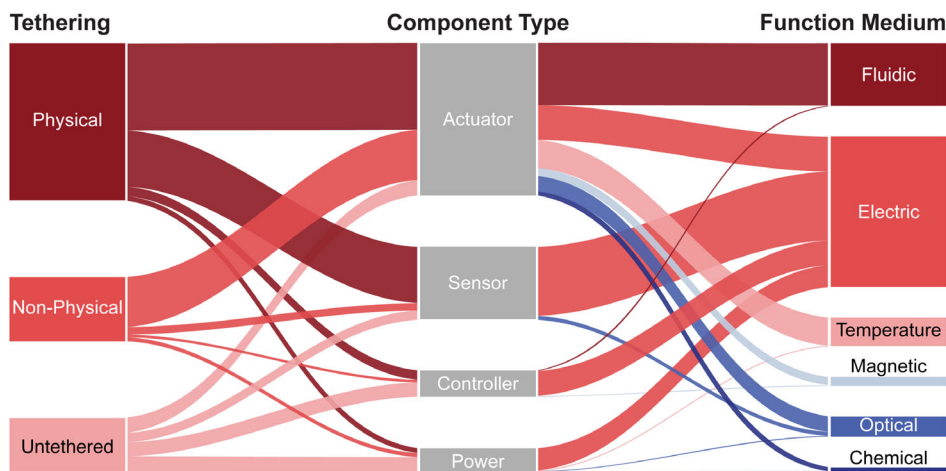


Figure 7. Alternate view of analyzed data: device tethering and function medium relationship with aggregated component types from publications in the top 10%.

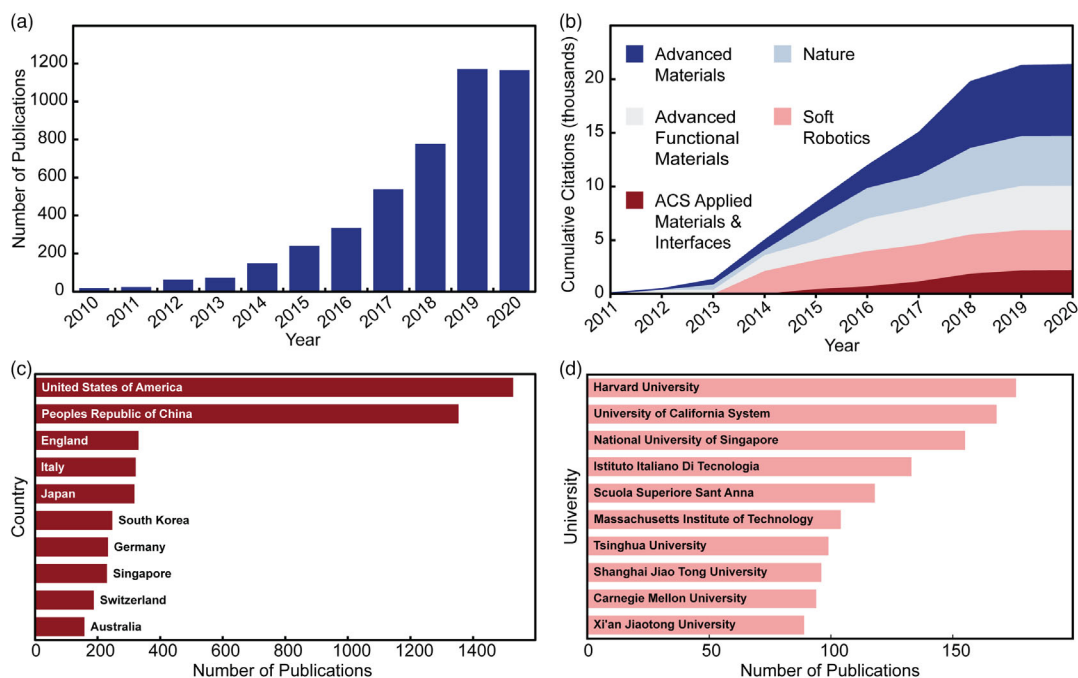


Figure 8. Bibliometric analysis. a) Total number of publications in soft robotics research for each year. b) Top five journals' running summation of citations for the past ten years. c) Top ten countries according to cumulative number of publications in soft robotics research. d) Top ten universities ranked by number of publications in soft robotics research.

view. **Figure 8a** demonstrates the exponential increase in publications of the soft robotics field with just a few publications in 2010 (and earlier) to over 1200 publications in 2020.

Figure 8b presents the five most cited journals of all 4609 publications contained within our analysis. *Advanced Materials* has maintained a strong position as the most influential and recognized soft robotics publication, followed by *Nature* and then *Advanced Materials'* sister journal, *Advanced Functional Materials*. Mary Ann Liebert's *Soft Robotics* has quickly gained traction as the dedicated soft-robotics-specific journal since its inception in 2014. The American Chemical Society's *ACS Applied Materials and Interfaces* follows as the fifth most cited journal.

The two remaining plots in **Figure 8** show the most published countries and universities. The USA and People's Republic of China both strongly lead as the first and second countries most published in soft robotics. Finally, **Figure 8d** indicates no overtly superior academic institution as a front runner, but Harvard University, the University of California system of schools, and the National University of Singapore have garnered recognition as the top three most published universities in soft robotics.

5. Conclusion

Our literature review presents a data-driven synopsis of the most recent decade of soft robotics, deviating from the typical format of a holistic review (many of which are from 2015 or earlier—and much has changed in the field over the past 5 years). We provide high-level insight for all 4609 publications resulting from a broad

search in the WoS databases. High-level analyses were conducted at the publication level and on the whole field. We provide an initial comparison of the top 10% sample relative to the remaining 90% (**Figure 2**) as well as an overarching bibliometric analysis of the field (**Figure 1, 2, and 8**). This generalized data provides perspective on the growth, tendencies, and trends of the field.

The cutoff for the top 10% was determined by a CPY metric, which allows the selection of works based on the collective intelligence of researchers within soft robotics. We show that the top 10% also reflects the majority of cumulative CPY as analogized by the Pareto principle (**Figure 1**). Low-level, detailed analyses were conducted at three different tiers for the top 10% most cited (and consequently most influential) publications. Through these analyses, we present the current state of the art, describe the methodologies to achieve these technologies, and identify areas where data are lacking that may reveal the next steps in evolving soft robots.

Our data-driven review is intended to institute a new and robust method of examining a field with both historical and forward-looking context, yet there are some limitations. Our broad search criteria were limited to WoS databases and included only documents containing some version of either "soft robot" or "soft device" in their title, keywords, or abstract; these constraints may have excluded works not indexed by WoS or works by authors who did not use these particular terms. We further detailed the limitations imposed by a top 10% threshold, as well as the limitations of expanding that threshold in **Section 3.1.1**.

Though our selection criteria are derived from a collective intelligence of the field, the very same field may have systemic biases pertaining to the subject matter or authors of a given

publication.^[106–108] Furthermore, our analysis of the technical subject matter of each publication introduces a degree of bias and subjectivity. Our analyses are presented with a filter for soft robotic components or overall soft devices (in the case of tethering), yet data on all components without regard for compliance is provided in the Supporting Information with sample sizes and data for all years (including those before 2010). As suggested by the incubation time of ≈ 2 years for a publication to reach peak influence, new research is likely underrepresented in the data, especially works initiating new directions within soft robotics. However, to combat this underrepresentation, throughout our discussion of results, we cited many recent publications that are innovative and exciting yet not accounted for in the top 10%.

There are, of course, many permutations in which one can present data such as ours. Moreover, the data can be presented in different visual techniques, as highlighted in our Sankey diagram (Figure 7) which deviates from the other plots shown throughout this review. Finally, our conclusions in this data-driven review are only some of the insights to be inferred and gleaned from the visualized data. Further examination and outside perspectives could yield deeper insight into the trends of soft robotics, providing more answers, or perhaps even more questions, on the future directions of the field.

Nevertheless, this work identifies several key areas for future inquiry. We present large gaps in the data on current research where new, exploratory investigations should be conducted. The investigation of robotic components beyond actuators (and, to an extent, sensors), such as controllers and power sources, will help soft robots approach autonomy and independence through a greater likelihood of being untethered. Implementation of new materials will broaden our available tools and assist in integrating soft robots into our everyday lives. For instance, textiles have hardly been seen in the top 10%, yet we use textiles every day in clothing, furniture, automobile interiors, blankets, toys, and more; upon further development of textiles in soft robots, there is an apparent and facile approach to integration for such devices directly into society.

Function media have not been explicitly addressed in a general sense for soft robotic components until this work. Further research should determine the ways in which different function media can be integrated between components. Understanding and documenting the benefits and drawbacks of various function media can help inform first steps in other investigations, whether in response rates, efficiencies, or intercomponent compatibility. We report a large reliance on specific medium-component combinations, such as fluidic actuators, electric sensors, and chemical power. We should explore if these common combinations of a given function medium and component type are simply suitable for single component types without intent to integrate with other robotic components. On the other hand, the argument could be made that these robotic components can be so well developed within their respective media that other robotic components can be easily integrated into the same device in future work.

Future research should probe these notions, which will perhaps spur ideation and culminate in seminal research. Thrusting the field of soft robotics into a position where it can go beyond our subdisciplines and impact other fields and society as a whole requires formative and groundbreaking

research. Such investigations are a necessity if we want the field to perpetuate through the next decade and beyond.

Our review quantitatively documents the historical and current trends of the field of soft robotics, yet this analysis is a projection of the field's predominantly academic stance. We foresee the advancement and maturation of soft robots impacting more than just academia through further societal adoption and consequent commercialization. We also anticipate the emergence of contributions from an increasingly wide array of research fields not yet directly involved with soft robotics. Such fields could include zoology, environmental science, psychology, fashion, sports science, video game development (e.g., augmented and virtual reality), aerospace engineering, and many others that are currently disparate from soft robotics. For instance, decades ago Harlow's "The Nature of Love" infamously explored the idea that compliant materials can emulate the comfort of a mother to fearful young primates;^[601] now, today's research has circled back to investigating the use of soft robots in psychotherapy. This example indicates how external research fields could introduce new directives, applications, and insights to further soft robotics beyond our outlined notions, especially as the field progresses toward more human-centric, biomimetic, and intelligent soft robots.

In summary, this data-driven review provides overarching themes and granularized insight into the field with a focus on leading soft robotics into promising future work based on an informed snapshot of the past decade's methodologies. Future directions of this work could include a larger population size with more search terms; a more lenient cutoff for inclusion of the most influential works; more detailed analyses; text-based or machine learning algorithms employed to synthesize our field (or any field); increased interrelations of the content-based data with other quantifiable metrics; or other content analyses, such as fabrication methods or applications of each device. Through this review, we intend to provide inspiration for researchers working in soft robotics and researchers reviewing other fields, with the ultimate goal that work within each field will not only progress but also generate broader impacts for others through answering introspective questions about its current state and subsequent future directions.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

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bibliometric analysis, compliant mechanisms, Pareto principle, robotic components, soft devices

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