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FY24 Soft Robotics Report

Jennifer C. Case
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Abstract

Advances in robotics research have begun incorporating non-traditional materials, such as elastomers and smart materials (e.g., shape memory alloys, responsive hydrogels, etc.), into the structure of robots giving them new capabilities. This inclusion of soft materials has highlighted a number of metrology challenges related to highly deformable objects or systems. The purpose of this report is to identify the measurement challenges faced by the soft robotics community and propose NIST research to help support these challenges. To accomplish this goal, we surveyed literature including proposed roadmaps for the field, engaged the community through workshops, and engaged industry. This report summarizes challenges for the community and industry and provides a detailed survey of material testing and modeling, including limitations in current practices. We conclude by proposing steps that NIST can take to support metrology within the field which will, in turn, improve industry's ability to take advantage of this new technology.

Keywords

Roadmap; Soft Robotics

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Author Contributions

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1. Introduction

Robotic technologies have been demonstrated to play key roles in manufacturing across the globe, and are primed to assist with more challenging tasks in industry applications in healthcare, service, and defense. In 2011, several U.S. agencies including the National Science Foundation (NSF), U.S. Department of Agriculture (USDA), National Institutes of Health (NIH), Department of Energy (DOE), National Aeronautics and Space Administration (NASA), and Department of Defense (DOD) funded the National Robotics Initiative (NRI), a program that targeted the development of collaborative robots [1]. This funded research in the area of collaborative robots to advance sensing, perception, robotic design, materials, modeling, robotic analysis, human-robot interaction, planning, and control [2]. Subsequent programs, NRI 2.0 and 3.0, addressed scalability, customizability, lowering barriers to entry, societal impacts, robot integration, and safety [1, 3]. NRI funding also helped accelerate research in soft robotics, a field which focuses on building robotic systems from soft materials.

By integrating soft and flexible materials into robotic systems, soft robotics expands the capabilities of robotic systems. Soft robotics is an emerging field of research in robotics, and is key to solving problems that are challenging for “traditional”[1] robotic systems. For example, the compliant material properties of soft grippers can simplify handling of fragile materials, such as food or fluid-filled bags, and improving grasp stabilization to further enable automation within manufacturing. Handling these types of materials with common robotic grippers requires sensing and carefully-designed controllers, whereas pneumatically-driven soft grippers have been demonstrated to work with simple binary open-close functionality [4]. Additionally, soft robotics is expected to have a significant role in creating human-robot collaborative spaces. Specifically, soft robot technologies are expected to be integrated directly into the structures of robots increasing safety via softening impacts and to be used as physical artifacts for evaluating, verifying, and validating the contact safety of rigid robots [2]. Moreover, soft robotics is primed to expand into more human-centric domains, including biomedical applications, consumer robots, wearable technologies, and prostheses.

1.1. Why is Soft Robotics Hard?

To understand the challenges of implementing and integrating soft robotics, one must first understand how robots and other integrated systems are created. Robotic and mechatronic systems are an integration of mechanical, electrical, information, and computer systems to perform tasks automatically [5]. The mechanical and electrical systems used in traditional robotics are built from modular components made from rigid materials, particularly metals

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[1] The overall design of industrial robots have not changed significantly since their introduction in the 1960s. While new materials and drive technologies have significantly impacted performance and cost of robotic solutions, the robots are still effectively motors driving rigid links to position a tool in a specific place and orientation in Cartesian space.

and plastics. There are three principal aspects of robotics that are benefited by the structures of traditional robotics: design, modeling, and control.

In terms of design, traditional robotic systems are assembled by selecting various structural components (e.g., sensors, actuators, and end-of-arm tooling) based on the robot's intended application and capabilities, which are then integrated into a complete manufacturing system. There are additional, well-known design requirements and component limitations to assist with the selection of components (e.g., motors have torque limits, and materials used in links have known mass, strength, and rigidity). Additionally, the design of these robots is assisted via modeling and simulation software, enabling manufacturers to establish the expected performance and capabilities of the robots before they are ever built.

In terms of modeling, there are numerous assumptions built into models of traditional robotic systems based on their materials. Rigid materials are typically assumed to undergo no deformation[2]. This assumption simplifies stress analysis of the mechanical structures by enabling the principle of superposition where the single and total deformation of a structure is calculated based on a composition of "building" blocks and linear elastic material modeling.

In terms of control, many traditional robots are designed such that the control is decoupled. Often, this means that each joint motor directly controls or impacts a specific degree-of-freedom (DOF) independently of the other joints. Additionally, most manufacturing robots operate in controlled environments, and will typically not experience unexpected interactions within that environment[3].

In a striking contrast with traditional robotics, the field of soft robotics effectively combines the aspects of mechanical design, electronics, information science, and computers with the addition of material science. Because soft robots incorporate soft materials, which experience continuous and large deformations under a myriad of conditions, many of the modeling assumptions, such as the principle of superposition and linear elastic material modeling, may no longer be valid or their use comes at the cost of accuracy. Additionally, actuators used in soft robotics may generate complex motions including twisting, elongation, and bending that are not easily predictable, and soft sensors may respond to multiple stimuli, which will complicate control of soft robots. By relaxing the rigidity requirement of the structural components, the assumptions and capabilities that have driven robotics

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[2] All materials are subject to some bending or warping along the lengths of the robot's segments–or backlash at the connecting joints–due to external forces such as gravity. This does impact the uncertainty of the actual location of the tool flange at the end of the robot's kinematic chain. The design of the robots' structural components are intended to provide as much rigidity as possible without making them overly brittle.

[3] Unexpected changes in the environment, including parts or workpieces being out of tolerance or presented in a way the application did not intend, often result in damage to the robots, tools, and parts. If people are also present, these interactions may also result in injury or death. As such, the underlying expectation is that humans and robots are strictly separated in the workplace by means of physical barriers. Recent technology advancements have enabled these barriers to be removed, but the end user is ultimately responsible for conducting a thorough risk assessment and minimizing the risks to acceptable levels.

research and development for more than half a century may no longer be applicable.

As such, there are many challenges surrounding the integration of soft materials that must be addressed to help realize the full potential of this robotic sub-field.

1.2. Report Objective

In this report, we summarize efforts to gauge the current state of metrology within the field of soft robotics. These efforts have consisted of literature surveys and discussions with the soft robotics community and industry to identify challenges they are facing and to identify the existing state and limitations within a key building block of soft robotics: modeling materials.

2. Community Perspective

The soft robotics community spans academia and industry and works towards creating materially soft robots that expand the capabilities of robotics as a whole. The soft robotics community has summarized challenges and opportunities in the field across numerous roadmaps [6–10] and workshop reports [11]. In this section, we accumulate the existing challenges across these roadmaps and reports into six areas: design, modeling, control, materials, sustainability, and reporting.

2.1. Design

System design determines not only its behavior but also how the system can be controlled. Current design methodologies used in soft robotics follow those of traditional systems and focus on developing individual components (e.g., sensors, actuators, etc.) separately and then integrating them into a full robotic system. Relative to soft robotic systems, this approach must also consider that the behavior of many components will change when they are integrated into a structure and that behavioral change may depend on the structure itself. For example, many soft strain sensors are also responsive to pressure [12], which means the response from “strain” sensors built into a structure may not be purely due to changes in strain if the sensor is also experiencing pressure or compression. The field would benefit from new design methodologies or tools aimed at developing systems with interdependencies between components, including actuator, sensor, and power selection and integration.

To assist in the design and development of soft robots, component-level advancements are needed. Various components (e.g., pumps, valves, batteries, energy harvesters) need soft alternatives that are small, cheap, and energy efficient. Actuators can be improved in terms of efficiency, power consumption, and response time. To improve soft sensor technology, alternative conductive materials and advances in electrical interfaces are necessary. Both sensors and actuators would benefit from advances in modeling to predict behavior and the identification of performance metrics to select suitability to support the system under development during the design process.

2.2. Modeling

A key component to the development of robotic systems is modeling. Accurate modeling can enable design optimization to help select robot materials and geometries. Modeling can also enhance control of soft robots via better feedforward models, off-line testing of feedback models, and generation of training data for artificial intelligence/machine learning (AI/ML) based controllers.

For soft robotics, there are a number of modeling challenges. At a fundamental level, improvements are needed in terms of modeling materials ranging from non-functionalized materials, such as elastomers and foams, to functionalized materials, such as variable stiffness materials and shape memory polymers. Most finite element modeling (FEM) software can generate hyperelastic material models based on empirical data to capture the nonlinearities seen in soft material stress-strain curves. However, these models do not account for viscous material behavior, changes in material properties due to temperature, humidity, or strain rate, nor do they account for behavior of functionalized materials that are responsive to various stimuli, such as temperature, ultraviolet (UV) light, asymmetrical compression-stretch stress response, etc. While some material models do integrate certain physical characteristics, a majority of these characteristics go unaddressed due to lack of data. Improved material models accounting for plasticity, viscoelasticity, viscoplasticity, wear, and multiphysics (e.g., mechanical, electrical, thermal, chemical) and integration of those models with existing modeling software are vital for long-term and future uses of soft robotics.

In addition to accurately modeling the materials themselves, advances are needed to model full robotic systems made from multiple materials and complex geometries operating in environments. Modeling contacts between materials within a structure, modeling self-collisions, and modeling contacts between a soft robot and the environment are additional modeling challenges for soft robotics that need to be solved.

2.3. Control

A key component to robotic systems is controlled behavior. Developing control strategies for soft robots is greatly helped by having accurate models and, in some cases, real-time models, which may require trading model accuracy for computational speed. Feedback control strategies rely on being able to accurately sense various states of the system.

For soft robotics, control strategies are needed to control non-linear, time-varying systems where various aspects of the system may be varying on different time scales (e.g., material property changes in a foam over time may differ from the response time of a shape memory polymer deforming the foam). Control strategies are also needed to control instabilities, such as snap-through instabilities, and coupled systems where there are interdependencies of components.

In addition to developing control strategies, advances in sensing and system design are needed to be able to measure and control the state of the robot. Sensors are needed to measure deformation of the robot and forces experienced by the robot. For self-repairing or self-healing systems[4], sensors to measure damage are necessary to trigger a non-automatic healing method, such as applying heat or UV light. Some actuators can also provide sensory feedback, but further work is needed to determine how to best use or integrate that feedback.

2.4. Materials

The choice of materials used in the construction of soft robots is indelibly linked to the final performance of the completed system, but the actual selection of the materials is often determined by the designer's familiarity of and accessibility to said materials. For example, "traditional" materials, such as aluminum and steels, have well-defined material properties that have been built into many modeling software systems. Currently, there is no widespread or integrated equivalent in commercial modeling solutions for soft materials and, although some soft material databases have been created [13, 14], these databases may be missing relevant information or properties necessary for modeling soft robots.

In the case of soft robotics, there is a need for test methodologies that assist in (1) defining various material properties and (2) identifying parameters for material models across bulk materials, such as elastomers, functionalized materials, anisotropic materials, and self-healing materials.

Additionally, tools are needed to help identify materials with specific properties, such as oil- and chemical-resistance, high deformability, waterproof, and negligible non-linearity, hysteresis, and viscous behavior in deformation region. Tools are also needed to create new materials with desired properties and functionalities. The use of machine learning algorithms is anticipated to assist in this regard, provided quality training data and reinforcement strategies.

2.5. Sustainability

There has been increased concern about the impacts of e-waste on the environment and, as a result, sustainability is an emerging aspect of both traditional and soft robotics. For soft robotics, there is increased interest in using biodegradable or recyclable materials/components and using more environmentally-friendly manufacturing techniques, such as additive man-

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[4] Researchers have demonstrated systems capable of repairing damages to soft materials via embedding beads of uncured materials that will automatically cure and repair any minor damage. Other self-healing methods require an external stimulus to repair any damage.

ufacturing, that reduce the use of solvents or molds[5]. However, these technologies are under-developed and advances need to be made to make them practical alternatives to their unsustainable counterparts.

2.6. Reporting

There have been calls in soft robotics to improve reporting practices both for repeatability and comprehensibility. When reporting fabrication or test methods, key details are sometimes left out making it hard to recreate the component, system, or test. These details may also obscure what is actually being reported as readers either consciously or unconsciously apply assumptions to fill in the missing details. For certain publications, page limits can affect the level of details; however, to overcome this limitation, authors can host more detailed methodologies and data on online platforms, such as Github or GitLab. When reporting characterizations of various components, such as actuators, authors have a tendency to report results that show their components in the best light while failing to report other important properties, which makes it hard to compare components and select the most appropriate one for a given application. It has been proposed that certain metrics, such as energy density, energy efficiency, and lifetime be commonly reported for actuators, although community-wide consensus on metrics is still pending.

3. Industry Perspective

There is active interest in utilizing soft robotic technology across a wide array of applications including collaborative robot systems, manufacturing, wearable devices for augmented reality or virtual reality, healthcare, environment monitoring, defense, and automotive applications [15]. However, there are hurdles in the way that are slowing adoption of these technologies.

One major hurdle facing producers of soft robotic technologies is the ability to communicate with stakeholders about the technology capabilities. Industry standards have been established to communicate capabilities and performance of established technologies, such as robot arms. Oftentimes, these industry standards either do not apply to or do not highlight the benefits of soft robotic technologies, which complicates communication with stakeholders.

Producers of soft robotic technologies would benefit from industry-trusted metrics and test methodologies that can be used to thoroughly communicate their technologies' capabilities. Broadly, metrics and test methodologies are needed to verify that soft robots are safe around humans and robust. Specifically, some example measurement problems include measuring

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[5] Environmentally-friendly manufacturing practices are generally those that minimize impacts on ecosystems and the environment by limiting waste and leveraging sustainable materials. While additive manufacturing processes typically reduce the amount of waste created during the manufacturing process, it is not waste-free. Unused materials such as plastic filaments, and toxic metal powders and resin baths may see limited reuse and recycling as part of the manufacturing process.

compliance, damage to surfaces and the robot after falling from a height, contact pressures and forces between multiple soft interfaces, conformability, lifespan, general wear of soft materials, and compactability among others.

In addition to these metrology-focused challenges, there are still fundamental challenges in creating soft robotic solutions themselves. Answering these fundamental challenges will likely lead to more metrology-related problems. One driving limitation in building soft robots is finding appropriate actuators for them, especially lightweight, energy efficient actuators for untethered soft robots. Many common actuators in soft robotics either rely on heavy off-board equipment, which will limit robot mobility, or have high energy draws, which limits battery life.

Another key issue affecting soft robotics is system integration. Many soft components are typically designed, developed, and tested independently; while independent testing will provide the behavior of that component in isolation, that behavior does not necessarily translate when integrated into a soft system since the behavior will be influenced by the structure of the system and the behavior of other components. When various soft components are integrated into a system, they may need to be redesigned and retested on a systems-level. Another hindrance of system integration is wiring. Soft sensors typically connect to traditional wires in order to take measurements and this interface from soft-to-hard is often a point of failure in the system, especially if stress is applied to the interface.

Another challenge facing soft robotics is related to state estimation and controls. Adding sensors to soft robots is challenging, especially when trying to measure the state of the robot. State estimation of soft robots lags behind state estimation of traditional robots which, in turn, affects the ability to control soft robots. The ability to control a robot is key to accomplishing the task the robot is intended to perform.

4. Materials Infrastructure

To understand the current practices of measuring materials used for soft materials, reviews were conducted of (1) existing ASTM International material standards for rubbers, rubber-coated fabrics, and elastomers, (2) existing standards used by elastomer manufacturers when reporting material properties of cured elastomers, (3) test methodologies used by soft roboticists, and (4) material models used by soft roboticists. The material component is arguably the most defining characteristic of soft robots, and as such warrants the most discussion. The results of each of these reviews are discussed alongside the limitations of current practices.

4.1. Mechanical Performance Standards for Rubbers and Elastomers

This review focuses on measures to characterize mechanical properties and does not address the broad spectrum of material- and application-specific standards for rubbers and elastomers (e.g., flexible adhesives, seals for automotive applications, and regulations for food safety), as these are out of scope. Table 1 lists standards that cover a range of mechanical properties of these materials. There are additional standards for taking measurements under various conditions which are shown in Table 2.

4.1.1. Limitations of the Standards Landscape

It is important to note that the standards specified in Tables 1-2 were developed primarily for specific application domains (e.g., vulcanized rubbers for automotive tires), and no standards have been developed specifically to support soft robotics. As a consequence, the existing standards landscape does not fully encapsulate the needs of material-focused measurements for soft robotics. As a specific example, the standards for tension involve tests that are pull-to-failure. Such test methods do not capture or evaluate data on how the stress-strain curve changes due to repeated cycling. Since soft robotic technology is intended to undergo cycling, that information is vital for understanding the material behavior.

Additionally, no standards exist to support the validation of material models for use in simulation. Simulating soft materials enables computed-aided design of soft robotic systems, which could speed up adoption of these technologies as well as enable those unfamiliar with soft robotics to integrate the technology into their own designs.

4.2. Standards used by Elastomer Manufacturers

Elastomer manufacturers leverage existing standards to take and report measurements of various properties of their materials. In this report, we only consider standards used by the manufacturers to measure properties of the cured elastomers[7]. Table 3 shows standards used to measure four properties that were reported across five leading elastomer manufacturers:

- Shore hardness: Measuring the depth of penetration of a standardized “indenter” (usually a steel tip with known material properties) pushed into the surface of a material with a known force, as specified by ASTM D2240 [29]. Shore hardness may be measured either by the initial indentation, or the indentation created after a set period of time.
- Tear resistance: Measuring the ability of a material to withstand the effects of tearing. The tear resistance (or tear strength) can be evaluated based on tearing of an existing cut (ASTM D412 [16]), or the formation of a new cut (ASTM D624 [30]).
- Tensile strength: Measuring the ability of a material to withstand breaking by being stretched or pulled.

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[7] The curing process for elastomers involves a catalyst such as ultraviolet light or a chemical hardener that fundamentally alters the chemical and material properties of the elastomer base. Both the base and the catalyst may be evaluated using a number of different standardized test methods. However, these measurements are not necessarily directly correlated with the material properties of the cured elastomers, as different mixing ratios of base and catalyst can result in vastly different properties of the cured elastomers.

Table 1. ASTM Standards for mechanical properties of rubbers, rubber-coated fabrics, and elastomers.

Mechanical Property	**Standard**					
Tension data / ultimate elongation / tensile strength	ASTM D412 [16]	ASTM D1456 [17]	ASTM D751 [18]			
Compression data	ASTM D395 [19]	ASTM D575 [20]	ASTM D945 [21]	ASTM D1229 [22]	ASTM D6147 [23]	ASTM D6049 [24]
Dynamic data	ASTM D5992 [25]					
Shear data	ASTM D945					
Stress relaxation	ASTM D6147	ASTM D8363 [26]				
Hardness	ASTM D531 [27]	ASTM D1415 [28]	ASTM D2240 [29]			
Tear strength	ASTM D624 [30]					
Vapor transmission	ASTM D814 [31]					
Electrical conductivity	ASTM D991 [32]					
Torsional stiffness	ASTM D1053 [33]					
Retraction	ASTM D1329 [34]					
Dimensional changes during liquid immersion	ASTM D1460 [35]					
Resilience	ASTM D2632 [36]	ASTM D7121 [37]				
Dimensions	ASTM 3767 [38]	ASTM D751				
Rheological properties	ASTM D6601 [39]					
Glassy transition temperature	ASTM D7426[6] [40]					
Air retention	ASTM D5193 [41]					
Fracture due to bending	ASTM D2136 [42]					
Waterproofness	ASTM D3393 [43]					
Brittleness	ASTM D2137 [44]					
Mass	ASTM D751					
Bursting strength	ASTM D751					
Puncture resistance	ASTM D751					

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[6] Withdrawn 2022.

Table 2. ASTM Standards for various conditions under which to measure rubbers and elastomers.

Condition	Standard	
Low Temperature	ASTM D832 [45]	ASTM D3847 [46]
Room Temperature	ASTM D1349 [47]	
Making samples from existing products	ASTM D3183 [48]	

Table 3. Common properties reported by elastomer manufacturers and their associated standards.

Property	Standard		
Shore hardness	ASTM D2240 [29]	DIN 53505[8] [49]	DIN ISO 48-4 [50]
Tear resistance	ASTM D624 [30]	DIN 53515[9] [51]	ISO 34-1 [52]
Tensile strength	ASTM D412 [16]	DIN 53504 [53]	ISO 37 [54]
Elongation at break	ASTM D412	DIN 53504	ISO 37

- Elongation at break: Measuring the amount a material stretches before breaking while being pulled.

4.2.1. Limitations of the Manufacturer-Specified Standards

While useful from a static materials perspective, the properties reported by manufacturers are insufficient for soft roboticists to understand the dynamic properties of materials, or used to generate a material model to determine whether a given elastomer is practical for the systems being designed or the intended applications. These properties capture single data points in the material response and fail to fully encapsulate the often non-linear and time-dependent nature of soft materials. Additionally, the material properties discussed in Section 4.2 often assume specific testing conditions[10], and are unable to capture the fully dynamic world in which soft robots operate.

Not having well-measured materials often leads soft roboticists to heavily rely on a small number of familiar elastomers. This, in turn, results in robotic system designs that are indelibly tied to specific elastomer products, and cannot be generalized, expanded upon, or recreated by other laboratories. Moreover, the specific conditions and early trials that resulted in the dependency on specific elastomers are not generally documented, but only shared with contemporary associates at the time of testing. Such "tribal knowledge" is therefore lost as the degrees of separation increase.

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[8] Superseded by DIN ISO 48-4, though some manufacturers still present specifications using this standard.

[9] Superseded by ISO 34-1.

[10] Such conditions include specific mixing ratios of base and catalyst, curing time, and environmental conditions at the time of testing.

4.3. Test Methods Used by Soft Roboticists

While soft roboticists measure various material properties, this report focuses specifically on test methods for collecting stress-strain data due to its importance for structural simulation. Researchers have leveraged test methods from standards (ISO 37 [54], ASTM D412 [16], ASTM D6147 [23], ASTM D395 [19], ASTM D575 [20], NFT 46-002 [55]) and have also leveraged material performance tests that have not yet been standardized. Common tests include:

- Pull-to-failure tensile testing: straining a material sample (usually in a dog-bone shape as specified in ASTM D412) axially at a constant strain rate until the sample breaks. This test shows the relationship between stress and strain when the material is strained along a single axis.
- Tensile testing to a specified strain: straining a material sample axially at a constant strain rate until a certain sample strain or machine displacement (e.g., the distance between the grippers) is reached. This test also shows the relationship between stress and strain when the material is strained along a single axis.
- Cyclic tensile testing: straining and un-straining a material sample axially at a constant strain rate to a certain sample strain or machine displacement for a specified number of cycles. Cyclic testing may involve moving through a series of sample strains or machine displacements. This test shows how the relationship between stress and strain evolves over many cycles when the material is strained along a single axis.
- Stress relaxation at a single strain: a material sample is strained axially at a rapid strain rate to a specified sample strain or machine displacement and held in place for a specified time. This test shows how the stress in a sampled strained along a single axis changes over time, which provides insight into the viscous or time-dependent behavior of the material.
- Stress relaxation at multiple strains: a material sample is strained axially at a rapid rate to specified sample strains or machine displacements and held in place for a specified times at each strain or displacement. This test shows how the stress in a sampled strained along a single axis changes over time, which provides insight into the viscous behavior of the material.
- Stress recovery: a sample undergoes a test, such as a tensile test to a specified strain, and then is allowed to relax for an extended period of time (e.g., hours to months) upon which time it is tested again under the same circumstances. This test provides insight into the viscous or time-dependent behavior of the material on a long time scale.
- Biaxial testing: straining a material sample equally across a plane at a constant strain rate. This test also shows the relationship between stress and strain when the material

is strained along a plane.

Handouts from Axel Products and a book by Jorgen Bergstrom discuss specific tests that can assist in defining material models for finite element analysis software [56–58]. These tests include: tensile testing, shear testing, compression testing, biaxial testing, and volumetric compression testing.

4.3.1. Limitations of Roboticists' Test Methods

One key issue seen in the literature is incomplete reporting of test methods and testing equipment. This makes it difficult to fully understand and trust the reported results, to replicate the tests, or to extend or advance the research. As such, research along certain vectors is frequently limited to a single laboratory, and many of the conclusions and best practices developed during the original research must be re-acquired by subsequent researchers.

Of particular concern is the insufficient documentation of the equipment leveraged (or even *not* used) during testing, including the equipment's calibration, testing conditions, and sampling methodologies. A partial list of important equipment details that are often missing from publications is provided below along with explanations of their importance:

- **Extensometer.** Extensometers are used to measure changes in the length of objects, and are commonly left out of testing which results in inaccurate measurements for soft materials. In general, when materials deform, the entire structure held between the grippers deforms. For rigid materials, like metals, a dog-bone sample is used to encourage deformation in the narrow region and the total deformation is generally small before failure occurs. For this reason, it is assumed that the deformation between the grippers closely matches the deformation in just the narrow region of the sample. While it should be noted that this assumption is inaccurate even for metals, the degree of inaccuracy is considered small enough to be negligible. *This assumption does not hold for soft materials and can result in high inaccuracy in reported material properties.* By reporting strain as the displacement between the grippers rather than the actual displacement of the sample, a material will appear softer than it actually is, which will affect model accuracy, as demonstrated in Figure 1.
- **Load cell.** Load cells measure induced forces, torques, pressures, tensions, and compression through an elastomer sample. Load cells can be based on strain gauges, pneumatic or hydraulic pressures, capacitance variation, piezoelectric voltage induction, or optical deformation. Different load cell designs are optimized for different measurements (e.g., strain gauges are typically used for measuring static loads, while piezoelectric cells can only be reliably used during high-frequency changes in loads). The specifications of these load cells are occasionally not reported, which makes it impossible to evaluate whether the reported data is affected by the accuracy of the load cell. When testing materials, it is desirable to have an appropriately sized load cell for the testing. While there is some forgiveness in load cell accuracy if an over-

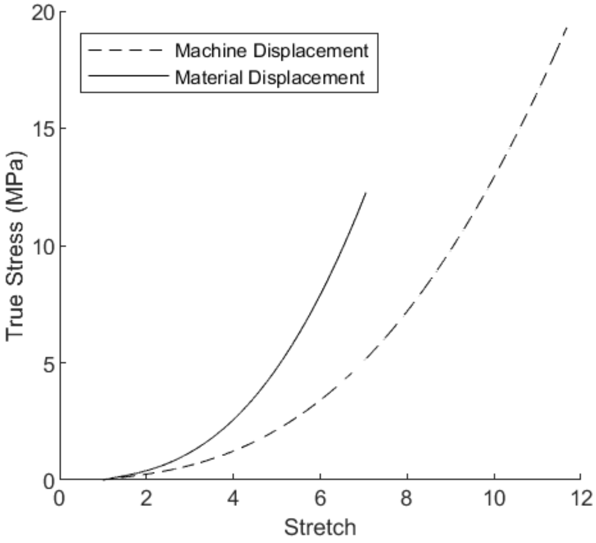

Fig. 1. Example stress-stretch data for a single material sample during the same test demonstrating the difference between using the displacement reported by the materials testing machine and using the actual material displacement. Stretch (λ) is the ratio of the current length (l) of a sample over its initial length (l_0): $\lambda = l/l_0$.

sized load cell is used, when very large load cells are used to test soft materials, it can affect the accuracy of the reported values. Additionally, factors such as load cell mounting, prior overloading, or mechanical or electrical damage will impact the accuracy of measurements. While the trend caught by the load cell may *appear* accurate, the values themselves may be off, leading to inaccuracies if the data is used to model materials. For example, using a 50 kN load cell with an accuracy of ±100 N is likely going to be insufficient for measuring soft materials.

- **Grippers.** The mechanical components used to “grip” the elastomer samples during testing are commonly not reported during description of the experimental test setup. While this omission may seem trivial, it is relevant for understanding the reported results. There are specialized grippers for rubber-like materials that self-tighten, and the use of such grippers is encouraged but not strictly required. Certain grippers can lead to slippage during testing, which can exacerbate results if no extensometer is used.
- **Material testing machine.** Also known as “universal testing machines” and “material test frames,” material testing machines are a catch-all term for test apparatuses that are used to measure tensile and compressing strengths of materials. Some manufacturers will incorporate additional sensors and tests to distinguish their products on the market. As such, some material testing machines may also assess tearing, peeling, bending and deformation, and external force and thermal responsiveness.

> Occasionally, exact models of materials testing machines are not reported. Different equipment models have different capabilities and measurement resolutions and, thus, exact models should be reported to fully explain the test methodology. Some material testing machines are also purpose-built for specific applications and materials, and may not necessarily be appropriate for soft robotics.

When reporting test results in terms of stress-strain, it is important for researchers to specify whether they use engineering or "true" stress and strain. Engineering stress and strain are typically used in analyzing materials that undergo small deformations, and incorporate several assumptions that are impractical for materials undergoing large deformations. The calculations for engineering stress and strain are given by

$$\sigma_{eng} = F/A_0, \tag{1}$$

$$\varepsilon_{eng} = (l - l_0)/l_0 = \lambda - 1, \tag{2}$$

where σ_{eng} is engineering stress, F is force, A_0 is the undeformed cross-sectional area, ε_{eng} is engineering strain, l is deformed length, l_0 is the undeformed length, and λ is the stretch ratio ($\lambda = l/l_0$). Eq. 1 shows that engineering stress assumes negligible change in cross-sectional area. In contrast, true stress does not have this assumption; true stress is calculated by

$$\sigma_{true} = F/A = \sigma_{eng}\lambda^{2\nu}, \tag{3}$$

where σ_{true} is true stress, A is deformed cross-sectional area, and ν is Poisson's ratio[11]. If incompressibility of a material is assumed (i.e., $\nu = 0.5$), Eq. 3 simplifies to $\sigma_{true} = \sigma_{eng}\lambda$.

In general, it is preferable to use true stress and stretch for soft materials that undergo large deformations because the assumptions of engineering stress and strain–such as constant cross-sectional area–do not hold for large deformations. This may result in significant differences between the engineering and true stress values, as is illustrated in Fig. 2. However, there are a couple of exceptions: (1) it is possible to convert from engineering stress-strain to true stress and stretch and (2) some software systems expect engineering stress and strain to calculate material models and, thus, providing true stress and strain will result in inaccuracies. Regardless, specifying which stress and strain is being reported adds clarification about the data being reported. Moreover, stating the assumptions used in the stress and strain model enables reproducibility and replicability of research.

4.4. Materials Models used by Soft Roboticists

Having accurate material models is necessary to properly simulate behavior of soft robots. In the literature, various classical linear elastic models have been used by researchers such as Neo-Hookean [59], Arruda-Boyce [60, 61], Mooney-Rivlin [62, 63], Yeoh [64–66], and

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[11] Poisson's ratio is the ratio of the change in the width to the change in its length. Effectively, Poisson's ratio is a measurement of a material's resistance to compression under load.

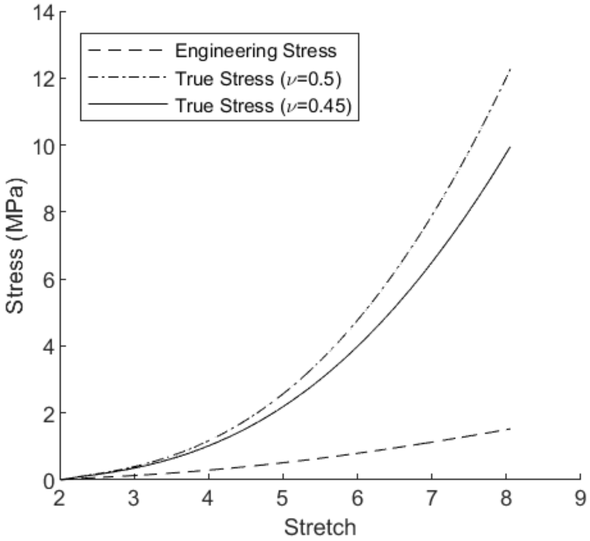

Fig. 2. Stress-stretch data from the same material test demonstrating the difference between engineering and true stress-strain as well as different true stress calculations.

Ogden [67] to approximate the behavior of elastomers. Other models that were considered, but ultimately not utilized, include Polynomial [68], Gent [69], and Van-der-Waals [70].

To develop these models, researchers generally take one of several approaches, including:

1. relying on an elastic modulus values from company-reported data,
2. relying on models and assumptions from similar published literature not originating from the manufacturer,
3. using sporadic trial-and-error tests to estimate and refine material parameters based on visual comparisons of how the robot moves between the simulation and reality,
4. collecting experimental data to generate numerical (e.g., machine learning) or static models, or
5. using a method that was not documented sufficiently.

4.4.1. Limitations of Roboticists' Material Models

Regardless of which method described in Section 4.4 is used to develop the models used by soft roboticists, each approach has some limitation. Obviously, reporting incomplete models (item 5) is not recommended. Using trial-and-error to estimate material model parameters (item 3) results in a model that may only be applicable to the specific use-case under which it was developed and is questionable in terms of accuracy if only qualitative comparison is used. Using a company-generated modulus (item 1) may result in an inaccurate material model since elastomers tend to only exhibit linear stress-strain curves up

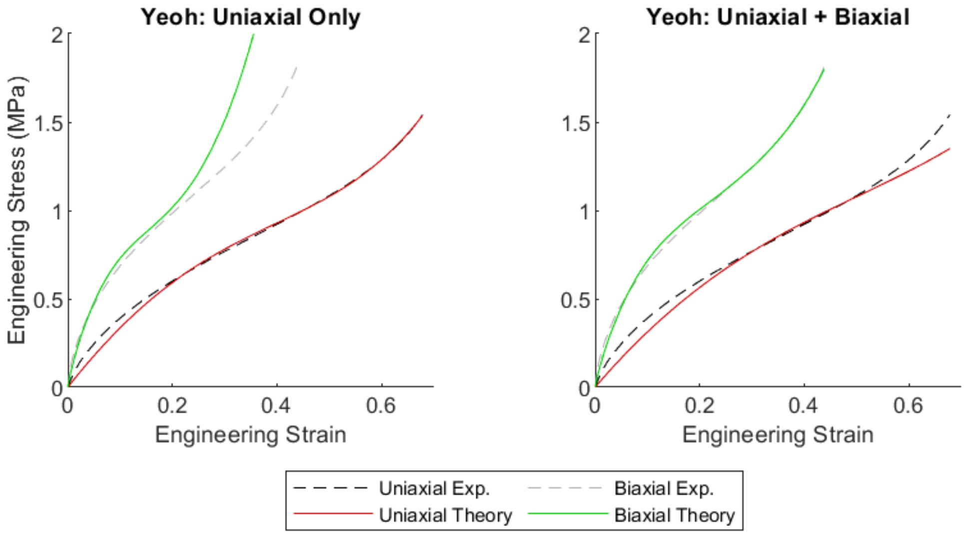

Fig. 3. Example fitting a Yeoh material model using only the uniaxial data and using both the uniaxial and biaxial data. Note that the accuracy in predicting the stress response of the biaxially strained sample is poor when only the uniaxial data was used to create the material model.

to 40-50%. Using a modulus derived from a higher strain (e.g., 100% strain) will likely result in an elastic modulus that is higher than the actual modulus in the linear region of the material. As such, it is important that researchers ensure the moduli provided by companies is relevant for their purposes. Collecting experimental data (item 4) means the data is subject to the limitations discussed in Section 4.3.1. This is not to assert that models derived from such methods are inaccurate or subject to higher magnitudes of uncertainty, but only that clear documentation of assumptions and testing conditions is critical to the reliability and validity of such models. In general, when collecting experimental data, it is not uncommon for only tensile test data to be used to fit the data, which can result in inaccurate material and, thus, robot models. Fig. 3 shows how fits of material models can be improved by adding biaxial tensile test data. If a model is used from other publications (item 2), researchers should be aware of the limitations listed above related to various modeling methods.

5. Next Steps

To help support the soft robotics community, both in and outside of industry, it is necessary to promote and support that transparent and traceable metrology that underlines the foundations of soft robotics, and continue building upon that foundation with quality documentation, novel test methods and metrics, and standards. In support of this, we propose the following next steps for the soft robotics research activities at NIST:

- identification and documentation of best practices from industry and the research community for measuring and modeling materials used in soft robotics;
- identification of relevant metrics and identification/development of test methods and tools for characterizing soft materials to support modeling/simulation and material selection;
- engage the soft robotics research community to establish protocols, standards, and best practices for reporting elastomer material properties and data collection methods;
- identification of relevant metrics and development of test methods for measuring deformations, conformability, and contacts of soft materials to support sensing, modeling/simulation, and control;
- identification of relevant metrics and identification/development of test methods for characterizing soft actuators to support modeling/simulation and actuator selection;
- identification of relevant metrics and identification/development of test methods for characterizing soft sensors to support modeling/simulation and sensor selection; and
- re-assessment of system-level metrology issues in soft robotics after the foundational metrology issues have been addressed.

Despite impressive demonstrations of new, one-off soft robot designs, the field of soft robotics is still in its infancy. Soft robots are frequently presented as novelties, and the field lacks the solid corpus of measurement science literature that supports research in more traditional robot technologies. Developing, promoting, and supporting the metrology of soft robotics will help with the development of soft robotic solutions to existing manufacturing challenges, and help soft robotic companies to properly communicate with stakeholders the benefits and functionalities of their solutions.

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