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The need for reproducible research in soft robotics

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Recent years have witnessed the rise of commercialization efforts for soft robotics technology, which includes soft grippers, stretchable sensors and platforms for human–robot interactions. However, this commercialization lags behind the trends seen with other robotics technologies at equivalent points in their respective lifecycles. For example, the first patent for an industrial robotic manipulator was filed in 1954, and within two decades, robotic manipulators were adopted onto assembly lines across the world[1]. By comparison, despite their origins in the 1980s and an influx of publications starting around 2004, soft robotics technologies are scarce in society[2]. This deployment gap is due largely to uncertainties surrounding the absence of standards, as well as difficulties in replicating published solutions.

Research comprises a dynamic interplay between discovery and distillation into practice. So far in soft robotics, novelty presides. Little emphasis has been placed on rigorous comparisons across studies, and consequently soft robotics lacks standard benchmarks, metrics, data sets, measurement and characterization workflows, and manufacturing recipes. These challenges can be seen across scales.

Down at the materials level, many characterization studies use bespoke setups and procedures. Reliance on ad hoc test methods, although convenient on a study-to-study basis, has negative consequences for reproducibility. For example, measuring the resistance of stretchable electronics results in radically varied outputs, ranging from flatlined to quadratic, depending on the technique[3].

At the structures and systems levels, issues persist. Nuances of manufacturing – casting, vacuuming and temperature treatments for soft robotic materials – vary from lab to lab, and are infrequently discussed in publications. Owing to the lack of commercially available soft robotics building blocks, labs often create and deploy soft robots entirely in-house, using custom recipes for sensors, actuators, energy sources and controllers.

In other cases, the absence of standards makes it impossible to objectively compare figures of merit. For instance, terms such as soft robot 'robustness' are routinely mentioned in the literature, but rarely justified through quantitative metrics. When quantified, different metrics are used, including maximum strain, cycles to failure and ultimate tensile strength, precluding systematic comparison.

Fortunately, the soft robotics community has begun to acknowledge the importance of consistent testing and comprehensive reporting. The Institute of Electrical and Electronics Engineers (IEEE)'s Technical Committee for Soft Robotic was established in 2013, providing an official forum for dialogue on barriers toward standardization. More recently, the 2022 IEEE International Conference on Robotics and Automation included a workshop on soft robotics metrics and testing methods, the 2023 IEEE International Conference on Intelligent Robots and Systems featured a workshop dedicated to the standardization of soft robotics, and the Working Group on Reproducibility in Soft Robotics was officially established. These initiatives are a start, but soft robotics requires systematic changes in how research is conducted, funded, published, commercialized and promoted for more widespread adoption.

Recommendations to stakeholders in soft robotics

The adoption of new technologies hinges on public trust. The prerequisite to trust is reliable, consistent, and clear research and reporting, because this allows end-users to objectively make comparisons between available technologies. Therefore, the vested interests in soft robotics – including researchers, research funders and publishers – should engage in public projects and reproducibility-conscious research (Box 1). To assist with such efforts, we propose the checklist in Box 1. The checklist presents steps towards reproducible soft robotics research, and was synthesized on the basis of common challenges faced by the authors in their experience.

To researchers. Adopting consistent and community-accepted methods and metrics for a common suite of soft robotics tasks, such as grasping and tactile perception, is necessary for objective comparison to prior art. Use of shared metrics would also eliminate tendencies to co-develop invention and baseline – a practice that is inherently vulnerable to gamesmanship. By engaging with standards development groups, researchers can ensure that adopted standards adequately address the needs of their research niche. We therefore encourage participation in the newly-formed Working Group on Reproducibility in Soft Robotics. Other examples that soft roboticists could emulate include the IEEE P3108 working group on best practices for research into human–robot interactions, and the ASTM (formerly the American Society for Testing and Materials) F45 working group on developing test methods for applications such as mobile manipulation.

Barring technology developed under non-disclosure agreements, labs must share their results in a transparent manner. Releasing robot code and designs as open source lowers the barrier to adoption and encourages common frameworks to develop organically, akin to how open-sourced Arduinos became the de facto prototyping board for research over the past decade[4]. Enhancing public visibility of results will allow the development of a common set of core soft robot building blocks that are commercial off-the-shelf or fabricable in-house – akin to the vision supported by the soft robotics toolkit.

To research funders. To promote reproducible and accessible scientific communication with statistically sound conclusions, funding agencies and managers must carefully design evaluation criteria and reporting requirements. Funders of research should also sponsor workshops, require submission of the final research outcomes to the funding agency, and/or create a reproducibility readiness level, analogous to the technology readiness level and manufacturing readiness level that are already a part of agencies' evaluations. Adherence to readiness-level markers would give project principal investigators clear targets to aim for, while providing quantified metrics for reporting of funders' outcomes.

BOX 1

Key points for collaboration among academic, industry and government in soft robotics

Collaboration among academia, industry and government is essential for widespread adoption of soft robots. This collaboration should focus on maintaining rigorous reporting practices and establishing universal testing methodologies for benchmarking. Here, we propose a checklist of key points that will contribute to reproducible research.

Code and datasets

- Use commented code that is easily readable
- Upload all code, data and files to a public repository
- Provide a one-line install for code
- Specify data-acquisition equipment
- Specify calibration procedures
- Report accuracy and precision of data

Materials and methods

- List the part number, brand, and source for all equipment and materials
- Explain how data is stored and organized
- Report all steps when processing data
- Specify models and their parameters
- Verify equipment specifications in data sheets

Statistics

- Report sample sizes for measures of central tendency
- Define error bars in figure captions
- Double-check claims of statistical significance
- Ensure that the analysis method is reproducible

Accessibility

- Check whether figures are colour blind friendly
- Submit to open-access publishing options
- Ensure that text is concise, cogent, and clear
- Explain maths verbally and symbolically

To publishers. Publishers should instruct reviewers to factor in reproducibility during their peer evaluations, and to incentivize reproducibility-focused articles and features. The replication studies ('R- and r-articles') sponsored by *RA Magazine* provide one model. Ongoing developments in the machine-learning community — in which conferences request more reproducibility information in manuscripts — would be well-heeded by venues that publish soft robotics research. As an example, the Conference on Neural Information Processing Systems (NeurIPS) has a publication readiness checklist similar to that in Box 1.

To industry

Data sheets and marketing materials released by vendors of soft robotics centric and adjacent technologies must be objectively comparable. Established standards for reporting and testing should be included in data sheets when possible, but when unavailable, materials and methods sections in externally referenced application notes are imperative. In offering manufacturing processes for the creation of soft robots, formal design-for-manufacturing guidelines should be established that will enable systematic analysis of a design, and will flag if it would suffer manufacturing defects. For example, with next-generation manufacturing technology, such as 3D printers, a preprocessing program that screens input designs for adherence to feasible construction practices and estimates yield rates would streamline design and reduce uncertainty through development cycles.

Finally, as with standards working groups such as the ASTM F45.05 subcommittee on grasping and manipulation, industry engagement is crucial to ensure that the standards have commercial relevance and sufficient buy-in to see widespread adoption.

Conclusion

Without concerted efforts toward rigorous reproducible reporting and consensus on test standards, soft robotics faces substantial barriers. As the field advances, we must remain cognizant of these challenges and come together as a community to prepare soft robots to have a greater impact on society.

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Competing interests

The authors declare no competing interests.