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Beyond Soft Materials: The Future of Intelligent Soft Robotics

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Commentary

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Abstract

Soft robotics has emerged as one of the most promising frontiers in robotics engineering, offering a fundamentally different design philosophy from conventional rigid robotic systems. Inspired by the flexibility and adaptability of biological organisms, soft robots are increasingly being explored for applications ranging from minimally invasive surgery and wearable assistive devices to precision agriculture and industrial automation. While remarkable advances in materials, actuation, sensing, and artificial intelligence have accelerated research, widespread industrial adoption remains limited. This commentary argues that the future of soft robotics will depend less on creating softer materials alone and more on integrating intelligent control, advanced manufacturing, and hybrid robotic architectures. We further contend that collaboration among robotics engineers, materials scientists, clinicians, and AI researchers is essential to overcome current barriers and translate laboratory innovations into real-world solutions. Soft robotics should therefore be viewed not as a replacement for conventional robotics but as a complementary technology that expands the capabilities of intelligent robotic systems.

Keywords: Soft Robotics; Intelligent Materials; Artificial Intelligence; Human–Robot Interaction; Bio-inspired Robotics; Wearable Robotics

Introduction

Robotics has traditionally relied on rigid mechanical structures designed for precision, repeatability, and high-load industrial operations [1]. Although these systems have transformed manufacturing and automation, their inherent rigidity limits their ability to safely interact with humans and delicate biological environments. Soft robotics has emerged as an alternative paradigm by replacing rigid structures with compliant materials capable of bending, stretching, and adapting to complex surroundings [2].

The rapid growth of this field reflects increasing recognition that future robots must coexist with people rather than simply operate independently. Applications such as robotic rehabilitation, minimally invasive surgery, food handling, wearable assistive devices, and environmental exploration illustrate how compliance can become an engineering advantage instead of a limitation [1,2].

Softness Alone is Not Enough

One misconception is that making robots softer automatically makes them more useful. Material compliance undoubtedly improves safety and adaptability, yet it also introduces significant engineering challenges. Highly deformable structures are difficult to model mathematically, harder to control precisely, and often exhibit nonlinear behaviour that complicates prediction and optimization [3].

In our view, the next stage of progress should focus on developing intelligent soft robotic systems rather than

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simply softer robots. Artificial intelligence, machine learning, embedded sensing, and adaptive control should become integral components of future soft robotic platforms.

Artificial Intelligence Will Define the Next Generation of Soft Robots

Artificial intelligence is transforming robotics by enabling perception, reasoning, and autonomous decision-making. For soft robots, AI has an even greater role because conventional analytical control methods often struggle to represent continuously deformable structures.

Data-driven control, reinforcement learning, digital twins, and physics-informed machine learning offer promising alternatives for improving manipulation, locomotion, and environmental adaptation. Instead of relying exclusively on predefined models, future soft robots may continuously learn from interaction with their surroundings, improving performance over time [4].

Hybrid Robotics Represents the Most Practical Future

Although soft robotics has received considerable attention, entirely soft robots are unlikely to replace rigid robotic systems across all applications. Industrial robots still require high positional accuracy, load-bearing capacity, and operational speed that fully compliant systems currently cannot consistently deliver [1].

A more realistic direction is the development of hybrid robots, combining rigid structural components with compliant actuators, flexible grippers, and soft interfaces. Such systems can integrate the precision of traditional robotics with the safety and adaptability of soft materials. This balanced approach is likely to accelerate industrial adoption and broaden application domains.

Translating Laboratory Success into Clinical and Industrial Practice

Despite impressive demonstrations in research laboratories, relatively few soft robotic technologies have reached widespread commercial deployment. The barriers extend beyond technical performance and include manufacturing scalability, durability, regulatory approval, long-term reliability, and economic feasibility.

Addressing these challenges requires interdisciplinary collaboration among robotics engineers, materials scientists, clinicians, manufacturing experts, and regulatory agencies. Standardised testing methods and benchmarking protocols will also be important for comparing technologies and accelerating commercialisation.

Sustainability Should Become a Design Objective

Future development should also consider sustainability. Many soft robots rely on polymeric materials that present recycling and disposal challenges. Researchers should prioritise biodegradable materials, energy-efficient actuation, modular design, and environmentally responsible manufacturing.

Sustainability should become a primary engineering objective rather than an afterthought. As robotics becomes increasingly integrated into healthcare, manufacturing, and public infrastructure, environmental responsibility will become an essential criterion for future innovation [5].

Future Perspective

The coming decade is likely to witness rapid advances in self-healing materials, artificial muscles, multifunctional sensors, additive manufacturing, and AI-driven adaptive control. These innovations could enable robots capable of safely assisting surgeons, supporting elderly individuals, inspecting fragile ecosystems, and collaborating seamlessly with human workers.

Rather than competing with conventional robotics, soft robotics should complement existing technologies by addressing problems where flexibility, compliance, and safe interaction are critical. Success will depend on integrating intelligent algorithms with advanced materials and robust engineering design.

Conclusion

Soft robotics represents one of the most exciting developments in modern robotics engineering because it challenges traditional assumptions about how robots should be designed and how they should interact with people and their environment. However, the field must now transition from demonstrating novel prototypes toward developing reliable, scalable, and intelligent systems capable of delivering measurable societal impact.

The future of soft robotics will not be determined solely by advances in materials science but by the successful convergence of artificial intelligence, intelligent manufacturing, sensing technologies, and interdisciplinary collaboration. If these elements develop together, soft robotics has the potential to become a cornerstone of next-generation healthcare, industry, and human-centred automation.

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