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Emerging Frontiers and Technological Challenges in Soft Robotics

Jiangtao Su,[1, 2, 3] Pablo Valdivia y Alvarado,[1, 4] Lucia Beccai,[5] Xingyu Chen,[1, 6] Lei Chen,[1, 4] Lioz Etgar,[1, 7] Amir D. Gat,[8] Huajian Gao,[9] Qi Ge,[10] Shang Gong,[1, 3] Cuntai Guan,[11] Robert K. Katzschmann,[12] Cecilia Laschi,[13] Jiaji Li,[14] Pooi See Lee,[1, 3] Chwee Teck Lim,[15, 16, 17] Qingyang Liu,[1, 3] Ziwei Liu,[11] Daniel Mandler,[1, 7] Yoav Matia,[18] Barbara Mazzolai,[19] Han Wei Ng,[11] Soo Jay Phee,[1, 6] Meital Reches,[1, 7] Ignazio Roppolo,[20, 21, 22] Robert F. Shepherd,[23, 24, 25] Rou Yun Teo,[1, 4] Ryan Truby,[26, 27] Ziwei Wang,[28] Lydia H. Wong,[1, 3] Joel K. W. Yang,[1, 4] Chen Hua Yeow,[15] Shlomo Magdassi,[1, 7, *] Xiaodong Chen [1, 2, 3, 28 *]

[1]Singapore-HUJ Alliance for Research and Enterprise (SHARE), The Smart Grippers for Soft Robotics (SGSR) Programme, Campus For Research Excellence and Technological Enterprise (CREATE), Singapore, Singapore
[2]Innovative Centre for Flexible Devices (iFLEX), Max Planck-NTU Joint Lab for Artificial Senses, Nanyang Technological University, Singapore, Singapore.
[3]School of Materials Science and Engineering, Nanyang Technological University, Singapore, Singapore.
[4]Engineering Product Development, Singapore University of Technology and Design, Singapore 487372, Singapore
[5]Soft BioRobotics Perception, Istituto Italiano di Tecnologia (IIT), Genova, Italy
[6]School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, Singapore.
[7]Institute of Chemistry, The Center for Nanoscience and Nanotechnology, Casali Center for Applied Chemistry, The Hebrew University of Jerusalem, Jerusalem 91904, Israel
[8]Faculty of Mechanical Engineering, Technion - Israel Institute of Technology, Haifa 3200003, Israel
[9]Mechano-X Institute, Applied Mechanics Laboratory, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China
[10]Shenzhen Key Laboratory for Additive Manufacturing of High-Performance Materials, Department of Mechanical and Energy Engineering, Southern University of Science and Technology, Shenzhen, 518055 China
[11]College of Computing & Data Science, Nanyang Technological University, Singapore
[12]Soft Robotics Laboratory, Department of Mechanical and Process Engineering, ETH Zurich, Tannenstrasse 3, Zurich, 8092 Switzerland
[13]Department of Mechanical Engineering and Advanced Robotics Centre, National University of Singapore, Singapore.
[14]Computer Science and Artificial Intelligence Laboratory (CSAIL), Massachusetts Institute of Technology (MIT)
[15]Institute for Health Innovation and Technology (iHealthtech), National University of

Singapore, Singapore, 117599, Singapore
[16]Department of Biomedical Engineering, National University of Singapore, Singapore, 117583, Singapore
[17]Mechanobiology Institute, National University of Singapore, Singapore, 117411, Singapore
[18]Department of Mechanical Engineering, Ben-Gurion University of the Negev, Be'er Sheva, Israel
[19]Bioinspired Soft Robotics Laboratory, Istituto Italiano di Tecnologia, Via Morego 30, Genova 16163, Italy
[20]Department of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24, Turin 10129, Italy
[21]PoliTOBioMEDLab, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy
[22]Center for Sustainable Future Technologies, Italian Institute of Technology, Via Livorno 60, Turin 10144, Italy
[23]Department of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY, USA
[24]Center for Research on Programmable Plant Systems, Cornell University, Ithaca, NY, USA
[25]Engineering Living Materials Institute, Cornell University, Ithaca, NY, USA
[26]Department of Materials Science and Engineering, Northwestern University, Evanston, IL, 60208, USA
[27]Department of Mechanical Engineering, Northwestern University, Evanston, IL, 60208, USA
[28]School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore
Email: Shlomo.Magdassi@mail.huji.ac.il, chenxd@ntu.edu.sg

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1. Introduction

Soft robotics emerged from a simple but transformative realization: many real-world environments are fundamentally incompatible with the assumptions underlying traditional rigid machines.[1-3] Biological organisms achieve remarkable adaptability not through rigid precision alone, but through the intimate coupling of compliant tissues, distributed sensing, morphology, and environmental interaction.[4-7] Inspired by systems such as octopus,[8] elephant trunks,[9] worms,[10] starfish,[11] and human musculoskeletal

structures,[12] early soft robots demonstrated how deformable bodies could passively conform to uncertain environments, simplify grasping and locomotion, and enable inherently safer interaction with humans and delicate objects.[13-14] Over the past decade, rapid advances in soft materials, flexible electronics, fluidic and electroactive actuation, additive manufacturing, and machine learning have transformed soft robotics into a highly interdisciplinary research frontier spanning robotics, materials science, mechanics, chemistry, photonics, manufacturing, and artificial intelligence (**Figure 1**).[15-21]

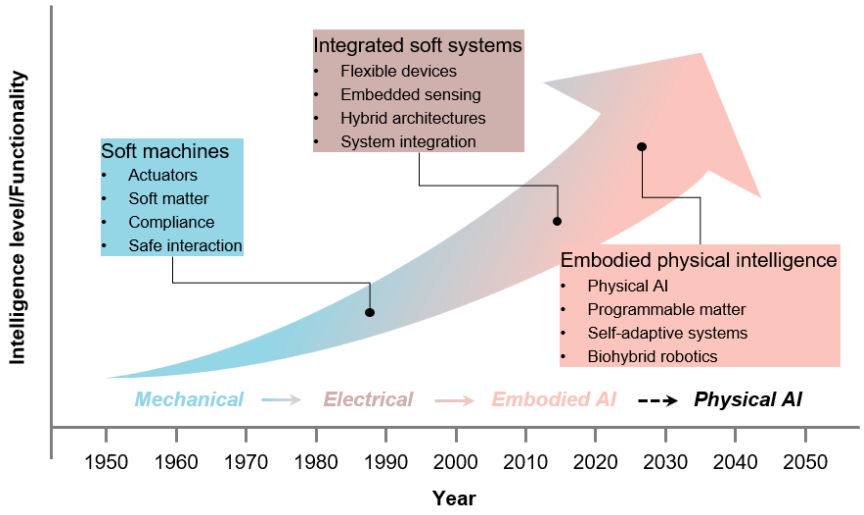

Figure 1. The evolution of soft robots.

Despite this progress, the field is now entering a critical transition phase. While soft robotic systems have demonstrated compelling capabilities in laboratory settings, many remain constrained by limited force output, low energetic efficiency, material fatigue, weak embedded perception, bulky external hardware, poor manufacturability, and limited long-term autonomy.[22-23] These limitations increasingly suggest that the major challenges facing soft robotics are not isolated component-level problems, but rather system-level challenges arising from the complex coupling between materials, mechanics, sensing, actuation, control, and environmental interaction (**Figure 2**).[24-25] As a result, the field is progressively shifting away from viewing softness merely as a mechanical property and toward treating soft robots as integrated physical systems whose functionality emerges from distributed interactions across multiple spatial and

temporal scales.

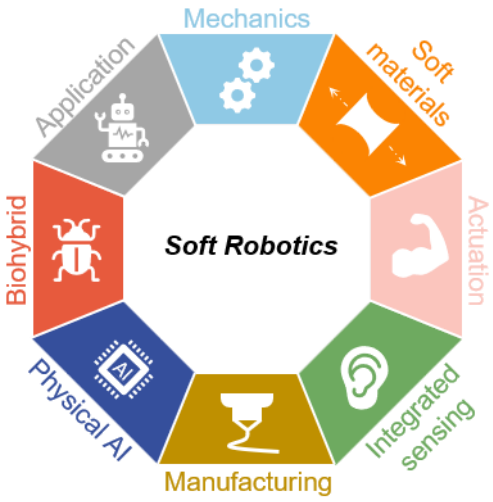

Figure 2. The fields covered by soft robots, including materials, mechanics, sensing, actuation, manufacturing, AI, etc.

This shift reflects a broader conceptual evolution in how intelligence itself is understood in embodied systems. Early soft robotics primarily emphasized compliant actuation and bioinspired motion. More recently, however, emerging directions increasingly focus on embodied intelligence, mechanomaterials, physical computation, multifunctional matter, and adaptive physical AI. Within these paradigms, intelligence is no longer regarded solely as centralized computation performed by external processors or abstract algorithms. Instead, adaptive behavior may emerge directly from morphology, material dynamics, distributed sensing, mechanical feedback, and environmental coupling. In this context, the physical body itself increasingly participates in perception, control, computation, and adaptation.

The convergence of these ideas raises several fundamental scientific and technological questions that now define the future trajectory of the field. Can mechanics itself function as a computational substrate? Can multifunctional materials simultaneously sense, actuate, adapt, and process information? How can reliable perception be achieved in highly deformable systems with complex embodiment-dependent dynamics?

Can additive manufacturing directly program functionality and intelligence into material architectures? How should artificial intelligence integrate with nonlinear soft bodies that continuously interact with uncertain environments? And critically, how can soft robots transition from proof-of-concept demonstrations toward scalable, durable, untethered, and sustainable real-world systems?

The perspectives collected in this article reveal a striking convergence across disciplines (**Figure 3**). Researchers from mechanics, materials science, photonics, manufacturing, chemistry, wearable robotics, surgery, biohybrid systems, and artificial intelligence increasingly point toward a shared vision in which future soft robotic systems are not assembled as collections of independent subsystems, but are instead designed as deeply embodied physical systems where structure, material composition, sensing, computation, control, and environmental interaction collectively generate adaptive function. Viewed from this perspective, soft robotics may ultimately evolve beyond a subfield of robotics and contribute to a broader scientific foundation for adaptive matter, programmable physical intelligence, and life-like engineered systems.

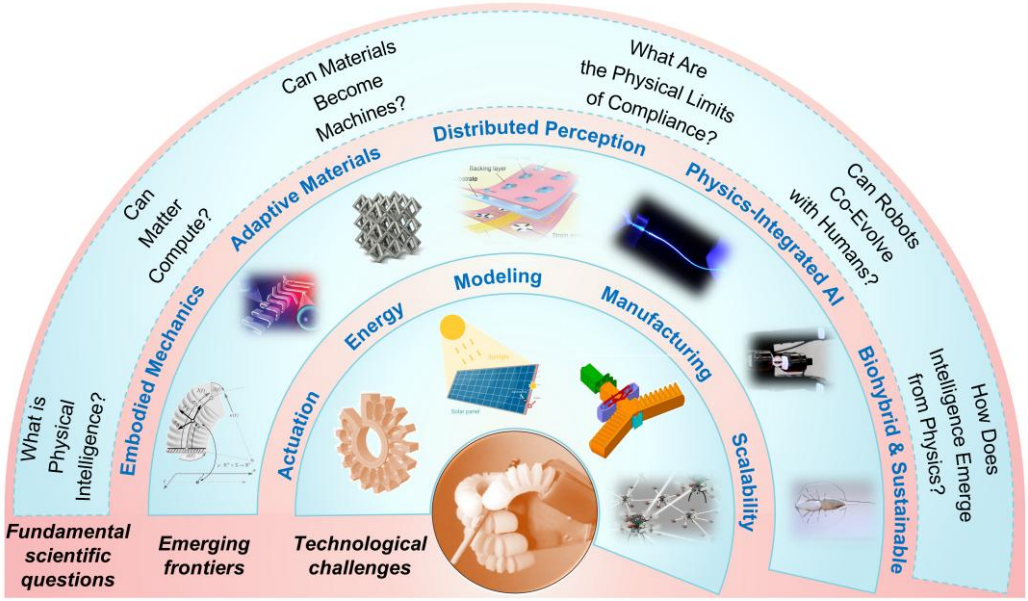

Figure 3. Representative technological challenges, emerging frontiers and fundamental scientific questions in soft robotics.

2. Mechanics, Embodiment, and Physical Intelligence

2.1 Can Mechanics Itself Become a Source of Intelligence?

One of the most important conceptual shifts in soft robotics is the growing recognition that mechanics is not merely a passive descriptor of system behavior, but can itself become a functional design principle capable of encoding sensing, adaptation, computation, and control.[26-31] Traditionally, robotics has treated mechanics and intelligence as separate domains: mechanics defined the physical body, while computation and control were implemented through centralized algorithms. Soft robotics increasingly challenges this separation.

Recent developments in mechanomaterials, morphological computation, and embodied intelligence suggest that compliant structures can physically perform functions that would otherwise require active control.[32] Architected materials capable of programmable instability, nonlinear deformation, and multistable transitions demonstrate how desired behaviors may emerge directly from material geometry and force interactions.[33-34] In this context, mechanics evolves from a supporting tool into a generative framework for functionality.

Embodied intelligence should not simply be viewed as an engineering optimization strategy, but as a broader scientific paradigm.[35-36] Soft robotic bodies can offload computation into morphology and environmental interaction, allowing physical systems to adapt without explicitly calculating every state transition.[37] Physical reservoir computing further extends this idea by treating compliant bodies as nonlinear computational substrates capable of processing temporal information through structural dynamics alone.[38-39] Fluidic logic systems and mechanically programmable architectures provide particularly compelling examples of this concept.[40] Pneumatic oscillators, fluidic logic gates, and compliant mechanical reservoirs demonstrate that sensing, control, and actuation can be embedded directly into physical matter rather than implemented through conventional electronics.[41-42] These developments challenge long-standing assumptions in robotics regarding where computation resides. These

approaches may also provide pathways toward lower-energy and more scalable robotic intelligence. Conventional AI systems increasingly rely on computationally intensive architectures requiring substantial power and centralized processing. In contrast, embodied mechanical intelligence may reduce computational overhead by allowing morphology itself to simplify interaction and adaptation.[43]

Despite these advances, major scientific challenges remain unresolved. The field still lacks a unified framework connecting material properties, geometry, dynamics, and task-level performance. Current demonstrations often exploit emergent physical behaviors without principled design methodologies. Furthermore, the repeatability, scalability, and robustness of physical computation remain limited by material variability, noise sensitivity, and insufficient understanding of nonlinear compliant dynamics. In the future, tighter integration between continuum mechanics, nonlinear dynamics, machine learning, materials science, and robotic control is required.[44-45] Rather than treating mechanical embodiment as a secondary consideration, future soft robotic systems may increasingly use mechanics itself as a programmable information-processing medium.

2.2 What Are the Fundamental Physical Limits of Soft Robots?

As soft robotics continues to mature, the field is increasingly confronting a fundamental scientific question: what are the intrinsic physical limits governing compliant robotic systems? Although soft robots demonstrate unique advantages in adaptability, conformal contact, and mechanically safe interaction, these capabilities are often accompanied by reduced force transmission, limited load-bearing capacity, and lower positional precision compared with rigid robotic systems.[46] These limitations should not be interpreted merely as engineering shortcomings, but rather as consequences of the underlying mechanics of compliant matter.[47] In particular, soft manipulators are fundamentally constrained in their ability to transmit large transverse forces and torques because highly compliant bodies cannot easily isolate or selectively constrain individual degrees of freedom.[48] As a result, compliant structures frequently experience

distributed deformation, mechanical instability, and reduced structural rigidity under external loading, thereby limiting efficient traction transmission and high-load operation.

Recent studies have begun to establish generalized scaling relationships linking force transmission capability to actuator density, material modulus, geometric topology, and stress distribution within deformable architectures.[49-51] These analyses increasingly suggest that soft and rigid robotic systems should not be viewed as competing paradigms, but rather as occupying complementary regions within a broader mechanical design space. Rigid robotic systems typically excel in environments where structural stiffness greatly exceeds environmental stiffness and where accurate sensing, modeling, and motion planning are available.[52-54] Under such conditions, rigid mechanisms provide superior positional accuracy, load-bearing performance, and dynamic controllability. However, these systems often struggle in uncertain or unstructured environments because they depend heavily on precise environmental representation and accurate inverse kinematic planning.[55] Soft robots, by contrast, exploit compliance to physically absorb uncertainty through deformation and passive adaptation.[56] This capability enables robust interaction under incomplete environmental information and reduces the computational burden associated with precise control and contact modeling. Nevertheless, the same compliance that enables adaptability also inherently limits the ability to resist buckling, maintain geometric stability, and generate large torques or high-bandwidth motion.[57]

At a deeper level, the very definition of softness itself remains highly context dependent. Softness should not simply be interpreted as low elastic modulus, but rather as a relative mechanical relationship between the robot and its surrounding environment.[58] Biological systems achieve remarkable versatility not merely because they are compliant, but because they integrate gradients in stiffness, anisotropic architectures, hierarchical organization, multifunctional tissues, and dynamically tunable mechanical properties across multiple scales.[59-61] Consequently, future soft robotic systems may

increasingly rely on spatially heterogeneous architectures that combine rigid and compliant regions, programmable stiffness modulation, and mechanically adaptive interfaces to balance competing demands between adaptability and structural performance.

Collectively, these perspectives indicate that future progress in soft robotics will require a transition from qualitative notions of softness toward quantitatively grounded mechanics-based design principles. Establishing rigorous physical scaling laws, stability criteria, failure-mode analyses, and mechanics-informed optimization frameworks will likely become essential for guiding next-generation soft robotic architectures.

2.3 Are Hybrid Soft-Rigid Architectures the Real Future of Robotics?

The long-standing dichotomy between "soft" and "rigid" robotics is increasingly giving way to a more integrated and physically grounded perspective in which future robotic systems are expected to combine compliance, structural rigidity, adaptive mechanics, and distributed intelligence within unified architectures.[62] While early soft robotics emerged partly in opposition to conventional rigid robotics, emphasizing safety, adaptability, and morphological compliance, it has become increasingly clear that softness alone cannot satisfy the broad mechanical and functional requirements demanded by real-world applications.[63] Instead, the next generation of robotic systems will likely rely on principled hybrid soft-rigid architectures capable of balancing environmental adaptability with force transmission, positional accuracy, and long-term mechanical robustness.[64-66]

The motivation for hybridization arises from fundamental physical constraints. Highly compliant bodies excel at safe interaction, conformal contact, and operation in uncertain or unstructured environments, yet they often struggle to sustain large transverse forces, resist torsional loading, or maintain geometric precision under deformation.[67] Conversely, rigid systems provide excellent load-bearing capability and controllability

but remain poorly suited for delicate interaction, morphological adaptation, and embodied environmental compliance. Hybrid systems offer a pathway to reconcile these competing demands by strategically distributing stiffness, compliance, and control authority across different structural regions.[68] Examples already emerging include musculoskeletal robots with tendon-driven rigid skeletons and soft interfaces,[69] variable-stiffness manipulators,[70] jamming-based rigidity tuning systems,[71] and selective degree-of-freedom locking mechanisms that enable transitions between compliant exploration and mechanically stable operation.[72]

Hybrid architectures should not be interpreted merely as engineering compromises. Rather, they may represent a more biologically and physically realistic paradigm for embodied intelligence.[73] Biological organisms themselves rarely rely on purely soft or purely rigid structures. Instead, they achieve remarkable functionality through hierarchical combinations of bones, tendons, muscles, fascia, connective tissues, and adaptive interfaces operating across multiple length scales.[74] Such systems dynamically redistribute stiffness, store and release elastic energy, and integrate sensing with mechanical response in ways that remain unmatched by current robotic systems.

Future hybrid robots may therefore evolve toward deeply integrated mechano-intelligent systems in which rigid and compliant domains are co-designed alongside distributed sensing, local stiffness modulation, embedded computation, and adaptive control.[75-76] Advances in architected materials, mechanical metamaterials, programmable interfaces, and bioinspired musculoskeletal systems may further enable robotic bodies whose mechanical properties vary spatially and temporally in response to task demands.[77] At the same time, AI-assisted design optimization and digital-twin frameworks may help identify optimal stiffness distributions and hybrid morphologies that would be difficult to derive analytically. Ultimately, the future of robotics may not lie in choosing between softness and rigidity, but in understanding how these properties can be synergistically integrated to create systems that are simultaneously robust, adaptive, energy-efficient, and intelligent.

3. Advanced Soft Materials and Actuation

3.1 Why Do Soft Actuators Still Struggle with Force, Efficiency, and Bandwidth?

Despite major advances in compliant actuation technologies, soft actuators remain constrained by persistent trade-offs between force output, energy efficiency, bandwidth, durability, manufacturability, and portability.[48, 78-79] These limitations continue to represent one of the primary barriers preventing soft robotics from transitioning into large-scale real-world deployment.

Pneumatic and hydraulic actuators remain dominant because they provide large deformation, simplicity, and strong force generation. However, they also require bulky compressors, pumps, valves, or fluidic infrastructure that restrict portability and untethered operation.[80] Electrostatic and dielectric elastomer actuators offer rapid response and high efficiency, yet often generate limited force and depend on high-voltage operation.[81] Among ionically driven systems, Ionic polymer-metal composites (IPMCs) actuators illustrate these trade-offs particularly clearly. Their low-voltage operation and wet-chemistry tunability make them attractive for compliant actuation, yet the softness of ion-conducting phases inherently limits blocking force and load-bearing capability.[82] Attempts to stiffen ionic materials often reduce ionic mobility, displacement amplitude, or operational bandwidth. This challenge reveals a broader issue across the field: soft actuators frequently achieve desirable compliance at the expense of structural robustness and mechanical power density. Future progress may therefore require architectures that decouple ionic transport, solvent management, and electromechanical response from bulk material modulus.

Possible solutions may involve hybrid multifunctional architectures integrating ionically conductive networks with mechanically robust elastomer matrices, high-modulus nanomaterials, or dielectric layers.[83-84] Such approaches may combine the low-voltage operation of ionic systems with the bandwidth and stress robustness of dielectric elastomers. Other emerging strategies involve liquid crystal elastomers,

phase-change materials, self-healing polymers, and stimuli-responsive composites capable of dynamically altering mechanical properties under external fields.[85] However, many of these materials still suffer from slow response times, poor durability, or low energy efficiency. The challenge is therefore not simply discovering new actuator materials, but developing integrated material systems capable of balancing compliance, strength, adaptability, manufacturability, and energetic efficiency simultaneously.[86]

3.2 Can Soft Matter Simultaneously Sense, Actuate, and Compute?

One of the most ambitious and conceptually transformative frontiers in soft robotics is the development of multifunctional matter capable of simultaneously sensing, actuating, computing, and adapting within unified material architectures.[87] In conventional robotic systems, sensing, actuation, control, and structural support are typically implemented as physically separated modules connected through centralized computation. Biological systems, however, operate according to fundamentally different principles. In living tissues, mechanical response, force generation, biochemical signaling, energy transport, and information processing are deeply intertwined across hierarchical scales.[88] Muscles, nerves, extracellular matrices, and cellular networks function collectively as integrated adaptive matter rather than isolated subsystems.[89] Reproducing even a fraction of this integration remains one of the grand scientific challenges in soft robotics.

Consequently, future soft robotic systems may increasingly evolve from compliant machines toward active life-like soft matter, where functionality emerges directly from material organization itself rather than from externally attached hardware.[90] In this vision, the material is no longer merely a passive substrate supporting embedded electronics or actuators; instead, it becomes the robotic system itself.[91] Mechanically responsive materials capable of coupling deformation with electrical, optical, thermal, or chemical responses may provide foundational pathways toward this objective.[92-93] Recent advances in self-sensing elastomers,[94] mechanoresponsive polymers,[95] conductive hydrogels,[96] liquid crystal elastomers,[97] and architected multifunctional

composites increasingly demonstrate how sensing and actuation can become intrinsically embedded within deformable matter.

This direction also strongly intersects with the broader concepts of embodied intelligence and physical computation.[98-99] Materials capable of mechanically processing environmental information while simultaneously generating adaptive responses may fundamentally redefine the architecture of robotic systems.[100-101] Rather than relying exclusively on centralized digital computation, future robots may increasingly distribute computation throughout their bodies, allowing morphology, material dynamics, and local physical interactions to directly contribute to control and decision-making.[102] Such approaches may dramatically reduce computational overhead while improving adaptability, robustness, and energy efficiency in uncertain environments.

Despite these exciting possibilities, substantial scientific and technological challenges remain unresolved. Multifunctional materials often face severe trade-offs between softness, conductivity, mechanical durability, signal fidelity, and manufacturability.[103] Materials optimized for electrical transport may become mechanically stiff or brittle, whereas highly compliant materials often suffer from hysteresis, signal drift, or limited long-term stability. Similarly, integrating sensing, actuation, and computational behavior within a single homogeneous material frequently leads to interference between functionalities and degradation of overall system performance. Future progress may therefore depend less on fully homogeneous multifunctional matter and more on hierarchical multifunctional architectures in which sensing, actuation, energy transport, and information processing are distributed across multiple length scales. Biological tissues again provide important inspiration, where local specialization coexists with global integration. Emerging strategies involving multilayered materials, architected microstructures, distributed ionic networks, mechanically programmable metamaterials, and adaptive interfaces may allow future soft robots to achieve increasingly sophisticated forms of physical intelligence. Ultimately, the convergence of materials

science, mechanics, bioinspired design, and machine learning may enable robotic matter that not only moves and senses, but also physically interprets and adapts to its environment in real time.

3.3 How Can Soft Robots Achieve Untethered Operation?

Untethered operation remains one of the defining technological bottlenecks preventing soft robotics from transitioning fully from laboratory demonstrations to practical autonomous systems[104-105]. Despite impressive progress in compliant actuation, adaptive locomotion, and bioinspired manipulation, many existing soft robots continue to depend heavily on external compressors, pumps, tethered power supplies, hydraulic infrastructure, or off-board computation. These dependencies significantly limit portability, operational range, scalability, and real-world deployment, particularly in applications requiring mobility, long-duration autonomy, or wearable integration.

A central challenge lies in the fact that many soft actuation strategies fundamentally struggle to reconcile compliance with energetic performance. Pneumatic and hydraulic systems remain attractive because they provide large deformation, mechanical simplicity, and high compliance, yet they typically require bulky fluidic infrastructure that is difficult to miniaturize efficiently.[106] Stimuli-responsive materials, including thermally driven polymers and liquid crystal elastomers, often exhibit low energetic efficiency, slow response times, or complex onboard energy delivery requirements.[107] Similarly, electrostatic and dielectric elastomer actuators can provide rapid and electrically compatible actuation but frequently suffer from limited force generation and high-voltage requirements.[108]

For this reason, future soft robotic systems will likely require electrically drivable actuation platforms compatible with compact onboard batteries, embedded electronics, sensors, and AI hardware already dominant in modern robotic systems.[62, 109] Electrically driven systems offer substantial advantages for untethered operation because they integrate naturally with distributed sensing, wireless communication, and

power supply. However, realizing compact, lightweight, and energy-efficient electrically powered soft actuators remains an unresolved materials and systems challenge. In wearable robotics and assistive devices, these limitations become especially critical because actuator mass, power consumption, thermal management, and energy storage directly affect comfort, portability, and operational endurance.[110-112]

Future solutions may therefore require fundamentally new approaches to energy management and robotic system architecture. Rather than relying on centralized power delivery, next-generation soft robots may increasingly distribute energetic functionality throughout the body itself, mimicking biological organisms where energy storage, sensing, actuation, and structural mechanics are tightly integrated.[113] Emerging strategies may include soft energy storage devices, mechanically coupled energy recycling systems, distributed electrochemical actuation networks, fluidic energy redistribution architectures, and multifunctional materials capable of simultaneously storing and converting energy.[114] In parallel, reducing the energetic burden of control itself may become equally important. Embodied intelligence and physical computation approaches may allow future soft robots to exploit morphology, passive mechanics, and material dynamics to reduce active control requirements and computational load. Such strategies could significantly improve energetic efficiency while enabling more adaptive and resilient behavior in unstructured environments. Advances in low-power electronics, soft wireless systems, flexible photovoltaics, and bioinspired metabolic energy strategies may further contribute to fully autonomous soft robotic platforms.[115-116] Ultimately, achieving untethered operation will require not only better actuators, but a complete rethinking of how energy, intelligence, mechanics, and materials are integrated throughout the robotic body.

4. Integrated Sensing and Perception in Deformable Systems

4.1 How Can Soft Robots Reliably Sense Their Own Bodies?

A defining scientific challenge in soft robotics is the absence of reliable distributed perception within continuously deformable bodies.[117] Unlike rigid robots, whose

motion can often be described through discrete joints and well-defined kinematic chains, soft robots exhibit effectively infinite degrees of freedom, nonlinear deformation, strong environmental coupling, and history-dependent mechanical responses.[118] As a result, accurate state estimation becomes fundamentally difficult. The body itself continuously changes shape during interaction, while sensing elements deform simultaneously with the structure they are intended to measure. This creates a perception problem that is not merely technological, but deeply physical and computational in nature.

Integrated sensing has therefore emerged as one of the central frontiers in soft robotics research.[117, 119] Increasingly sophisticated sensing architectures now combine distributed pressure, strain, temperature, and proximity sensing within compliant robotic bodies.[120] Such systems allow soft robots to estimate internal deformation while simultaneously monitoring environmental interaction.[121-124] Multimodal sensing may allow robots not only to estimate shape and motion, but also to infer object properties, contact conditions, frictional states, and interaction dynamics in real time.[125-126] However, perception in soft robots remains fundamentally constrained by observability limitations.[127] Vision systems primarily capture external morphology, while embedded tactile and strain sensors provide localized internal measurements. Because these sensing modalities operate at different spatial and temporal resolutions, similar observations may correspond to multiple underlying physical states. This ambiguity becomes especially severe in systems exhibiting material hysteresis, viscoelasticity, sensor drift, contact uncertainty, and embodiment-dependent dynamics. Furthermore, sensor outputs are often noisy, weakly labeled, and difficult to temporally synchronize across modalities, complicating reliable sensor fusion and control.[128]

These challenges suggest that future progress will depend not simply on adding more sensors, but on developing unified sensing architectures capable of integrating heterogeneous information streams into physically meaningful representations.[129] Future systems may increasingly combine proprioception, tactile perception,

environmental awareness, and predictive modeling within tightly integrated frameworks. Wireless and untethered sensing will also become increasingly important as soft robots move toward wearable, surgical, and mobile applications where external instrumentation becomes impractical.[130] At the same time, advances in self-sensing materials, distributed electronics, neuromorphic sensing, and machine learning may allow robotic bodies themselves to become active perceptual systems.[131] Ultimately, reliable perception in soft robotics will likely require deep co-design between sensing hardware, deformable mechanics, physical modeling, and AI-driven interpretation.[132]

4.2 Can Optical Sensing Enable Fully Perceptive Soft Robots?

Optical sensing is rapidly emerging as one of the most promising sensing paradigms for soft robotics because it uniquely combines high sensitivity, fast response speed, electromagnetic immunity, and compatibility with compliant structures.[133] Unlike conventional electrical sensors, optical systems can detect subtle mechanical deformations through changes in light propagation, reflection, scattering, or color, enabling highly distributed and minimally invasive sensing architectures.[134] As soft robots become increasingly complex and multifunctional, optical sensing may provide critical pathways toward fully perceptive deformable systems capable of simultaneously monitoring shape, contact, force, and environmental interaction.[135]

Coherent optical sensing approaches, particularly fiber Bragg gratings (FBGs), have already demonstrated strong capabilities for proprioception and shape reconstruction in deformable systems.[136-137] By monitoring wavelength shifts induced by local strain, embedded optical fibers allow soft robots to estimate curvature, deformation, and spatial configuration with high precision. Stretchable distributed optical fibers further extend this concept by enabling continuous strain sensing throughout compliant structures.[138] Such approaches are especially attractive for continuum robots, wearable devices, and soft surgical systems, where accurate shape estimation remains difficult using conventional sensing technologies. At the same time, incoherent optical sensing strategies are enabling increasingly rich forms of tactile and environmental perception.

Vision-based tactile systems inspired by platforms such as GelSight and TacTip reconstruct contact geometry and surface texture through imaging of deformable interfaces.[139-141] Mechanochromic materials, including cholesteric liquid crystal elastomers, further demonstrate how mechanical deformation can be directly translated into visible color changes that are remotely detectable.[142-143] These systems suggest that future soft robotic skins may rely heavily on distributed optical sensing because optical architectures naturally support large-area coverage, remote imaging, and high-density information acquisition.[144] AI-enhanced imaging may further allow soft robots to infer slip, pressure distribution, object geometry, and dynamic interaction states from optical signals in real time.

Despite these advantages, substantial material and fabrication challenges remain unresolved. Most current soft photonic systems rely on polymeric materials exhibiting relatively high optical loss, poor refractive index contrast, and strong deformation-induced signal degradation.[145] Mechanical stretching, environmental exposure, and repeated deformation can significantly compromise optical fidelity and long-term reliability.[146-147] Moreover, many soft optical waveguides continue to rely on molding or casting methods that remain poorly compatible with scalable multimaterial additive manufacturing.[145] Recent advances in molecularly engineered polymers, printable photonic materials, and soft photonic architectures suggest that these limitations may eventually be overcome through integrated co-design of polymer chemistry, mechanical compliance, and optical functionality.[148-149] Future research will likely focus on ultralow-loss printable polymers, embedded waveguide networks, distributed optical skins, and multifunctional photonic systems capable of simultaneously sensing, communicating, and adapting.[150] Ultimately, optical sensing may become a foundational enabling technology for future soft robots that are not only mechanically compliant, but also continuously perceptive across their entire bodies.

4.3 How Should AI Interpret Soft Robotic Sensor Data?

As soft robotic systems become increasingly perceptive and sensor-rich, artificial

intelligence is emerging as an essential tool for interpreting the resulting high-dimensional, nonlinear, and multimodal data streams.[151-153] Unlike rigid robots, where state estimation often relies on relatively structured kinematic models and discrete sensor measurements, soft robots generate complex sensory information shaped by distributed deformation, viscoelasticity, environmental coupling, material hysteresis, and embodiment-dependent dynamics.[154] Consequently, conventional estimation and control frameworks are frequently insufficient for interpreting the behavior of deformable robotic systems.[155] Machine learning increasingly provides powerful tools for addressing these challenges. Self-supervised learning, multimodal fusion, physics-informed neural networks, and foundation-model-based perception architectures may allow soft robots to infer hidden physical states from incomplete and noisy sensor observations.[156-158] In addition, AI enables the integration of heterogeneous sensing modalities, including tactile, visual, force, strain, thermal, and proprioceptive information, into unified representations that may more accurately capture the true physical state of deformable bodies.[159-160] Such approaches are particularly important because no single sensing modality alone is typically sufficient to uniquely determine deformation and interaction states in soft systems.

This capability becomes especially significant in complex applications such as surgical robotics. In transluminal and minimally invasive robotic surgery, for example, AI-driven multimodal sensing frameworks may fuse endoscopic imaging, distributed force sensing, fiber-optic proprioception, ultrasound, and preoperative CT or MRI data into unified context-aware scene representations.[161] Foundation models and vision-language architectures may further support tissue segmentation, depth estimation, predictive tool-tissue interaction modeling, and shared autonomy.[162-163] More broadly, AI may eventually enable soft robots to reason about contact mechanics, environmental uncertainty, and adaptive interaction in ways that extend far beyond classical control theory. However, substantial challenges continue to limit progress. Soft robotic datasets are often small, weakly labeled, noisy, and poorly standardized. Sensor drift, material aging, fabrication variability, and platform-specific mechanics further reduce

transferability across systems. Moreover, purely data-driven models frequently struggle to generalize under changing physical conditions and may require prohibitively large training datasets. These limitations are particularly problematic in safety-critical domains such as surgery, rehabilitation, and wearable robotics.[164-165]

Future progress will therefore likely depend on hybrid frameworks that tightly integrate AI with physics-based understanding. Physics-informed learning, continual adaptation, self-supervised representation learning, and simulation-enhanced training may allow models to learn more efficiently while preserving physical consistency.[166] Standardized benchmarks, shared datasets, and generalized representations for deformable systems may also become increasingly important for cumulative progress across the field. Ultimately, the future of soft robotic perception may depend not simply on collecting more sensory data, but on developing intelligent systems capable of interpreting deformable physical reality itself.[167]

5. Manufacturing, 3D/4D Printing, and System Integration

5.1 Why Is Scalable Manufacturing Still a Bottleneck?

Although additive manufacturing has dramatically expanded the geometric complexity and design freedom available in soft robotics, scalable fabrication remains one of the field's most significant unresolved bottlenecks.[168] Many of the most compelling demonstrations in soft robotics continue to rely on labor-intensive fabrication procedures, handcrafted assembly, or highly specialized manufacturing conditions that are difficult to scale toward industrial production and real-world deployment.[169-170] Consequently, the gap between laboratory prototypes and robust manufacturable systems remains substantial.

A primary limitation lies in the materials themselves. Most printable soft materials still struggle to simultaneously achieve high stretchability, toughness, fatigue resistance, environmental stability, and processability.[171] Elastomeric systems frequently exhibit poor interlayer adhesion, curing-induced shrinkage, viscoelastic creep, or mechanical

degradation under cyclic loading.[172] These limitations become particularly problematic in applications requiring long-term durability, repeatable actuation, or exposure to harsh operating environments.[173-174] Furthermore, many high-performance soft materials remain incompatible with existing additive manufacturing processes because of viscosity constraints, slow curing kinetics, or insufficient print resolution.[175] Multimaterial integration presents an additional and equally important challenge. Functional soft robots often require seamless coupling between compliant actuators, rigid structural supports, embedded electronics, sensing networks, and conductive pathways. However, existing extrusion-based and photopolymerization-based printing methods frequently struggle to maintain reliable interfaces between chemically and mechanically distinct materials. Delamination, residual stress accumulation, interfacial failure, and differential mechanical response remain common failure modes in multimaterial systems.[176-177] These issues become even more severe as device complexity and operational strain increase.

Scalability challenges extend beyond fabrication alone. Reproducibility, manufacturing speed, quality control, and post-processing complexity continue to limit commercialization and broader technological adoption.[178] Many soft robotic systems still require extensive manual assembly, curing, alignment, or calibration, reducing throughput and increasing variability between devices.[83] Moreover, existing computational design tools remain insufficient for highly deformable systems exhibiting strong nonlinear coupling between actuation, deformation, and material response.[179] Conventional topology optimization frameworks often fail to account for print-induced anisotropy, residual stress, viscoelasticity, or multimaterial interface mechanics, forcing designers to rely heavily on iterative trial-and-error approaches. Future scalable manufacturing will therefore require simultaneous advances across multiple domains, including printable material chemistry, interface engineering, multimaterial additive manufacturing, and computational design automation.[180] Emerging approaches involving hybrid manufacturing, embedded printing, digital materials, AI-assisted process optimization, and closed-loop manufacturing control

may eventually enable reliable large-scale production of multifunctional soft robotic systems.[181] Ultimately, manufacturing may become not merely a downstream implementation step, but a central determinant of soft robotic functionality itself.

5.2 Can 4D Printing Program Intelligence into Matter?

4D printing is emerging as one of the most transformative frontiers in soft robotics because it extends additive manufacturing beyond static geometry toward dynamically adaptive matter.[182-183] Unlike conventional 3D printing, where fabricated structures maintain fixed properties after production, 4D printing incorporates stimuli-responsive materials capable of changing shape, stiffness, morphology, or functionality in response to external inputs such as temperature, light, magnetic fields, humidity, electric fields, or chemical environments.[184-185] This capability fundamentally shifts fabrication from a passive manufacturing process toward the programming of dynamic physical behavior directly into material architectures.

A central scientific challenge in 4D printing lies in controlling local morphology, anisotropy, and internal organization during fabrication. In biological systems, highly organized hierarchical structures allow tissues to exhibit directional mechanical response, adaptive deformation, and programmable functionality. Replicating such capabilities in synthetic materials requires precise control over the alignment of nanoparticles, liquid crystals, polymer chains, or reinforcing fillers within printed architectures.[186] Directional alignment can generate anisotropic mechanical behavior and programmable shape transformation, enabling structures that bend, twist, contract, or morph predictably under external stimulation.[187-188] Emerging fabrication strategies, including magnetic-field-assisted extrusion,[189] electrically assisted photopolymerization,[190] shear-induced macromolecular orientation,[191] and spatially controlled curing,[192] are beginning to provide pathways toward such programmable matter. 4D printing also intersects deeply with broader concepts of embodied intelligence and physical adaptation. Structures capable of dynamically altering morphology, stiffness distribution, sensing behavior, or mechanical response begin to

blur the traditional distinction between fabrication and function.[193] In such systems, intelligence may become partially embedded within the material architecture itself rather than relying exclusively on centralized computation or active control.[194] Shape-changing structures, programmable mechanical metamaterials, and adaptive morphologies may allow future soft robots to physically respond to environmental uncertainty through intrinsic material dynamics.

Beyond shape transformation alone, future 4D-printed systems may integrate distributed sensing, self-healing behavior, energy management, and local computation within unified architectures.[195] Such multifunctional systems could enable robotic bodies that continuously adapt their geometry and mechanical properties in response to changing tasks or environmental conditions. For example, soft grippers may dynamically tune stiffness during grasping,[196] wearable robots may locally adapt compliance to human movement,[197] and soft locomotion systems may alter gait through morphology reconfiguration.[198] Nevertheless, substantial technological barriers remain. Many stimuli-responsive materials still exhibit limited actuation force, slow response times, poor fatigue resistance, or restricted environmental stability.[199] Simultaneously controlling multi-material interfaces, local anisotropy, and large-scale manufacturing reproducibility remains highly challenging.[200-201] Future advances will therefore require tighter integration between material chemistry, additive manufacturing physics, multiphysics simulation, and AI-assisted design optimization. Ultimately, 4D printing may evolve from a fabrication technique into a platform for programming adaptive physical intelligence directly into matter itself.

5.3 How Can Manufacturing and Design Be Co-Optimized?

As soft robotic systems become increasingly multifunctional and structurally complex, manufacturing and computational design can no longer be treated as independent sequential processes. In conventional engineering workflows, structures are first designed computationally and then fabricated using available manufacturing techniques. However, in soft robotics, material behavior, fabrication processes, sensing integration,

and mechanical functionality are strongly interdependent. Consequently, future soft robotic systems will likely require deeply integrated co-design frameworks that simultaneously optimize geometry, materials, sensing architectures, actuation strategies, and fabrication constraints.[202-205]

This challenge arises because soft robotic functionality is fundamentally governed by coupled multiphysics interactions. Mechanical deformation, embedded sensing, local stiffness distribution, actuation response, and environmental interaction are tightly linked across scales. Designers must simultaneously consider geometry, material distribution, structural compliance, and fabrication techniques and other parameters. Traditional design methodologies based on simplified analytical models or isolated component optimization therefore become insufficient for predicting the performance of highly deformable systems. Future computational frameworks will likely rely heavily on AI-assisted inverse design, topology optimization, digital twins, and manufacturing-aware simulation environments.[206-207] AI-driven optimization tools may become particularly important and may therefore help identify non-intuitive architectures that maximize functionality while satisfying manufacturing constraints.[208-209] Digital twin frameworks may further enable continuous integration between simulation, fabrication, and experimental validation.[210-211] By incorporating real-time manufacturing data, material characterization, and sensor feedback into adaptive simulation environments, future systems may iteratively refine both design and fabrication processes simultaneously. This capability could become particularly important for personalized wearable robotics, biointegrated devices, and multimaterial soft machines where small variations in fabrication significantly influence performance.

At the same time, manufacturing constraints themselves must increasingly become active variables within the design process.[212] Future frameworks may directly optimize print trajectories, local microstructure alignment, curing conditions, interface formation, and material gradients alongside robotic functionality. Such approaches would represent a shift from designing robots first and fabricating them afterward, toward

designing fabrication processes and robotic behavior as inseparable components of a unified system. Ultimately, co-optimization of manufacturing and design may become essential for realizing scalable, reliable, and multifunctional soft robotic systems.

6. AI-Integrated Soft Robotics and Physical AI

6.1 Can Soft Bodies Reduce the Need for Computation?

One of the most profound conceptual contributions of soft robotics is the realization that intelligent behavior does not necessarily emerge solely from centralized computation.[213-214] Traditional robotics has historically relied on computationally intensive planning, sensing, and control architectures to manage interaction with uncertain environments. In contrast, soft robotic systems exploit morphology, compliance, and material dynamics to physically adapt to environmental variability, effectively offloading portions of computation into the body itself. This concept, often referred to as embodied intelligence or physical intelligence, suggests that the mechanical structure of a robot can actively participate in sensing, control, and decision-making processes.[90, 215-216]

This capability may become increasingly important as robotics moves toward the broader vision of physical AI.[217] Current AI-driven robotic systems often depend heavily on large-scale neural networks, centralized processing, extensive simulation infrastructure, and massive computational resources. While such approaches have achieved remarkable progress in perception and planning, scaling them toward real-world embodied systems remains challenging due to energetic cost, latency, safety concerns, and environmental unpredictability. Soft robotic bodies offer an alternative pathway by enabling passive adaptation, shock absorption, environmental conformity, and robust interaction through intrinsic mechanical properties rather than explicit algorithmic computation.[218] For example, compliant bodies can naturally conform to uncertain geometries during grasping, locomotion, or human interaction without requiring exhaustive environmental modeling or high-frequency control updates.[219] Such physical adaptation dramatically simplifies planning and control requirements.

Similarly, soft mechanical systems can absorb impacts, redistribute forces, and stabilize interaction dynamics through passive mechanics alone. In this sense, morphology itself becomes computationally functional and intelligence comes from the interaction between body structure, environmental physics, and adaptive morphology.[220]. Physical reservoir computing further extends this concept by treating the nonlinear dynamics of soft structures as computational substrates capable of processing temporal information directly.[221-222] Rather than executing all computation digitally, the body itself may perform aspects of filtering, memory, adaptation, and signal transformation through intrinsic physical dynamics.[90] Such approaches suggest that future robots may increasingly combine material computation with lightweight digital control architectures, reducing energetic and computational overhead.

Nevertheless, embodied intelligence does not eliminate the need for computation altogether. Instead, the key challenge lies in determining how computation should be distributed across morphology, materials, sensing, and digital control. Future progress will likely require frameworks that seamlessly integrating conventional computation intelligence with physical intelligence into one robotic agent. Ultimately, soft robotics may provide one of the most promising pathways toward physically efficient, scalable, and resilient forms of machine intelligence.

6.2 How Can AI Learn the Physics of Deformable Robots?

Artificial intelligence systems developed for rigid robotics frequently struggle when applied to soft and deformable systems because soft bodies exhibit highly nonlinear, high-dimensional, and often poorly modeled dynamics. Unlike rigid mechanisms with discrete joints and relatively predictable kinematics, soft robots continuously deform under environmental interaction, resulting in complex coupling between actuation, sensing, contact mechanics, and material behavior. These dynamics are strongly influenced by hysteresis, viscoelasticity, environmental variability, and embodiment-specific properties, making accurate analytical modeling extremely difficult. Consequently, one of the central challenges in AI-integrated soft robotics is enabling

learning systems to acquire physically meaningful representations of deformable behavior.[223]

Purely data-driven approaches, while powerful, often remain insufficient for this task. Large neural networks trained only on experimental data frequently suffer from poor sample efficiency, limited interpretability, and weak generalization under changing operating conditions.[224] Collecting sufficiently large and representative datasets for soft robotic systems is also inherently challenging because fabrication variability, material aging, and environmental interaction produce significant system-to-system differences.[225] These limitations become especially problematic in applications requiring reliability and safety, including surgical robotics, wearable devices, and human-interactive systems. Future soft robotic AI will therefore likely require hybrid learning frameworks that integrate physics-based priors with data-driven learning strategies.[226-227] Physics-informed neural networks, differentiable simulators, self-supervised learning, and model-constrained optimization may provide pathways toward more robust and physically grounded learning.[228] By embedding conservation laws, constitutive mechanics, geometric constraints, or contact physics directly into learning architectures, such approaches may improve sample efficiency and generalization while preserving physical consistency. Sim-to-real transfer remains another major unresolved challenge.[229] High-fidelity simulation of deformable systems is computationally expensive and often fails to fully capture the complex material and environmental interactions observed in reality. Bridging this gap may require adaptive simulation environments, online system identification, domain randomization, and continual learning strategies capable of updating models during real-world interaction. Digital twin frameworks integrating real-time sensor feedback with adaptive simulation may further help synchronize learned models with evolving physical systems.

Beyond learning deformable robot dynamics alone, another emerging frontier involves modelling soft robotic interaction as a continuously evolving coupled system between humans and machines rather than as a static control problem.[230-231] Future assistive and

wearable soft robotic systems may increasingly rely on closed-loop co-adaptation, in which both the robot and the user continuously learn from one another over time.[232-233] Such frameworks may enable robotic systems to dynamically adjust assistance strategies, feedback modalities, and interaction behaviors according to the user's evolving neural, physical, and behavioural state. Moreover, future AI systems may need to learn not only robot dynamics, but also how morphology itself contributes to behavior. Because embodiment fundamentally shapes interaction dynamics in soft robotics, learning architectures may increasingly need to jointly model materials, geometry, control, and environmental coupling as a unified physical system. Achieving this objective will require much deeper integration between mechanics, simulation, machine learning, and embodied interaction theory. Ultimately, enabling AI to understand deformable physics may become one of the defining scientific challenges underlying the future of intelligent soft robotic systems.

6.3 Is Soft Robotics Essential for the Future of Physical AI?

Soft robotics may ultimately become essential for realizing practical and scalable forms of physical artificial intelligence.[90] Although recent advances in robotics have been driven largely by progress in machine learning, large-scale simulation, and foundation-model-based perception, computation alone may not be sufficient for achieving robust autonomy in the physical world.[234] Biological intelligence does not emerge exclusively from centralized information processing. Instead, adaptive behavior arises through deep coupling between body mechanics, sensing, environmental interaction, and distributed control across multiple scales. Soft robotics provides a compelling framework for reproducing aspects of this embodied intelligence in artificial systems. Importantly, future physical AI systems may not only interact with environments, but also continuously co-adapt with human users through closed-loop neural, sensory, and behavioural interaction.[235] In assistive robotics, rehabilitation, and wearable systems, intelligent soft machines may increasingly function as adaptive partners rather than passive tools.[236] Such systems could continuously personalize assistance according to evolving neural activity, motor behaviour, and user engagement, enabling more natural

and biologically integrated forms of human–robot interaction.[237]

Current AI-driven robotic platforms increasingly depend on enormous computational infrastructure, centralized processing pipelines, and data-intensive training procedures. While highly effective in structured environments, these approaches often struggle when robots encounter uncertain terrain, physical variability, contact-rich manipulation, or incomplete environmental information.[55, 238] In contrast, soft robotic bodies naturally provide passive adaptation, resilience, compliance, and safe interaction through their intrinsic material properties.[239] By physically embedding adaptability into morphology itself, soft robots may substantially reduce the computational burden associated with planning, perception, and control. In such systems, intelligence emerges not solely from abstract algorithms, but from the interaction between materials, sensing, and environmental physics. Compliance allows robots to absorb uncertainty physically rather than resolving every interaction computationally.[240] Morphological adaptation enables robust behavior under incomplete information.[241] Distributed sensing and self-organizing material responses further contribute to decentralized intelligence that may complement conventional AI architectures.[242-243]

In addition, soft robotics also introduces new opportunities for energy-efficient and sustainable AI systems. Purely computational approaches to physical intelligence may become increasingly impractical as robotic systems scale in complexity and autonomy. Soft robotic architectures capable of leveraging passive mechanics, embodied adaptation, and material-level intelligence may significantly reduce energetic cost, sensing complexity, and control overhead.[244] Physical reservoir computing and programmable mechanical systems further suggest that future robots may partially compute through body dynamics themselves rather than relying exclusively on GPU-intensive processing.[245-246] At the same time, soft robotics should not be viewed as replacing traditional AI, but rather as complementing and extending it. In this sense, soft robotics may represent not merely a subfield of robotics, but a foundational paradigm for next-generation intelligent machines whose cognition is inseparable from

their physical embodiment.

7. Biohybrid Systems, Sustainability, and Living Soft Matter

7.1 Can Soft Robots Become More Life-Like?

One of the most ambitious long-term visions in soft robotics is the transition from compliant machines toward life-like adaptive matter capable of growth, self-regulation, environmental adaptation, and distributed intelligence.[247-248] Unlike conventional robotic systems that separate sensing, actuation, control, and energy management into discrete subsystems, living organisms integrate these functionalities seamlessly across hierarchical biological architectures. Muscles generate force while simultaneously providing proprioceptive feedback; vascular networks distribute energy and biochemical signals; cellular assemblies continuously remodel tissue properties in response to environmental stimuli. Replicating even a fraction of this multifunctional integration remains a major scientific frontier.

Consequently, future soft robotics may increasingly move beyond the paradigm of embedding rigid electronic components into compliant substrates. Instead, researchers are beginning to explore active matter systems whose functionality emerges intrinsically from coupled mechanical, chemical, and biological interactions.[249] Biohybrid robotics, for example, integrates living muscle cells, engineered tissues, or microbial systems with synthetic scaffolds to create actuators capable of self-healing, biochemical adaptation, and energy-efficient force generation.[250-251] Similarly, chemically driven soft matter systems may exploit osmotic transport, ionic gradients, or reaction-diffusion dynamics to generate autonomous behavior without centralized electronic control. Plants and soft-bodied organisms are also becoming important biological inspirations for future adaptive systems.[252-253] Unlike animals that primarily rely on rapid locomotion, plants achieve intelligence through slow but highly adaptive growth, distributed sensing, and environmental responsiveness.[254] Root-inspired robots, growing robotic structures, and morphologically adaptive materials illustrate how robotic intelligence may emerge through physical interaction with the environment

itself.[255] Such approaches challenge conventional assumptions that robotic intelligence must rely exclusively on centralized computation.

However, substantial challenges remain unresolved before truly life-like soft robots become feasible. Living systems possess extraordinary capabilities for self-organization, metabolic energy management, self-repair, and long-term adaptation that synthetic materials still struggle to reproduce.[256] Biohybrid systems frequently face limited lifespan, poor environmental stability, and difficulties in maintaining biological viability outside controlled laboratory conditions.[257] Moreover, integrating biochemical processes with electronic sensing and robotic control introduces significant challenges in interfacing fundamentally different physical domains. Future progress may therefore depend on hybrid frameworks that combine synthetic soft matter, programmable materials, biological components, etc. Rather than attempting to replicate biology directly, the next generation of soft robots may instead selectively incorporate life-like principles such as distributed adaptation, self-organization, and multifunctional embodiment into engineered systems.

7.2 How Can Sustainability Become a Design Principle Rather Than an Afterthought?

As soft robotics moves closer toward real-world deployment, sustainability is emerging as a critical scientific and technological consideration rather than a secondary engineering concern.[258] Many existing soft robotic systems rely heavily on synthetic elastomers, fluorinated coatings, petroleum-derived polymers, and difficult-to-recycle composite materials that present significant environmental challenges throughout their lifecycle.[259] While such materials often provide excellent mechanical compliance and chemical stability, their environmental persistence and limited recyclability increasingly conflict with broader societal demands for sustainable technologies.

Future soft robotic systems will therefore require environmentally conscious material design from the earliest stages of development. Biodegradable elastomers, recyclable polymer networks, peptide-based coatings, and naturally derived soft materials are

becoming increasingly important research directions.[260-263] Bioinspired material systems may provide particularly promising pathways because biological organisms routinely achieve remarkable combinations of adaptability, durability, and environmental compatibility using abundant and biodegradable building blocks.[264] Emerging fluorine-free surface chemistries, self-healing hydrogels, and dynamic covalent polymer networks illustrate how sustainability and functionality may eventually become mutually reinforcing rather than competing objectives.[265-266] Sustainability in soft robotics extends far beyond material selection alone. Manufacturing methods, energy consumption, device lifespan, repairability, and end-of-life recovery must increasingly be considered within integrated lifecycle design frameworks. Current fabrication processes often involve solvent-intensive manufacturing, multi-step curing procedures, and non-recoverable multimaterial assemblies that complicate large-scale sustainable production.[267] Future scalable systems may therefore require modular architectures, reversible interfaces, and reprocessable material systems that support repair, disassembly, and recycling.

Sustainability may also fundamentally reshape how robotic systems interact with natural environments.[268-269] Soft robots designed for agriculture, environmental monitoring, marine exploration, or biomedical applications must increasingly minimize ecological disruption while maintaining long-term operational stability.[270] In this context, environmental compatibility becomes deeply linked to embodied interaction itself. Soft robots capable of physically adapting to ecosystems through compliant mechanics, biodegradable interfaces, and low-impact environmental coupling may ultimately provide more sustainable modes of robotic deployment.[271] At a deeper level, sustainability may evolve into a core design philosophy for soft robotics rather than an external engineering constraint. Biological systems do not optimize exclusively for performance metrics such as speed or force output; instead, they balance adaptability, resilience, energy efficiency, repairability, and environmental integration simultaneously. Future soft robotic systems may increasingly adopt similar principles, prioritizing long-term coexistence with complex environments over purely maximal

mechanical performance.

7.3 Can Surface Engineering Redefine Environmental Interaction?

Surface engineering plays a uniquely important role in soft robotics because compliant systems often interact intimately with delicate, wet, contaminated, biologically active, or highly unstructured environments.[272] Unlike rigid robots that frequently rely on isolated point contacts or mechanically constrained interfaces, soft robots establish large-area conformal contact with surrounding surfaces. Consequently, interfacial phenomena such as adhesion, friction, wettability, biofouling, and contamination become central determinants of robotic functionality and reliability.[273]

Current surface engineering strategies, however, remain limited by both material and environmental constraints. Many existing superhydrophobic and antifouling coatings depend on fluorinated compounds that exhibit poor environmental compatibility, limited long-term durability, and mechanical instability under repeated deformation.[274] When applied to highly deformable soft materials, these coatings frequently suffer from cracking, delamination, or loss of functionality during cyclic loading. Such limitations become particularly problematic in biomedical robotics, underwater systems, and wearable devices that require continuous operation under complex environmental conditions.[275-277] Emerging research is therefore increasingly shifting toward bioinspired adaptive interfaces capable of dynamically responding to environmental stimuli. Biological surfaces such as lotus leaves, butterfly wings, gecko feet, fish skin, and human tissue provide remarkable examples of multifunctional interfaces combining self-cleaning, directional adhesion, antimicrobial activity, drag reduction, and environmental responsiveness simultaneously.[278-280] Inspired by these systems, researchers are developing peptide-based coatings, anisotropic microstructures, switchable wettability surfaces, and mechanically adaptive interfaces capable of maintaining functionality under large deformation.[281]

In soft robotics, surface engineering may ultimately evolve far beyond passive

protective coatings. Future robotic skins may become active interfacial systems capable of dynamically regulating adhesion, friction, permeability, sensing sensitivity, and biochemical interaction in real time.[135, 282] Such adaptive surfaces could allow robots to transition between gripping and release states, regulate fluid transport, resist biofouling, or selectively interact with biological tissues depending on environmental conditions.[283] Coupling surface functionality with embedded sensing may further enable robots to locally adapt interfacial behavior in response to tactile feedback or environmental stimuli.[284]

Surface engineering also intersects with broader questions regarding embodied intelligence and environmental adaptation. In many biological organisms, intelligent behavior emerges not only from neural processing but also from highly specialized physical interfaces with the environment.[285] Similarly, future soft robots may increasingly rely on adaptive surface properties to simplify control, enhance perception, and improve environmental robustness. In this sense, surfaces may become computational and functional components of the robotic body itself rather than merely external protective layers.[286]

8. Real-World Applications of Soft Robotics

8.1 What Are the True Killer Applications of Soft Robotics?

As soft robotics matures beyond its early exploratory phase, the field is increasingly identifying application domains where compliance enables fundamentally new interaction capabilities that rigid systems cannot easily replicate.[287] Rather than directly replacing conventional rigid robots, soft robotic systems appear most transformative in environments characterized by uncertainty, fragility, biological interaction, or complex physical contact.[1, 14, 58]

Surgical robotics represents one of the clearest examples of this opportunity.[288] Human anatomy contains highly constrained, deformable, and delicate structures that are often difficult to access safely using rigid instruments. Soft continuum manipulators,

compliant catheters, and deformable surgical devices can navigate tortuous anatomical pathways while reducing tissue damage and improving mechanical conformity.[289] Combined with multimodal sensing and AI-assisted control, future soft surgical systems may enable minimally invasive procedures with substantially enhanced dexterity and safety.[163] Wearable robotics and assistive technologies constitute another major translational frontier.[290] Traditional exoskeletons frequently suffer from discomfort, rigid misalignment with human joints, and restricted mobility. Soft wearable systems, in contrast, conform naturally to the body and distribute forces more safely across large contact areas.[291] Pneumatic artificial muscles, textile-based actuators, and compliant assistive devices are increasingly demonstrating potential for rehabilitation, mobility assistance, and long-duration human augmentation.[292-293] Underwater robotics also strongly benefits from soft-bodied adaptation.[294-295] Marine environments are highly dynamic, hydrodynamically uncertain, and biologically complex. Inspired by fish, cephalopods, and other aquatic organisms, soft underwater robots can exploit body compliance to achieve adaptive propulsion, enhanced maneuverability, and safer interaction with fragile ecosystems.[75] Similarly, agricultural robotics increasingly utilizes soft grippers to handle delicate crops such as fruits and vegetables without bruising or damage.[296-297]

Dexterous manipulation remains another highly promising application area.[298] Human hands achieve remarkable versatility through compliance, distributed tactile sensing, and adaptive contact mechanics. Soft robotic grippers capable of passive shape adaptation can simplify grasp planning and improve robustness when handling unknown objects.[299] Integrating tactile sensing, AI-driven perception, and variable stiffness control may further enable manipulation capabilities approaching biological dexterity.[300] These emerging applications reveal a broader principle: soft robotics is most valuable not where softness simply replaces rigidity, but where compliance fundamentally transforms physical interaction. The true “killer applications” of soft robotics are therefore likely to emerge in domains where adaptability, safety, conformability, and embodied environmental interaction are intrinsically required.

8.2 Why Do Most Soft Robots Still Remain Laboratory Prototypes?

Despite remarkable scientific progress over the past decade, the vast majority of soft robotic systems remain confined to laboratory demonstrations and proof-of-concept prototypes rather than achieving widespread real-world deployment. This translational gap reflects not a single technological limitation, but rather a combination of unresolved challenges spanning materials, actuation, sensing, manufacturing, power systems, and systems integration.[290, 293]

One of the most persistent obstacles involves durability and long-term reliability. Soft materials frequently experience fatigue, viscoelastic drift, tearing, delamination, and environmental degradation under repeated mechanical loading.[301] Interfaces between soft and rigid components often fail prematurely due to stress concentration and mismatch in mechanical properties.[302] Additionally, many soft sensors suffer from signal drift, hysteresis, and poor repeatability during long-term operation.[303] These limitations become especially problematic in wearable systems, surgical devices, and autonomous mobile robots where reliability and safety are essential. Power and actuation constraints further limit practical deployment. Many existing soft robots still depend on tethered pneumatic infrastructure, bulky external compressors, or laboratory-scale power supplies that severely restrict portability.[304] Electrically driven alternatives often struggle to simultaneously achieve high power density, large deformation, rapid response, and energy efficiency.[305] Similarly, onboard computation, sensing, and wireless communication remain difficult to integrate within highly deformable architectures.[306] Manufacturing scalability represents another major bottleneck. Many reported systems rely heavily on handcrafted fabrication procedures, laboratory-specific processes, or difficult-to-reproduce assembly techniques. Consequently, reproducibility across laboratories remains limited, while large-scale manufacturing and quality control remain poorly developed. Existing additive manufacturing approaches also continue to struggle with multimaterial integration, interface reliability, and throughput limitations.[307]

Beyond hardware limitations, system-level autonomy remains insufficiently developed. Many soft robotic demonstrations still rely on simplified environments, external motion tracking, open-loop control, or human supervision. Robust deployment in real-world environments requires tightly integrated sensing, adaptive control, embodied intelligence, and environmental robustness that current systems rarely achieve simultaneously.[67, 308] Future progress will therefore require a transition from isolated component optimization toward holistic system engineering. Materials science, mechanics, AI, manufacturing, energy systems, and control architectures must increasingly be co-designed rather than developed independently. Ultimately, overcoming the laboratory-prototype barrier may represent one of the most important milestones determining whether soft robotics evolves into a transformative technological platform or remains primarily an academic research domain.

8.3 What Will Define the Next Generation of Deployable Soft Robots?

The next generation of deployable soft robots will likely be defined not by softness alone, but by the successful integration of multiple capabilities into unified adaptive systems. Early soft robotics research primarily focused on demonstrating mechanical compliance and bioinspired deformation. Future systems, however, must simultaneously achieve autonomy, perception, untethered operation, durability, manufacturability, intelligence, and environmental adaptability if they are to operate reliably in complex real-world environments.

This transition fundamentally shifts the field from component-level innovation toward system-level integration. Future soft robots must integrate distributed sensing, embedded actuation, onboard power management, adaptive control, AI-driven perception, and robust material architectures within highly deformable bodies. Such integration presents extraordinary scientific challenges because soft systems exhibit strong coupling between mechanics, sensing, actuation, and environmental interaction. Consequently, future deployable systems will likely require extensive co-design across

materials science, mechanics, manufacturing, electronics, AI, and computational design. Multifunctional materials capable of simultaneously providing structural support, sensing, and actuation may reduce system complexity while improving robustness. Similarly, hybrid soft-rigid architectures may enable robots to combine compliance and adaptability with load-bearing capability and precision control. Artificial intelligence will also play an increasingly central role. Future robots must interpret high-dimensional multimodal sensory information under uncertain environmental conditions while continuously adapting to material drift, contact variability, and changing task requirements. Self-supervised learning, physics-informed AI, and embodied learning frameworks may therefore become essential for achieving scalable autonomy in deformable systems.

At a broader level, the next generation of soft robots may increasingly resemble embodied physical organisms rather than collections of independently optimized subsystems. In human-interactive applications, such systems may further evolve toward co-adaptive embodied platforms capable of continuously personalizing interaction through long-term neural, sensory, and behavioural feedback. Ultimately, the defining feature of future deployable soft robots may not be softness itself, but the emergence of physically integrated adaptive machines capable of robust operation across uncertain real-world environments.

9. Concluding Perspective

Soft robotics is undergoing a profound transition from a field primarily concerned with compliant mechanisms and bioinspired motion toward a broader scientific framework centered on embodied physical intelligence. Across the diverse perspectives presented throughout this article, a consistent theme emerges: future robotic systems will likely derive functionality not from isolated subsystems alone, but from the deep integration of materials, morphology, mechanics, sensing, actuation, computation, and environmental interaction.

Several major trends collectively define this transition. Mechanics is increasingly being explored not only as a structural framework but also as a potential computational substrate capable of shaping perception, control, and adaptation through physical dynamics. Multifunctional materials are beginning to blur the boundaries between sensing, actuation, communication, and energy management. Distributed perception architectures are transforming deformable bodies into continuously sensing physical systems. Advances in manufacturing and programmable matter increasingly enable functionality to be encoded directly into geometry, anisotropy, and material organization. At the same time, artificial intelligence is progressively moving toward tighter integration with embodiment, where adaptive behavior emerges through continuous interaction between learning algorithms, physical morphology, and environmental feedback.

These developments suggest that the future of soft robotics will not be defined by softness alone. Rather, the field appears to be converging toward hybrid, multifunctional, and highly integrated architectures capable of combining compliance, structural stability, distributed intelligence, and environmental adaptability. In this sense, the most important contribution of soft robotics may not simply be the development of safer or more flexible machines, but the introduction of new principles for designing adaptive physical systems whose intelligence is inseparable from their material embodiment. At a deeper level, this transition also reflects a broader conceptual shift regarding the nature of intelligence in engineered systems. Conventional robotics has historically treated the body as passive hardware controlled by centralized computation. In contrast, emerging soft robotic paradigms increasingly recognize that intelligence can arise through coordinated interactions among material properties, morphology, mechanical dynamics, sensing architectures, and environmental coupling. Biological organisms provide compelling evidence that adaptive behavior is rarely produced by computation alone, but instead emerges from deeply integrated physical embodiment across multiple scales.

Realizing this vision will require overcoming substantial scientific and technological challenges. Durable multifunctional materials, scalable manufacturing methods, reliable distributed sensing, untethered power systems, physically grounded AI frameworks, and robust system-level integration remain major unresolved problems. Addressing these challenges will require increasingly close collaboration across mechanics, materials science, chemistry, photonics, artificial intelligence, manufacturing, biology, and systems engineering. Ultimately, the long-term significance of soft robotics may extend far beyond robotics itself. The field is increasingly contributing to a broader foundation for adaptive matter, programmable mechanobiological systems, and physically embodied artificial intelligence. Future soft robotic systems may therefore resemble neither conventional machines nor simple bioinspired replicas, but instead entirely new classes of life-like engineered matter capable of sensing, adapting, learning, and interacting with complex environments through deeply integrated physical embodiment.

Acknowledgements

Reference

1. Su, J.; He, K.; Li, Y.; Tu, J.; Chen, X., Soft Materials and Devices Enabling Sensorimotor Functions in Soft Robots. *Chem. Rev.* **2025,** *125* (12), 5848-5977.
2. Whitesides, G. M., Soft Robotics. *Angew. Chem. Int. Ed.* **2018,** *57* (16), 4258-4273.
3. Laschi, C.; Mazzolai, B.; Cianchetti, M., Soft Robotics: Technologies and Systems Pushing the Boundaries of Robot Abilities. *Sci Robot.* **2016,** *1* (1), eaah3690.
4. Kim, S.; Laschi, C.; Trimmer, B., Soft Robotics: A Bioinspired Evolution in Robotics. *Trends Biotechnol.* **2013,** *31* (5), 287-294.
5. Majidi, C., Soft Robotics: A Perspective—Current Trends and Prospects for the Future. *Soft robotics* **2014,** *1* (1), 5-11.
6. Trivedi, D.; Rahn, C. D.; Kier, W. M.; Walker, I. D., Soft Robotics: Biological Inspiration, State of the Art, and Future Research. *Appl. Bionics Biomech.* **2008,** *5* (3), 99-117.
7. Calisti, M.; Giorelli, M.; Levy, G.; Mazzolai, B.; Hochner, B.; Laschi, C.; Dario, P., An Octopus-Bioinspired Solution to Movement and Manipulation for Soft Robots.

Bioinspiration & biomimetics **2011,** *6* (3), 036002.
8. Laschi, C.; Cianchetti, M.; Mazzolai, B.; Margheri, L.; Follador, M.; Dario, P., Soft Robot Arm Inspired by the Octopus. *Advanced robotics* **2012,** *26* (7), 709-727.
9. Schulz, A. K.; Kaufmann, L. V.; Smith, L. T.; Philip, D. S.; David, H.; Lazovic, J.; Brecht, M.; Richter, G.; Kuchenbecker, K. J., Functional Gradients Facilitate Tactile Sensing in Elephant Whiskers. *Science* **2026,** *391* (6786), 712-718.
10. Daltorio, K. A.; Boxerbaum, A. S.; Horchler, A. D.; Shaw, K. M.; Chiel, H. J.; Quinn, R. D., Efficient Worm-Like Locomotion: Slip and Control of Soft-Bodied Peristaltic Robots. *Bioinspiration & biomimetics* **2013,** *8* (3), 035003.
11. Garm, A., Sensory Biology of Starfish—with Emphasis on Recent Discoveries in Their Visual Ecology. *Integrative and Comparative Biology* **2017,** *57* (5), 1082-1092.
12. Kerkman, J. N.; Daffertshofer, A.; Gollo, L. L.; Breakspear, M.; Boonstra, T. W., Network Structure of the Human Musculoskeletal System Shapes Neural Interactions on Multiple Time Scales. *Sci. Adv.* **2018,** *4* (6), eaat0497.
13. Shepherd, R. F.; Ilievski, F.; Choi, W.; Morin, S. A.; Stokes, A. A.; Mazzeo, A. D.; Chen, X.; Wang, M.; Whitesides, G. M., Multigait Soft Robot. *Proceedings of the national academy of sciences* **2011,** *108* (51), 20400-20403.
14. Shintake, J.; Cacucciolo, V.; Floreano, D.; Shea, H., Soft Robotic Grippers. *Adv. Mater.* **2018,** *30* (29), 1707035.
15. Matia, Y.; An, H. S.; Shepherd, R. F.; Lazarus, N., Magnetohydrodynamic Levitation for High-Performance Flexible Pumps. *Proceedings of the National Academy of Sciences* **2022,** *119* (29), e2203116119.
16. Digumarti, K. M.; Cacucciolo, V.; Shea, H. In *Dexterous Textile Manipulation Using Electroadhesive Fingers*, 2021 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE: 2021; pp 6104-6109.
17. Gamus, B.; Salem, L.; Gat, A. D.; Or, Y., Understanding Inchworm Crawling for Soft-Robotics. *IEEE Robotics and Automation Letters* **2020,** *5* (2), 1397-1404.
18. Veksler, Y.; Ben-Abu, E.; Gat, A. D., Fluid-Driven Director-Field Design Enables Versatile Deployment of Multistable Structures. *Adv. Intell. Syst.* **2024,** *6* (8), 2400179.
19. Ben-Abu, E.; Zigelman, A.; Veksler, Y.; Givli, S.; Filipov, E.; Lipson, H.; Gat, A. D., Reprogrammable 3d Shapes from 1d Metamaterial. *Adv. Mater. Technol.* **2025,** *10* (4), 2401113.
20. Luo, Y.; Abidian, M. R.; Ahn, J.-H.; Akinwande, D.; Andrews, A. M.; Antonietti, M.; Bao, Z.; Berggren, M.; Berkey, C. A.; Bettinger, C. J., Technology Roadmap for Flexible Sensors. *ACS nano* **2023,** *17* (6), 5211-5295.
21. Li, Y.; Su, J.; Chen, X., Damage-Free Transfer Printing. *Nat. Mater.* **2024,** *23* (10), 1313-1314.
22. Yasa, O.; Toshimitsu, Y.; Michelis, M. Y.; Jones, L. S.; Filippi, M.; Buchner, T.; Katzschmann, R. K., An Overview of Soft Robotics. *Annual Review of Control, Robotics, and Autonomous Systems* **2023,** *6*, 1-29.
23. Hawkes, E. W.; Majidi, C.; Tolley, M. T., Hard Questions for Soft Robotics. *Sci Robot.* **2021,** *6* (53), eabg6049.
24. Iida, F.; Laschi, C., Soft Robotics: Challenges and Perspectives. *Procedia Computer Science* **2011,** *7*, 99-102.

25. Yang, G.-Z.; Bellingham, J.; Dupont, P. E.; Fischer, P.; Floridi, L.; Full, R.; Jacobstein, N.; Kumar, V.; McNutt, M.; Merrifield, R., The Grand Challenges of Science Robotics. *Sci Robot.* **2018,** *3* (14), eaar7650.
26. Matia, Y.; Gat, A. D., Dynamics of Elastic Beams with Embedded Fluid-Filled Parallel-Channel Networks. *Soft robotics* **2015,** *2* (1), 42-47.
27. Matia, Y.; Elimelech, T.; Gat, A. D., Leveraging Internal Viscous Flow to Extend the Capabilities of Beam-Shaped Soft Robotic Actuators. *Soft robotics* **2017,** *4* (2), 126-134.
28. Matia, Y.; Kaiser, G. H.; Shepherd, R. F.; Gat, A. D.; Lazarus, N.; Petersen, K. H., Harnessing Nonuniform Pressure Distributions in Soft Robotic Actuators. *Adv. Intell. Syst.* **2023,** *5* (2), 2200330.
29. Caasenbrood, B.; Pogromsky, A.; Nijmeijer, H., Control-Oriented Models for Hyperelastic Soft Robots through Differential Geometry of Curves. *Soft Robotics* **2023,** *10* (1), 129-148.
30. Mishra, M. K.; Chakraborty, G.; Samantaray, A. K., Trajectory Tracking Control of a Pneumatically Actuated Continuum Manipulator in the Presence of Obstacles by Using Terminal Sliding Mode Control. *ISA Trans.* **2023,** *143*, 79-93.
31. Ben Abu, E.; Veksler, Y.; Elbaz, S.; Zigelman, A.; Gat, A. D., Growing Structure Based on Viscous Actuation of Constrained Multistable Elements. *Adv. Mater. Technol.* **2023,** *8* (14), 2202184.
32. Cai, P.; Wang, C.; Gao, H.; Chen, X., Mechanomaterials: A Rational Deployment of Forces and Geometries in Programming Functional Materials. *Adv. Mater.* **2021,** *33* (46), 2007977.
33. Lee, R. H.; Mulder, E. A. B.; Hopkins, J. B., Mechanical Neural Networks: Architected Materials That Learn Behaviors. *Sci Robot.* **2022,** *7* (71), eabq7278.
34. Bertoldi, K.; Vitelli, V.; Christensen, J.; Van Hecke, M., Flexible Mechanical Metamaterials. *Nat. Rev. Mater.* **2017,** *2* (11), 1-11.
35. Kortman, V. G.; Mazzolai, B.; Sakes, A.; Jovanova, J., Perspectives on Intelligence in Soft Robotics. *Adv. Intell. Syst.* **2025,** *7* (1), 2400294.
36. Sun, F.; Chen, R.; Ji, T.; Luo, Y.; Zhou, H.; Liu, H., A Comprehensive Survey on Embodied Intelligence: Advancements, Challenges, and Future Perspectives. *CAAI Artificial Intelligence Research* **2024,** *3* (9150042), 1.
37. Füchslin, R. M.; Dzyakanchuk, A.; Flumini, D.; Hauser, H.; Hunt, K. J.; Luchsinger, R. H.; Reller, B.; Scheidegger, S.; Walker, R., Morphological Computation and Morphological Control: Steps toward a Formal Theory and Applications. *Artif. Life* **2013,** *19* (1), 9-34.
38. Zhao, Q.; Nakajima, K.; Sumioka, H.; Hauser, H.; Pfeifer, R. In *Spine Dynamics as a Computational Resource in Spine-Driven Quadruped Locomotion*, 2013 IEEE/RSJ International conference on intelligent robots and systems, IEEE: 2013; pp 1445-1451.
39. Wang, J.; Zhou, Z.; Kahak, A.; Li, S., Embodying Physical Computing into Soft Robots. *Nat. Commun.* **2026**.
40. Wehner, M.; Truby, R. L.; Fitzgerald, D. J.; Mosadegh, B.; Whitesides, G. M.; Lewis, J. A.; Wood, R. J., An Integrated Design and Fabrication Strategy for Entirely Soft, Autonomous Robots. *Nature* **2016,** *536* (7617), 451-455.

41. Drotman, D.; Jadhav, S.; Sharp, D.; Chan, C.; Tolley, M. T., Electronics-Free Pneumatic Circuits for Controlling Soft-Legged Robots. *Sci Robot.* **2021,** *6* (51), eaay2627.
42. Truby, R. L.; Lewis, J. A., Printing Soft Matter in Three Dimensions. *Nature* **2016,** *540* (7633), 371-378.
43. Wang, T.; Pierce, C.; Kojouharov, V.; Chong, B.; Diaz, K.; Lu, H.; Goldman, D. I., Mechanical Intelligence Simplifies Control in Terrestrial Limbless Locomotion. *Sci Robot.* **2023,** *8* (85), eadi2243.
44. Laschi, C.; Cianchetti, M., Soft Robotics: New Perspectives for Robot Bodyware and Control. *Frontiers in bioengineering and biotechnology* **2014,** *2*, 3.
45. Bajo, A.; Simaan, N., Hybrid Motion/Force Control of Multi-Backbone Continuum Robots. *The International journal of robotics research* **2016,** *35* (4), 422-434.
46. Xue, W.; Jian, B.; Jin, L.; Wang, R.; Ge, Q., Origami Robots: Design, Actuation, and 3d Printing Methods. *Adv. Mater. Technol.* **2025,** *10* (17), e00278.
47. Vanderborght, B.; Albu-Schäffer, A.; Bicchi, A.; Burdet, E.; Caldwell, D. G.; Carloni, R.; Catalano, M.; Eiberger, O.; Friedl, W.; Ganesh, G., Variable Impedance Actuators: A Review. *Robotics and autonomous systems* **2013,** *61* (12), 1601-1614.
48. Li, M.; Pal, A.; Aghakhani, A.; Pena-Francesch, A.; Sitti, M., Soft Actuators for Real-World Applications. *Nat. Rev. Mater.* **2022,** *7* (3), 235-249.
49. Greer, J. R.; Deshpande, V. S., Three-Dimensional Architected Materials and Structures: Design, Fabrication, and Mechanical Behavior. *MRS Bull.* **2019,** *44* (10), 750-757.
50. Li, S.; Fang, H.; Sadeghi, S.; Bhovad, P.; Wang, K. W., Architected Origami Materials: How Folding Creates Sophisticated Mechanical Properties. *Adv. Mater.* **2019,** *31* (5), 1805282.

51. Goswami, D.; Liu, S.; Pal, A.; Silva, L. G.; Martinez, R. V., 3d-Architected Soft Machines with Topologically Encoded Motion. *Adv. Funct. Mater.* **2019,** *29* (24), 1808713.
52. Pilania, V.; Gupta, K., Mobile Manipulator Planning under Uncertainty in Unknown Environments. *The International Journal of Robotics Research* **2018,** *37* (2-3), 316-339.
53. Saund, B.; Choudhury, S.; Srinivasa, S.; Berenson, D. In *The Blindfolded Robot: A Bayesian Approach to Planning with Contact Feedback*, The International Symposium of Robotics Research, Springer: 2019; pp 443-459.
54. Michaux, J.; Holmes, P.; Zhang, B.; Chen, C.; Wang, B.; Sahgal, S.; Zhang, T.; Dey, S.; Kousik, S.; Vasudevan, R., Can't Touch This: Real-Time, Safe Motion Planning and Control for Manipulators under Uncertainty. *IEEE Transactions on Robotics* **2025**.
55. Billard, A.; Kragic, D., Trends and Challenges in Robot Manipulation. *Science* **2019,** *364* (6446), eaat8414.
56. Manti, M.; Cacucciolo, V.; Cianchetti, M., Stiffening in Soft Robotics: A Review of the State of the Art. *IEEE Robotics & Automation Magazine* **2016,** *23* (3), 93-106.
57. Carton, M.; Kowalewski, J. F.; Guo, J.; Alpert, J. F.; Garg, A.; Revier, D.; Lipton,

J. I., Bridging Hard and Soft: Mechanical Metamaterials Enable Rigid Torque Transmission in Soft Robots. *Sci Robot.* **2025,** *10* (100), eads0548.
58. Rus, D.; Tolley, M. T., Design, Fabrication and Control of Soft Robots. *Nature* **2015,** *521* (7553), 467-475.
59. Naleway, S. E.; Porter, M. M.; McKittrick, J.; Meyers, M. A., Structural Design Elements in Biological Materials: Application to Bioinspiration. *Adv. Mater.* **2015,** *27* (37), 5455-5476.
60. Cedillo-Servin, G.; Al-Jehani, E. A.; Rossy, T.; Teixeira, S. P.; Sage, F.; Domingues, R. M.; Raman, R.; Castilho, M., Meta-Adaptive Biomaterials: Multiscale, Spatiotemporal Organization and Actuation in Engineered Tissues. *Trends Biotechnol.* **2025**.
61. Hao, M.; Chen, Y.; Meng, Y.; Yan, E.; Qiu, J.; Xia, Y., Functionally Graded Surfaces and Materials: From Fabrication to Biomedical Applications. *Chem. Rev.* **2026**.
62. Wang, X.; Wei, R.; Chen, Z.; Pang, H.; Li, H.; Yang, Y.; Hua, Q.; Shen, G., Bioinspired Intelligent Soft Robotics: From Multidisciplinary Integration to Next-Generation Intelligence. *Advanced Science* **2025,** *12* (32), e06296.
63. Choi, J. Y.; Ahn, S.; Kim, D.; Heo, J.; Yun, W.-j.; Hong, S.; Bae, S.; Ahn, S.-H., Exploring Challenges and Opportunities in Manufacturing and Intelligence for Future Robotics. *International Journal of Precision Engineering and Manufacturing* **2025,** *26* (9), 2203-2222.
64. Sirithunge, C.; Chandiramani, V.; Xie, Y.; Hauser, H.; Conn, A.; Iida, F. In *Soft-Rigid Coupled Blade Leg Achieves Spatio-Temporal Terrain Classification with Minimal Sensor Configuration*, 2025 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE: 2025; pp 6016-6023.
65. Patterson, Z. J.; Sologuren, E. R.; Rus, D. In *Design of Trimmed Helicoid Soft-Rigid Hybrid Robots*, 2025 IEEE 8th International Conference on Soft Robotics (RoboSoft), IEEE: 2025; pp 1-7.
66. Dontu, S.; Kanhere, E.; Stalin, T.; Dharmawan, A. G.; Hegde, C.; Su, J.; Chen, X.; Magdassi, S.; Soh, G. S.; Valdivia Y. Alvarado, P., Applications of a Vacuum-Actuated Multi-Material Hybrid Soft Gripper: Lessons Learnt from Robosoft Manipulation Challenge. *Frontiers in Robotics and AI* **2024,** *11*, 1356692.
67. Rahimi Nohooji, H.; Voos, H., Compliant Robotics in Space: A Prospective Review of Soft and Deformable Systems for Space Missions. *Adv. Intell. Syst.* **2025,** *7* (7), 2400785.
68. Cianchetti, M.; Ranzani, T.; Gerboni, G.; Nanayakkara, T.; Althoefer, K.; Dasgupta, P.; Menciassi, A., Soft Robotics Technologies to Address Shortcomings in Today's Minimally Invasive Surgery: The Stiff-Flop Approach. *Soft robotics* **2014,** *1* (2), 122-131.
69. Chen, J.; Qiu, Q.; Ji, J., A Soft-Rigid Hybrid Robot-Assisted Feeding System with a Tendon-Driven Continuum Robot. *IEEE Robotics and Automation Letters* **2025,** *10* (12), 13217-13224.
70. Guo, B.; Zhao, Z.; Zhang, Z.; Lei, H., Selective Variable Stiffness Flexible Manipulator for Dexterous in-Hand Manipulation. *Soft Robotics* **2025,** *12* (6), 756-765.
71. Jadhav, S.; Majit, M. R. A.; Shih, B.; Schulze, J. P.; Tolley, M. T., Variable Stiffness

Devices Using Fiber Jamming for Application in Soft Robotics and Wearable Haptics. *Soft Robotics* **2022,** *9* (1), 173-186.
72. Brown, E.; Rodenberg, N.; Amend, J.; Mozeika, A.; Steltz, E.; Zakin, M. R.; Lipson, H.; Jaeger, H. M., Universal Robotic Gripper Based on the Jamming of Granular Material. *Proceedings of the National Academy of Sciences* **2010,** *107* (44), 18809-18814.
73. Howard, D.; Eiben, A. E.; Kennedy, D. F.; Mouret, J.-B.; Valencia, P.; Winkler, D., Evolving Embodied Intelligence from Materials to Machines. *Nature Machine Intelligence* **2019,** *1* (1), 12-19.
74. Gao, H.; Ji, B.; Jäger, I. L.; Arzt, E.; Fratzl, P., Materials Become Insensitive to Flaws at Nanoscale: Lessons from Nature. *Proceedings of the national Academy of Sciences* **2003,** *100* (10), 5597-5600.
75. Li, L.; Qin, B.; Gao, W.; Li, Y.; Zhang, Y.; Wang, B.; Kong, S.; Wang, J.; He, D.; Yu, J., Bioinspired Underwater Soft Robots: From Biology to Robotics and Back. *npj Robotics* **2026,** *4* (1), 25.
76. Kim, H.; Shin, H.; Park, S.; Shim, C.; Joe, S., Towards Advanced Intelligent and Perceptive Soft Grippers. *Adv. Intell. Syst.* **2026**, e202501459.
77. Thomas, S.; Garg, A.; Lipton, J., Torque-Transmitting Architected Metamaterials for Flexible and Extendable Tubular Robotics. *Adv. Intell. Syst.* **2026,** *8* (2), 2500110.
78. El-Atab, N.; Mishra, R. B.; Al-Modaf, F.; Joharji, L.; Alsharif, A. A.; Alamoudi, H.; Diaz, M.; Qaiser, N.; Hussain, M. M., Soft Actuators for Soft Robotic Applications: A Review. *Adv. Intell. Syst.* **2020,** *2* (10), 2000128.
79. Lee, J. E.; Sun, Y.-C.; Naguib, H. E., Multifunctional Soft Actuator Hybrids: A Review. *RSC Applied Polymers* **2025,** *3* (4), 767-792.
80. Polygerinos, P.; Correll, N.; Morin, S. A.; Mosadegh, B.; Onal, C. D.; Petersen, K.; Cianchetti, M.; Tolley, M. T.; Shepherd, R. F., Soft Robotics: Review of Fluid-Driven Intrinsically Soft Devices; Manufacturing, Sensing, Control, and Applications in Human-Robot Interaction. *Adv. Eng. Mater.* **2017,** *19* (12), 1700016.
81. Jang, J.; Choi, K.; Lee, G.; Cho, S.; Lee, M. G.; Choi, D.; Choi, K.; Choi, D.; Lee, Y., Toward Self-Sustained Soft Robotics: Triboelectric Nanogenerator–Dielectric Elastomer Actuator Hybrids. *EcoMat* **2026,** *8* (4), e70066.
82. Zhang, X.; Yu, S.; Li, M.; Zhang, M.; Zhang, C.; Wang, M., Enhanced Performance of Ipmc Actuator Based on Macroporous Multilayer Mcnts/Nafion Polymer. *Sensors and Actuators A: Physical* **2022,** *339*, 113489.
83. Li, Y.; Schreiber, S.; Yang, H.; Liu, M.; Little, J. M.; Cao, W.; Luo, Y.; Bao, Y.; Shih, C.-J.; Bai, H., From Molecules to Machines: A Multiscale Roadmap to Intelligent, Multifunctional Soft Robotics. *Chem. Rev.* **2025,** *125* (17), 8123-8245.
84. Liu, Q.; Peng, Z.; Sun, C.; Yang, H., Recent Advances in Multifunctional Soft Robots: A Materials–Structures–Systems Co-Design Perspective for Synergistic Integration. *FlexMat* **2026**.
85. Van Meerbeek, I. M.; Mac Murray, B. C.; Kim, J. W.; Robinson, S. S.; Zou, P. X.; Silberstein, M. N.; Shepherd, R. F., Morphing Metal and Elastomer Bicontinuous Foams for Reversible Stiffness, Shape Memory, and Self-Healing Soft Machines. *Adv. Mater.* **2016,** *28* (14), 2801-2806.

86. Tang, Z.; Tian, L.; Xin, W.; Wang, Q.; Rus, D.; Laschi, C., A General Soft Robotic Controller Inspired by Neuronal Structural and Plastic Synapses That Adapts to Diverse Arms, Tasks, and Perturbations. *Sci. Adv.* **2026,** *12* (2), eaea3712.
87. Fischer, S.; Ay, N.; Landsiedel, O.; Mohammadi, E.; Otte, S.; Russwinkel, N., Beyond Silicon: Materials, Mechanisms, and Methods for Physical Neural Computing. *IEEE Access* **2026**.
88. Mao, Y.; Wickström, S. A., Mechanical State Transitions in the Regulation of Tissue Form and Function. *Nature Reviews Molecular Cell Biology* **2024,** *25* (8), 654-670.
89. Yang, L.; Jiang, P.; Stein, J. B.; Hou, Y.; Zhou, C.; Kang, H.; Lee, K. B., Mechanobiological Dynamics-Inspired Mechanomodulatory Biomaterials. *Advanced Science* **2026,** *13* (4), e16992.
90. Baulin, V. A.; Giacometti, A.; Fedosov, D. A.; Ebbens, S.; Varela-Rosales, N. R.; Feliu, N.; Chowdhury, M.; Hu, M.; Füchslin, R.; Dijkstra, M., Intelligent Soft Matter: Towards Embodied Intelligence. *Soft Matter* **2025,** *21* (21), 4129-4145.
91. McCaskill, J. S.; Karnaushenko, D.; Zhu, M.; Schmidt, O. G., Microelectronic Morphogenesis: Smart Materials with Electronics Assembling into Artificial Organisms. *Adv. Mater.* **2023,** *35* (51), 2306344.
92. Yang, S.; Ding, H.; Tan, J.; Zhang, Y.; Guo, Y.; Kang, R.; Zhu, X.; Wang, H.; Baughman, R.; Yin, Z., Multifaceted Mechanical Responsive Metamaterials: Mechanisms, Fabrications, and Applications. *The Innovation* **2026,** *7* (1).
93. Xia, X.; Spadaccini, C. M.; Greer, J. R., Responsive Materials Architected in Space and Time. *Nat. Rev. Mater.* **2022,** *7* (9), 683-701.
94. Min, J.; Wu, Z.; Zhang, W.; Liu, Y.; Luo, D., Intelligent Liquid Crystal Elastomer Actuators with High Mechanical Strength, Self-Sensing, and Automatic Control. *Advanced Sensor Research* **2024,** *3* (1), 2300117.
95. Wang, J.-J.; Zhang, X.-Y.; Bai, J.-Y.; Liu, Q.-Y.; Wen, J.; Zhu, R., Dynamic Mechanoresponsive Polymers Enabled by Ring-Opening Polymerization of Cyclic Propargyl Carbonates. *Chem* **2025,** *11* (12).
96. Liu, Y.; Omar, R.; Li, G.; Zhou, P.; Zhang, Y.; Yan, W.; Haick, H.; Guo, C. F.; Someya, T.; Wang, Y., Adaptable Conductive Hydrogel-Enabled Soft Electronics. *Prog. Mater Sci.* **2025**, 101590.
97. Liu, J.; Jiang, H. Y.; Tian, J. Q.; Tang, Y.; Feng, C. B.; Zhou, X. Y.; Huang, Z. J.; Li, B. X.; Lu, Y. Q.; Li, Q., Stimuli-Responsive Liquid Crystal Elastomers: From Materials to Applications. *Adv. Funct. Mater.* **2026,** *36* (27), e24606.
98. Pfeifer, R.; Bongard, J., *How the Body Shapes the Way We Think: A New View of Intelligence*. MIT press: 2006.
99. Qian, C.; Kaminer, I.; Chen, H., A Guidance to Intelligent Metamaterials and Metamaterials Intelligence. *Nat. Commun.* **2025,** *16* (1), 1154.
100. He, Q.; Yin, R.; Hua, Y.; Jiao, W.; Mo, C.; Shu, H.; Raney, J. R., A Modular Strategy for Distributed, Embodied Control of Electronics-Free Soft Robots. *Sci. Adv.* **2023,** *9* (27), eade9247.
101. Yasuda, H.; Buskohl, P. R.; Gillman, A.; Murphey, T. D.; Stepney, S.; Vaia, R. A.; Raney, J. R., Mechanical Computing. *Nature* **2021,** *598* (7879), 39-48.

102. Sitti, M., Physical Intelligence as a New Paradigm. *Extreme Mechanics Letters* **2021,** *46*, 101340.
103. Li, J.; Wang, C.; Su, J.; Liu, Z.; Fan, H.; Wang, C.; Li, Y.; He, Y.; Chen, N.; Cao, J., Observing Proton–Electron Mixed Conductivity in Graphdiyne. *Adv. Mater.* **2024**, 2400950.
104. Yin, S.; Yao, D. R.; Kim, I.; Zhou, W.; Heng, W.; Li, W.; Tang, S.; Ma, X.; Xu, Y.; Kim, G., Amphibious Passive Adaptation in Untethered Soft Robots. *Proceedings of the National Academy of Sciences* **2026,** *123* (17), e2532988123.
105. Zhao, L.; Jiang, Y.; She, C.-Y.; Chen, M.; Balkcom, D., Softsnap: Rapid Prototyping of Untethered Soft Robots Using Snap-Together Modules. *Soft Robotics* **2025,** *12* (6), 698-707.
106. Chen, A. E.; Adibnazari, I.; Nakoud, G.; Torres, G.; Tolley, M. T., Fluidic Control of Untethered Underwater Soft Robots. *IEEE Robotics and Automation Letters* **2025,** *11* (1), 466-473.
107. Dong, C.; Malliaras, G. G., Recent Advances in Stimuli-Responsive Materials and Soft Robotic Actuators for Bioelectronic Medicine. *Adv. Mater.* **2025,** *37* (27), 2417325.
108. Jafarzadeh, S.; Skov, A. L., Beyond Planar: Enhanced Performance of Hollow Fiber Dielectric Elastomer Actuators. *Advanced Science* **2025,** *12* (33), e04803.
109. Sarker, A.; Ul Islam, T.; Islam, M. R., A Review on Recent Trends of Bioinspired Soft Robotics: Actuators, Control Methods, Materials Selection, Sensors, Challenges, and Future Prospects. *Adv. Intell. Syst.* **2025,** *7* (3), 2400414.
110. Xia, H.; Zhang, Y.; Rajabi, N.; Taleb, F.; Yang, Q.; Kragic, D.; Li, Z., Shaping High-Performance Wearable Robots for Human Motor and Sensory Reconstruction and Enhancement. *Nat. Commun.* **2024,** *15* (1), 1760.
111. Perrelli, M.; Lago, F.; Garofalo, S.; Bruno, L.; Mundo, D.; Carbone, G., A Critical Review and Systematic Design Approach for Innovative Upper-Limb Rehabilitation Devices. *Robotics and Autonomous Systems* **2025,** *183*, 104835.
112. Lee, J.; Kwon, K.; Soltis, I.; Matthews, J.; Lee, Y. J.; Kim, H.; Romero, L.; Zavanelli, N.; Kwon, Y.; Kwon, S., Intelligent Upper-Limb Exoskeleton Integrated with Soft Bioelectronics and Deep Learning for Intention-Driven Augmentation. *npj Flexible Electronics* **2024,** *8* (1), 11.
113. Aubin, C. A.; Gorissen, B.; Milana, E.; Buskohl, P. R.; Lazarus, N.; Slipher, G. A.; Keplinger, C.; Bongard, J.; Iida, F.; Lewis, J. A., Towards Enduring Autonomous Robots Via Embodied Energy. *Nature* **2022,** *602* (7897), 393-402.
114. Afsar, O.; Pupillo, G.; Vitucci, G.; Babatain, W.; Ishii, H.; Cacucciolo, V., Electrofluidic Fiber Muscles. *Sci Robot.* **2026,** *11* (112), eady6438.
115. Wang, H.; Kong, L.; Fang, Z.; Zou, R.; Zhang, Z.; Zhao, X.; Zong, Q.; Xie, Z., Symbiotic Energy Paradigm for Self-Sustaining Aerial Robots. *Nature Reviews Electrical Engineering* **2025,** *2* (5), 302-319.
116. Harikrishnan, H.; Aishwarya, V., Bioinspired Energy Materials: A Comprehensive Review of Advances in Photovoltaics, Storage, and Catalysis for Sustainable Energy Technologies. *Energy Storage* **2025,** *7* (8), e70312.
117. Hegde, C.; Su, J.; Tan, J. M. R.; He, K.; Chen, X.; Magdassi, S., Sensing in Soft

Robotics. *ACS nano* **2023,** *17* (16), 15277-15307.
118. Webster III, R. J.; Jones, B. A., Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review. *The International Journal of Robotics Research* **2010,** *29* (13), 1661-1683.
119. Zhou, S.; Li, Y.; Wang, Q.; Lyu, Z., Integrated Actuation and Sensing: Toward Intelligent Soft Robots. *Cyborg and Bionic Systems* **2024,** *5*, 0105.
120. Egli, J.; Forrai, B.; Buchner, T.; Su, J.; Chen, X.; Katzschmann, R. K. In *Sensorized Soft Skin for Dexterous Robotic Hands*, 2024 IEEE International Conference on Robotics and Automation (ICRA), IEEE: 2024; pp 18127-18133.
121. Qiu, Y.; Sun, S.; Wang, X.; Shi, K.; Wang, Z.; Ma, X.; Zhang, W.; Bao, G.; Tian, Y.; Zhang, Z., Nondestructive Identification of Softness Via Bioinspired Multisensory Electronic Skins Integrated on a Robotic Hand. *npj Flexible Electronics* **2022,** *6* (1), 45.
122. Su, J.; Zhang, H.; Li, H.; He, K.; Tu, J.; Zhang, F.; Liu, Z.; Lv, Z.; Cui, Z.; Li, Y., Skin-Inspired Multi-Modal Mechanoreceptors for Dynamic Haptic Exploration. *Adv. Mater.* **2024**, 2311549.
123. Qiu, Y.; Ashok, A.; Nguyen, C. C.; Yamauchi, Y.; Do, T. N.; Phan, H. P., Integrated Sensors for Soft Medical Robotics. *Small* **2024,** *20* (22), 2308805.
124. Tu, J.; Wang, M.; Li, W.; Su, J.; Li, Y.; Lv, Z.; Li, H.; Feng, X.; Chen, X., Electronic Skins with Multimodal Sensing and Perception. *Soft Science* **2023**.
125. Ji, J.; Luo, H.; Su, J.; Wang, S.; Chen, X.; Song, J., Multisensory Electronic Skin with Decoupled Pressure–Temperature-Sensing Capabilities for Similar Object Recognition. *Proceedings of the National Academy of Sciences* **2025,** *122* (41), e2519693122.
126. Su, J.; Tan, J. M. R.; Liu, J.; He, K.; Wu, D.; Lai, W.; Cao, J.; Phee, S. J.; Magdassi, S.; Chen, X., Bioarchitectonics-Inspired Soft Grippers with Cutaneous Slip Perception. *Sci. Adv.* **2025,** *11* (33), eadx4206.
127. Xiao, Y.; Tan, W.; Hoffman, J.; Xia, T.; Amato, C., Asynchronous Multi-Agent Deep Reinforcement Learning under Partial Observability. *The International Journal of Robotics Research* **2025,** *44* (8), 1257-1286.
128. Lin, T.; Ren, Z.; Zhu, L.; Zhu, Y.; Feng, K.; Ding, W.; Yan, K.; Beer, M., A Systematic Review of Multi-Sensor Information Fusion for Equipment Fault Diagnosis. *IEEE Trans. Instrum. Meas.* **2025**.
129. Tu, J.; Cai, Z.; Liu, Z.; Su, J.; Li, Y.; Feng, X.; Cui, Z.; Chen, X., Quantitative Tactile Sensing of Surface Microstructures through Time-Domain Analysis of Piezoelectric Twin Signals. *Adv. Mater.* **2026,** *38* (2), e10393.
130. Lin, J.; Shao, G.; Wu, D.; Zhuang, Q., An Integrated Strategy for Soft Robotics: Wireless Sensing Enabled by Laser-Sintered Silver. *ACS Appl. Mater. Interfaces* **2025,** *17* (25), 37081-37089.
131. He, K.; Wang, C.; He, Y.; Su, J.; Chen, X., Artificial Neuron Devices. *Chem. Rev.* **2023,** *123* (23), 13796-13865.
132. Shih, B.; Shah, D.; Li, J.; Thuruthel, T. G.; Park, Y.-L.; Iida, F.; Bao, Z.; Kramer-Bottiglio, R.; Tolley, M. T., Electronic Skins and Machine Learning for Intelligent Soft Robots. *Sci Robot.* **2020,** *5* (41), eaaz9239.

133. Petrovich, M.; Numkam Fokoua, E.; Chen, Y.; Sakr, H.; Adamu, A. I.; Hassan, R.; Wu, D.; Fatobene Ando, R.; Papadimopoulos, A.; Sandoghchi, S. R., Broadband Optical Fibre with an Attenuation Lower Than 0.1 Decibel Per Kilometre. *Nature Photonics* **2025,** *19* (11), 1203-1208.
134. Wang, H.; Ye, D.; Wu, Q.; Yang, L.; Zhao, C.; Wu, D.; Guo, Y.; Xu, W.; He, W.; Xu, Z.; Wu, H.; Lu, W.; Li, W.; Sun, Q.; Huang, Y., Flexible, Multimodal, Electrical-Sensing–Optical-Transmission Mfiber-Sensors Via an on-Fiber Printed Electronics Strategy. *National Science Review* **2026**.
135. Linghu, C.; Liu, Y.; Yang, X.; Chen, Z.; Feng, J.; Zhang, Y.; Li, Y.; Zhao, Z.; Seo, Y.-J.; Li, J., Versatile Adhesive Skin Enhances Robotic Interactions with the Environment. *Sci. Adv.* **2025,** *11* (3), eadt4765.
136. Jin, K.; Li, Z.; Nan, P.; Xin, G.; Lim, K.-S.; Ahmad, H.; Yang, H., Fiber Bragg Grating-Based Fingertip Tactile Sensors for Normal/Shear Forces and Temperature Detection. *Sensors and Actuators A: Physical* **2023,** *357*, 114368.
137. Azmi, A.; Abdullah, A.; Noor, M. M.; Ibrahim, M.; Ibrahim, R. R.; Tan, T.; Zhang, J., Dynamic Bending and Rotation Sensing Based on High Coherence Interferometry in Multicore Fiber. *Optics & laser technology* **2021,** *135*, 106716.
138. Bai, H.; Li, S.; Barreiros, J.; Tu, Y.; Pollock, C. R.; Shepherd, R. F., Stretchable Distributed Fiber-Optic Sensors. *Science* **2020,** *370* (6518), 848-852.
139. Sun, H.; Kuchenbecker, K. J.; Martius, G., A Soft Thumb-Sized Vision-Based Sensor with Accurate All-Round Force Perception. *Nature Machine Intelligence* **2022,** *4* (2), 135-145.
140. Zhu, Y.; Hao, M.; Zhu, X.; Bateux, Q.; Wong, A.; Dollar, A. M., Forces for Free: Vision-Based Contact Force Estimation with a Compliant Hand. *Sci Robot.* **2025,** *10* (103), eadq5046.
141. Zhao, Z.; Li, W.; Li, Y.; Liu, T.; Li, B.; Wang, M.; Du, K.; Liu, H.; Zhu, Y.; Wang, Q., Embedding High-Resolution Touch across Robotic Hands Enables Adaptive Human-Like Grasping. *Nature Machine Intelligence* **2025,** *7* (6), 889-900.
142. Liu, J.; Li, W.; She, Y.; Blanchard, S.; Lin, S., Fatigue-Resistant Mechanoresponsive Color-Changing Hydrogels for Vision-Based Tactile Robots. *Adv. Mater.* **2025,** *37* (49), 2407925.
143. Chen, L.; Hegde, C.; Das, S.; Zhang, W.; Teo, R. Y.; Chan, J. Y. E.; He, N.; Fan, F.; Duan, H.; Wong, L. H., Visuo-Tactile Sensor Enabled by Cholesteric Liquid Crystal Elastomer for Soft Robotics. *Adv. Funct. Mater.* **2026**, e24139.
144. Li, L.; Yang, F.; Ma, Q.; Xu, T.; Su, M.; Zhao, Y.; Liu, X., Integrating an Optical Fiber Sensor and Artificial Intelligence for Enhanced Tactile Sensing in Human-Computer Interaction. *Optica* **2025,** *12* (2), 263-273.
145. Zimmermann, C. A.; Amouzou, K. N.; Ung, B., Recent Advances in Pdms Optical Waveguides: Properties, Fabrication, and Applications. *Advanced Optical Materials* **2025,** *13* (1), 2401975.
146. Nizamoglu, S.; Gather, M. C.; Humar, M.; Choi, M.; Kim, S.; Kim, K. S.; Hahn, S. K.; Scarcelli, G.; Randolph, M.; Redmond, R. W., Bioabsorbable Polymer Optical Waveguides for Deep-Tissue Photomedicine. *Nat. Commun.* **2016,** *7* (1), 10374.
147. Liu, X.; Rao, S.; Chen, W.; Felix, K.; Ni, J.; Sahasrabudhe, A.; Lin, S.; Wang,

Q.; Liu, Y.; He, Z., Fatigue-Resistant Hydrogel Optical Fibers Enable Peripheral Nerve Optogenetics During Locomotion. *Nat. Methods* **2023,** *20* (11), 1802-1809.
148. Kim, D. H.; Jang, W.; Choi, K.; Choi, J. S.; Pyun, J.; Lim, J.; Char, K.; Im, S. G., One-Step Vapor-Phase Synthesis of Transparent High Refractive Index Sulfur-Containing Polymers. *Sci. Adv.* **2020,** *6* (28), eabb5320.
149. Cui, C.; Wang, F.; Chen, X.; Xu, T.; Li, Z.; Chen, K.; Guo, Y.; Cheng, Y.; Ge, Z.; Zhang, Y., Covalent Adaptable Networks with Dual Dynamic Covalent Bonds for Self-Repairing Infrared Transmitting Materials. *Adv. Funct. Mater.* **2024,** *34* (24), 2315469.
150. Zhao, H.; O'brien, K.; Li, S.; Shepherd, R. F., Optoelectronically Innervated Soft Prosthetic Hand Via Stretchable Optical Waveguides. *Sci Robot.* **2016,** *1* (1), eaai7529.
151. Hu, D.; Giorgio-Serchi, F.; Zhang, S.; Yang, Y., Stretchable E-Skin and Transformer Enable High-Resolution Morphological Reconstruction for Soft Robots. *Nature Machine Intelligence* **2023,** *5* (3), 261-272.
152. Sun, T.; Feng, B.; Huo, J.; Xiao, Y.; Wang, W.; Peng, J.; Li, Z.; Du, C.; Wang, W.; Zou, G., Artificial Intelligence Meets Flexible Sensors: Emerging Smart Flexible Sensing Systems Driven by Machine Learning and Artificial Synapses. *Nano-Micro Letters* **2024,** *16* (1), 14.
153. Fu, X.; Cheng, W.; Wan, G.; Yang, Z.; Tee, B. C., Toward an Ai Era: Advances in Electronic Skins. *Chem. Rev.* **2024,** *124* (17), 9899-9948.
154. Wang, S.; Liu, D.; Fu, C.; Yuan, X.; Shan, P.; Leung, V. C., Predictive Body Awareness in Soft Robots: A Bayesian Variational Autoencoder Fusing Multimodal Sensory Data. *IEEE Transactions on Robotics* **2025**.
155. Caporali, A.; Cuiral-Zueco, I.; López-Nicolás, G.; Palli, G., Robotic Perception and Manipulation of Deformable Linear Objects: A Survey. *The International Journal of Robotics Research* **2026**, 02783649261432253.
156. Li, Z.; Wu, S.; Chen, W.; Sun, F., Physics-Informed Neural Networks for Compliant Robotic Manipulators Dynamic Modeling. *Journal of Computational Science* **2025,** *90*, 102633.
157. Firoozi, R.; Tucker, J.; Tian, S.; Majumdar, A.; Sun, J.; Liu, W.; Zhu, Y.; Song, S.; Kapoor, A.; Hausman, K., Foundation Models in Robotics: Applications, Challenges, and the Future. *The International Journal of Robotics Research* **2025,** *44* (5), 701-739.
158. Bi, J.; Ma, K. Y.; Hao, C.; Zheng, M. S.; Soh, H., Vla-Touch: Enhancing Vision-Language-Action Model with Dual-Level Tactile Feedback. *IEEE Robotics and Automation Letters* **2026**, 1-8.
159. Tian, C.; Cho, Y.; Song, Y.; Park, S.; Kim, I.; Cho, S.-Y., Integration of Ai with Artificial Sensory Systems for Multidimensional Intelligent Augmentation. *International Journal of Extreme Manufacturing* **2025,** *7* (4), 042002.
160. Pu, M.; Zhao, T.; Zhang, L.; Han, C.; Chai, Z.; Zhou, Y.; Ding, H.; Wu, Z., An Ai-Enabled All-in-One Visual, Proximity, and Tactile Perception Multimodal Sensor. *Advanced Robotics Research* **2025**, 202500062.
161. Zhu, K.; Nguyen, C. C.; Sharma, B.; Phan, P. T.; Hoang, T. T.; Davies, J.; Ji, A.; Nicotra, E.; Wan, J.; Pruscino, P., Development of a Bioinspired Soft Robotic

System for Teleoperated Endoscopic Surgery. *Cyborg and Bionic Systems* **2025,** *6*, 0289.
162. Li, C.; Zhang, G.; Zhao, B.; Xie, D.; Du, H.; Duan, X.; Hu, Y.; Zhang, L., Advances of Surgical Robotics: Image-Guided Classification and Application. *National science review* **2024,** *11* (9), nwae186.
163. Ma, J.; He, Y.; Li, F.; Han, L.; You, C.; Wang, B., Segment Anything in Medical Images. *Nat. Commun.* **2024,** *15* (1), 654.
164. McCandless, M.; Perry, A.; DiFilippo, N.; Carroll, A.; Billatos, E.; Russo, S., A Soft Robot for Peripheral Lung Cancer Diagnosis and Therapy. *Soft Robotics* **2022,** *9* (4), 754-766.
165. Cianchetti, M.; Ranzani, T.; Gerboni, G.; De Falco, I.; Laschi, C.; Menciassi, A. In *Stiff-Flop Surgical Manipulator: Mechanical Design and Experimental Characterization of the Single Module*, 2013 IEEE/RSJ international conference on intelligent robots and systems, IEEE: 2013; pp 3576-3581.
166. Liu, J.; Jiang, F.; Tashiro, S.; Chen, S.; Tanaka, M., A Physics-Informed and Data-Driven Framework for Robotic Welding in Manufacturing. *Nat. Commun.* **2025,** *16* (1), 4807.
167. Zhang, J.; Shen, C.; Zhu, Z.; Tong, H.; Fang, Q., Embodied Intelligence Technology for Next-Generation Soft Robots: A Survey. *Engineered Science* **2026,** *40*, 2073.
168. Wallin, T.; Pikul, J.; Shepherd, R. F., 3d Printing of Soft Robotic Systems. *Nat. Rev. Mater.* **2018,** *3* (6), 84-100.
169. Wang, D.; Wang, J.; Shen, Z.; Jiang, C.; Zou, J.; Dong, L.; Fang, N. X.; Gu, G., Soft Actuators and Robots Enabled by Additive Manufacturing. *Annual Review of Control, Robotics, and Autonomous Systems* **2023,** *6* (1), 31-63.
170. Liu, H.; Wu, C.; Lin, S.; Lam, J.; Xi, N.; Chen, Y., Advances in 3d and 4d Printing of Soft Robotics and Their Applications. *Adv. Intell. Syst.* **2025,** *7* (6), 2400699.
171. Lantean, S.; Barrera, G.; Pirri, C. F.; Tiberto, P.; Sangermano, M.; Roppolo, I.; Rizza, G., 3d Printing of Magnetoresponsive Polymeric Materials with Tunable Mechanical and Magnetic Properties by Digital Light Processing. *Adv. Mater. Technol.* **2019,** *4* (11), 1900505.
172. Ren, Z.; Fan, X.; Xie, H.; Sun, M., 4d-Printed Soft Microrobots: Manufacturing, Materials, Actuation and Applications. *Soft Science* **2026,** *6* (1), N/A-N/A.
173. Qing, H.; Vallabhuneni, S.; Chi, Y.; Zarei, M. J.; Sharbati, P.; Sun, H.; Yin, J.; Kota, A. K., Enhancing Soft Robots with Chemical Shielding for Harsh Corrosive Liquid Environments. *Materials Horizons* **2026**.
174. Wong, D. C. Y.; Luo, Y.; Scharff, R. B. N., Durability of Soft Pneumatic Actuators: A Review and Benchmarking Protocol. *Advanced Robotics Research* **2026**, e202500172.
175. Brown, N. C.; Ames, D. C.; Mueller, J., Multimaterial Extrusion 3d Printing Printheads. *Nat. Rev. Mater.* **2025,** *10* (11), 807-825.
176. Yuan, Z.; Bai, X.; Li, S.; Fu, Y.; Wan, Z.; Guo, X.; Zhai, M.; Yi, J.; Liu, Y.; Zhou, Y., Multimaterial and Multidimensional Bioprinting in Regenerative Medicine: Advances, Limitations, and Future Directions. *Advanced Healthcare Materials* **2025,**

14 (18), 2500475.
177. Xiang, H.; Xu, Z.; Lu, H.; Zhang, M., Advanced Micro-/Nano Additive Manufacturing of Multi-Materials. *Nano Research* **2026,** *19* (4), 94908451.
178. Wu, L.; Song, Y., Recent Innovations in Interfacial Strategies for Dlp 3d Printing Process Optimization. *Materials Horizons* **2025,** *12* (2), 401-417.
179. Milana, E.; Santina, C. D.; Gorissen, B.; Rothemund, P., Physical Control: A New Avenue to Achieve Intelligence in Soft Robotics. *Sci Robot.* **2025,** *10* (102), eadw7660.
180. Chen, J.; Liu, X.; Tian, Y.; Zhu, W.; Yan, C.; Shi, Y.; Kong, L. B.; Qi, H. J.; Zhou, K., 3d-Printed Anisotropic Polymer Materials for Functional Applications. *Adv. Mater.* **2022,** *34* (5), 2102877.
181. Aïdonidis, E.; Cosola, A.; Bourdon, P.; Dammak, H.; Sangermano, M.; Demoly, F.; Faustini, M.; Pérot, A.; Lairez, D.; Mouhoubi, R., Encoding Magnetic Anisotropies in Digital Light Processing 3d Printing. *Adv. Funct. Mater.* **2026,** *36* (26), e23995.
182. Ding, A.; Tang, F.; Alsberg, E., 4d Printing: A Comprehensive Review of Technologies, Materials, Stimuli, Design, and Emerging Applications. *Chem. Rev.* **2025,** *125* (7), 3663-3771.
183. Arsuffi, B.; Magrini, T.; Champeau, M.; Siqueira, G.; Titotto, S., 4d Printing of Natural Materials: A Review. *Sustainable Materials and Technologies* **2025,** *44*, e01346.
184. Chen, J.; Virrueta, C.; Zhang, S.; Mao, C.; Wang, J., 4d Printing: The Spotlight for 3d Printed Smart Materials. *Mater. Today* **2024,** *77*, 66-91.
185. Khalid, M. Y.; Arif, Z. U.; Ahmed, W.; Umer, R.; Zolfagharian, A.; Bodaghi, M., 4d Printing: Technological Developments in Robotics Applications. *Sensors and Actuators A: Physical* **2022,** *343*, 113670.
186. Mirasadi, K.; Yousefi, M. A.; Jin, L.; Rahmatabadi, D.; Baniassadi, M.; Liao, W. H.; Bodaghi, M.; Baghani, M., 4d Printing of Magnetically Responsive Shape Memory Polymers: Toward Sustainable Solutions in Soft Robotics, Wearables, and Biomedical Devices. *Advanced Science* **2026,** *13* (15), e13091.
187. Kim, Y.; Yuk, H.; Zhao, R.; Chester, S. A.; Zhao, X., Printing Ferromagnetic Domains for Untethered Fast-Transforming Soft Materials. *Nature* **2018,** *558* (7709), 274-279.
188. Ren, L.; Li, B.; He, Y.; Song, Z.; Zhou, X.; Liu, Q.; Ren, L., Programming Shape-Morphing Behavior of Liquid Crystal Elastomers Via Parameter-Encoded 4d Printing. *ACS Appl. Mater. Interfaces* **2020,** *12* (13), 15562-15572.
189. Xu, C.; Zhou, P.; Zhou, X.; Zhang, L.; Liu, Q.; Ren, L., Magnetically Assisted Direct Writing 3d Printing Programmable Magnetically Responsive Origami Actuator. *Additive Manufacturing* **2025**, 104898.
190. Huang, Y.; Cao, Y.; Qin, H., Electric Field Assisted Direct Writing and 3d Printing of Low-Melting Alloy. *Adv. Eng. Mater.* **2022,** *24* (9), 2200091.
191. Fernández-Gil, F.; Leyrer, J., From Random to Oriented: Shear-Induced Alignment of Fillers in Polymer Matrices. *Polym. Compos.* **2025**.
192. Höller, R. J.; Sivun, D.; Gvindzhiliia, G.; Müller, S. M.; Haiden, L.; Klar, T.

A.; Jacak, J.; Schlögl, S.; Griesser, T., Spatial Control of Curing Kinetics in Thiol-Ene-Systems through Antagonistic Photoreactions. *Nat. Commun.* **2025,** *16* (1), 8487.
193. Zaid, O.; Alanquri, O. K.; Al-Dala'ien, R. N., 4d Printing: Transformative Advances and Multidimensional Applications in Engineering and Additive Manufacturing. *Adv. Eng. Mater.* **2026**, e202503170.
194. Khalid, M. Y.; Otabil, A.; Mamoun, O. S.; Askar, K.; Bodaghi, M., Transformative 4d Printed Smps into Soft Electronics and Adaptive Structures: Innovations and Practical Insights. *Adv. Mater. Technol.* **2025,** *10* (19), e00309.
195. Wang, J.; Zheng, J.; Zhang, C.; Duan, Y.; Zhang, Y.; Guo, H.; Qiu, Y.; Wang, X.; Liu, L.; Yu, H., 4d-Printed Microrobots with Synergistic Integration of Magnetic Actuation, Diffractive Optical Sensing, and Ph-Adaptive Morphing. *Adv. Funct. Mater.* **2026,** *36* (16), e18838.
196. Guo, H.; Wu, H.; Wang, Y.; Xue, Y.; Wong, T.-W.; Li, T.; Dong, H., Enabling Tunable Stiffness, Adhesive Grasping, and Interaction-Driven Reconfiguration: A Shape-Memory-Polymer-Enhanced Fin-Ray Gripper. *Soft Robotics* **2025,** *12* (6), 766-776.
197. van Oosterhout, A.; Robertson, M. A.; Paik, J., Soft Robotics for Personalized and Sustainable Wearables. *Nat. Rev. Bioeng.* **2026,** *4* (1), 30-46.
198. Yu, C.; Matthews, D.; Wang, J.; Gu, J.; Blackiston, D.; Rubenstein, M.; Kriegman, S., Agile Legged Locomotion in Reconfigurable Modular Robots. *Proceedings of the National Academy of Sciences* **2026,** *123* (10), e2519129123.
199. Wu, P.; Yu, T.; Chen, M.; Kang, N.; Mansori, M. E., Electrically/Magnetically Dual-Driven Shape Memory Composites Fabricated by Multi-Material Magnetic Field-Assisted 4d Printing. *Adv. Funct. Mater.* **2024,** *34* (27), 2314854.
200. Li, X.; Xu, R.; Xie, C.; Ge, Z.; Gao, B.; Lim, C. T., Microscale Architectures for Intelligent Soft Robotics: From Functional Microneedles to Biointegrated Wearable Systems. *Nano-Micro Letters* **2026,** *18* (1), 179.
201. Ye, D.; Ding, Y.; Duan, Y.; Su, J.; Yin, Z.; Huang, Y. A., Large-Scale Direct-Writing of Aligned Nanofibers for Flexible Electronics. *Small* **2018,** *14* (21), 1703521.
202. Calais, T.; Sanandiya, N. D.; Jain, S.; Kanhere, E. V.; Kumar, S.; Yeow, R. C.-H.; Valdivia y Alvarado, P., Freeform Liquid 3d Printing of Soft Functional Components for Soft Robotics. *ACS Appl. Mater. Interfaces* **2021,** *14* (1), 2301-2315.
203. Kanhere, E.; Calais, T.; Jain, S.; Plamootil Mathai, A. R.; Chooi, A.; Stalin, T.; Joseph, V. S.; Valdivia y Alvarado, P., Upgrading and Extending the Life Cycle of Soft Robots with in Situ Free-Form Liquid Three-Dimensional Printing. *Sci Robot.* **2024,** *9* (97), eadn4542.
204. Boddeti, N.; Van Truong, T.; Joseph, V. S.; Stalin, T.; Calais, T.; Lee, S. Y.; Dunn, M. L.; Valdivia y Alvarado, P., Optimal Soft Composites for under-Actuated Soft Robots. *Adv. Mater. Technol.* **2021,** *6* (8), 2100361.
205. Yang, H.; Li, J.; Lim, K. Z.; Pan, C.; Van Truong, T.; Wang, Q.; Li, K.; Li, S.; Xiao, X.; Ding, M., Automatic Strain Sensor Design Via Active Learning and Data Augmentation for Soft Machines. *Nature Machine Intelligence* **2022,** *4* (1), 84-94.
206. Gao, L.; Song, S.; Lin, J.; Xu, Y.; Wang, L.; Du, L., Ai-Assisted Design of Advanced Polymeric Materials: Challenges and Solutions. *Adv. Mater.* **2026,** *38* (7),

e16857.
207. Fang, R.; Ghasemi, A.; Zeze, D.; Hedayati, M. K., Inverse Design of Lateral Hybrid Metasurfaces Structural Colour: An Ai Approach. *RSC Adv.* **2024,** *14* (35), 25678-25684.
208. Cheng, M.; Fu, C.-L.; Okabe, R.; Chotrattanapituk, A.; Boonkird, A.; Hung, N. T.; Li, M., Artificial Intelligence-Driven Approaches for Materials Design and Discovery. *Nat. Mater.* **2026,** *25* (2), 174-190.
209. Ghosh, S.; Maurya, R.; Roy, S., Pagdesa: An Automated Generative Design of Multimodal Soft Pneumatic Actuators. *IEEE Robotics and Automation Letters* **2025**.
210. Javaid, M.; Haleem, A.; Suman, R., Digital Twin Applications toward Industry 4.0: A Review. *Cognitive Robotics* **2023,** *3*, 71-92.
211. Ramasubramanian, A. K.; Mathew, R.; Kelly, M.; Hargaden, V.; Papakostas, N., Digital Twin for Human–Robot Collaboration in Manufacturing: Review and Outlook. *Applied Sciences* **2022,** *12* (10), 4811.
212. Kumar, S.; Gopi, T.; Harikeerthana, N.; Gupta, M. K.; Gaur, V.; Krolczyk, G. M.; Wu, C., Machine Learning Techniques in Additive Manufacturing: A State of the Art Review on Design, Processes and Production Control. *J. Intell. Manuf.* **2023,** *34* (1), 21-55.
213. Miriyev, A.; Kovač, M., Skills for Physical Artificial Intelligence. *Nature Machine Intelligence* **2020,** *2* (11), 658-660.
214. Blickhan, R.; Seyfarth, A.; Geyer, H.; Grimmer, S.; Wagner, H.; Günther, M., Intelligence by Mechanics. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **2007,** *365* (1850), 199-220.
215. Cangelosi, A.; Bongard, J.; Fischer, M. H.; Nolfi, S., Embodied Intelligence. In *Springer Handbook of Computational Intelligence*, Springer: 2015; pp 697-714.
216. Zhao, Z.; Wu, Q.; Wang, J.; Zhang, B.; Zhong, C.; Zhilenkov, A. A., Exploring Embodied Intelligence in Soft Robotics: A Review. *Biomimetics* **2024,** *9* (4), 248.
217. Li, Y.; Li, Z.; Duan, Y.; Spulber, A.-B., Physical Artificial Intelligence (Pai): The Next-Generation Artificial Intelligence. *FRONT INFORM TECH EL* **2023,** *24* (8), 1231-1238.
218. Han, X.; Guo, N.; Xu, R.; Wan, F.; Song, C., Anchoring Morphological Representations Unlocks Latent Proprioception in Soft Robots. *Adv. Intell. Syst.* **2025,** *7* (12), e202500444.
219. Shorthose, O.; Scimeca, L.; Albini, A.; Maiolino, P., Bioinspired Tactile Object Identification Leveraging Deep Learning and Soft Body Compliance. *Adv. Intell. Syst.* **2025,** *7* (7), 2400802.
220. Chen, H.; Sitti, M., Physical Intelligence in Small-Scale Robots and Machines. *Adv. Mater.* **2026,** *38* (12), e10332.
221. Nakajima, K., Physical Reservoir Computing—an Introductory Perspective. *Jpn. J. Appl. Phys.* **2020,** *59* (6), 060501.
222. Nakajima, K.; Hauser, H.; Li, T.; Pfeifer, R., Information Processing Via Physical Soft Body. *Sci. Rep.* **2015,** *5* (1), 10487.
223. Hu, D.; Dong, H.; Giorgio-Serchi, F.; Yang, Y., A Self-Supervised Learning Framework for Soft Robot Proprioception. *IEEE Transactions on Neural Networks and*

Learning Systems **2025**.
224. Della Santina, C.; Duriez, C.; Rus, D., Model-Based Control of Soft Robots: A Survey of the State of the Art and Open Challenges. *IEEE Control Systems Magazine* **2023,** *43* (3), 30-65.
225. Chen, Z.; Wu, D.; Guan, Q.; Hardman, D.; Renda, F.; Hughes, J.; Thuruthel, T. G.; Della Santina, C.; Mazzolai, B.; Zhao, H., A Survey on Soft Robot Adaptability: Implementations, Applications, and Prospects [Survey]. *IEEE Robotics & Automation Magazine* **2025**.
226. Meng, C.; Griesemer, S.; Cao, D.; Seo, S.; Liu, Y., When Physics Meets Machine Learning: A Survey of Physics-Informed Machine Learning. *Machine Learning for Computational Science and Engineering* **2025,** *1* (1), 20.
227. Huang, J.; Wu, Y.; Wang, F.; Fang, Y.; Nan, Y.; Alkan, C.; Abraham, D.; Liao, C.; Xu, L.; Gao, Z., Data-and Physics-Driven Deep Learning Based Reconstruction for Fast Mri: Fundamentals and Methodologies. *IEEE Rev. Biomed. Eng.* **2024,** *18*, 152-171.
228. Cuomo, S.; Di Cola, V. S.; Giampaolo, F.; Rozza, G.; Raissi, M.; Piccialli, F., Scientific Machine Learning through Physics–Informed Neural Networks: Where We Are and What's Next. *Journal of Scientific Computing* **2022,** *92* (3), 88.
229. Zhao, W.; Queralta, J. P.; Westerlund, T. In *Sim-to-Real Transfer in Deep Reinforcement Learning for Robotics: A Survey*, 2020 IEEE symposium series on computational intelligence (SSCI), IEEE: 2020; pp 737-744.
230. Yang, C.; Zhu, Y.; Chen, Y., A Review of Human–Machine Cooperation in the Robotics Domain. *IEEE Transactions on Human-Machine Systems* **2021,** *52* (1), 12-25.
231. Zhou, L.; Paul, S.; Demirkan, H.; Yuan, L.; Spohrer, J.; Zhou, M.; Basu, J., Intelligence Augmentation: Towards Building Human-Machine Symbiotic Relationship. *AIS Transactions on Human-Computer Interaction* **2021,** *13* (2), 243-264.
232. Yin, S.; Yao, D. R.; Song, Y.; Heng, W.; Ma, X.; Han, H.; Gao, W., Wearable and Implantable Soft Robots. *Chem. Rev.* **2024,** *124* (20), 11585-11636.
233. Bützer, T.; Lambercy, O.; Arata, J.; Gassert, R., Fully Wearable Actuated Soft Exoskeleton for Grasping Assistance in Everyday Activities. *Soft robotics* **2021,** *8* (2), 128-143.
234. Billard, A.; Albu-Schaeffer, A.; Beetz, M.; Burgard, W.; Corke, P.; Ciocarlie, M.; Dahiya, R.; Kragic, D.; Goldberg, K.; Nagai, Y., A Roadmap for Ai in Robotics. *Nature Machine Intelligence* **2025**, 1-7.
235. Habibian, S.; Alvarez Valdivia, A.; Blumenschein, L. H.; Losey, D. P., A Survey of Communicating Robot Learning During Human-Robot Interaction. *The International Journal of Robotics Research* **2025,** *44* (4), 665-698.
236. Wang, Y.; Xie, Z.; Huang, H.; Liang, X., Pioneering Healthcare with Soft Robotic Devices: A Review. *Smart Medicine* **2024,** *3* (1), e20230045.
237. Etemad-Sajadi, R.; Soussan, A.; Schöpfer, T., How Ethical Issues Raised by Human–Robot Interaction Can Impact the Intention to Use the Robot? *International journal of social robotics* **2022,** *14* (4), 1103-1115.
238. Bai, Z.; Pang, H.; He, Z.; Zhao, B.; Wang, T., Path Planning of Autonomous Mobile Robot in Comprehensive Unknown Environment Using Deep Reinforcement

Learning. *IEEE Internet of Things Journal* **2024,** *11* (12), 22153-22166.
239. Wang, Y.; Guo, H.; Wu, H.; Dong, H., Flexible Robotic Hand Harnesses Large Deformations for Full-Coverage Human-Like Multimodal Haptic Perception. *Nat. Commun.* **2025**.
240. Abadía, I.; Bruel, A.; Courtine, G.; Ijspeert, A. J.; Ros, E.; Luque, N. R., A Neuromechanics Solution for Adjustable Robot Compliance and Accuracy. *Sci Robot.* **2025,** *10* (98), eadp2356.
241. Ben Zion, M. Y.; Fersula, J.; Bredeche, N.; Dauchot, O., Morphological Computation and Decentralized Learning in a Swarm of Sterically Interacting Robots. *Sci Robot.* **2023,** *8* (75), eabo6140.
242. Liu, F.; Deswal, S.; Christou, A.; Sandamirskaya, Y.; Kaboli, M.; Dahiya, R., Neuro-Inspired Electronic Skin for Robots. *Sci Robot.* **2022,** *7* (67), eabl7344.
243. Julian, B. J.; Angermann, M.; Schwager, M.; Rus, D., Distributed Robotic Sensor Networks: An Information-Theoretic Approach. *The International Journal of Robotics Research* **2012,** *31* (10), 1134-1154.
244. Chen, C.; Wang, Z.; Wang, Y.; Shi, P.; Liu, Z.; Si, M.; Duan, S.; Hou, W.; He, X., Twirlbot: Tumbleweed-Inspired Rolling Robot. *Sci. Adv.* **2026,** *12* (18), eaeb8948.
245. Tanaka, G.; Yamane, T.; Héroux, J. B.; Nakane, R.; Kanazawa, N.; Takeda, S.; Numata, H.; Nakano, D.; Hirose, A., Recent Advances in Physical Reservoir Computing: A Review. *Neural Networks* **2019,** *115*, 100-123.
246. Hauser, H.; Ijspeert, A. J.; Füchslin, R. M.; Pfeifer, R.; Maass, W., Towards a Theoretical Foundation for Morphological Computation with Compliant Bodies. *Biol. Cybern.* **2011,** *105* (5), 355-370.
247. Kaspar, C.; Ravoo, B. J.; van der Wiel, W. G.; Wegner, S. V.; Pernice, W. H., The Rise of Intelligent Matter. *Nature* **2021,** *594* (7863), 345-355.
248. Walther, A., From Responsive to Adaptive and Interactive Materials and Materials Systems: A Roadmap. *Adv. Mater.* **2020,** *32* (20), 1905111.
249. Needleman, D.; Dogic, Z., Active Matter at the Interface between Materials Science and Cell Biology. *Nat. Rev. Mater.* **2017,** *2* (9), 17048.
250. Heisser, R. H.; Bawa, M.; Shah, J.; Bu, A.; Raman, R., Soft Biological Actuators for Meter-Scale Homeostatic Biohybrid Robots. *Chem. Rev.* **2025,** *125* (7), 3976-4007.
251. Shin, M.; Lim, J.; Kim, S.; Lee, S.; Su, W. W.; Yoon, J.; Choi, J. W., Human Nervous System-Based Biohybrid Robot-on-a-Chip with Sensing Function for Toxicity Screening. *Advanced Science* **2025,** *12* (37), e01452.
252. Meder, F.; Baytekin, B.; Del Dottore, E.; Meroz, Y.; Tauber, F.; Walker, I.; Mazzolai, B., A Perspective on Plant Robotics: From Bioinspiration to Hybrid Systems. *Bioinspiration & Biomimetics* **2023,** *18* (1), 015006.
253. Del Dottore, E.; Mondini, A.; Rowe, N.; Mazzolai, B., A Growing Soft Robot with Climbing Plant–Inspired Adaptive Behaviors for Navigation in Unstructured Environments. *Sci Robot.* **2024,** *9* (86), eadi5908.
254. Li, W.; Lou, C.; Liu, S.; Ma, Q.; Liao, G.; Leung, K. C. F.; Gong, X.; Ma, H.; Xuan, S., Climbing Plant-Inspired Multi-Responsive Biomimetic Actuator with Transitioning Complex Surfaces. *Adv. Funct. Mater.* **2025,** *35* (6), 2414733.

255. Sachin, S.; Mondini, A.; Mariani, S.; Del Dottore, E.; Mazzolai, B., Beerootbot: A Bioinspired Robotic Probe Exhibiting Apical Growth through in Situ Soil Binding. *Adv. Intell. Syst.* **2026,** *8* (2), 2500720.
256. Mazzolai, B.; Del Dottore, E.; Speck, T.; Rowe, N.; Laschi, C., Energy-Saving Movement Strategies in Animals and Plants for Robot Design. *Nat. Rev. Bioeng.* **2025,** *3* (11), 921-938.
257. Ye, J.; Gu, W.; Hu, J.; Chen, L.; Yang, C.; Gao, J.; Zhou, S., Toward Next-Generation Semiartificial Photosynthesis: Multidisciplinary Engineering of Biohybrid Systems. *Chem. Rev.* **2025,** *125* (24), 12198-12252.
258. Xie, Y.; Han, J.; Dai, X.; Zhang, X.; Xiao, K.; Huang, J.; Cao, Y.; Zhong, A.; Huang, L. B., A Review on Biodegradable Materials of Sustainable Soft Robotics and Electronics. *Advanced Science* **2026,** *13* (15), e10320.
259. Oh, M.-H.; Kim, Y.-H.; Lee, S.-M.; Hwang, G.-S.; Kim, K.-S.; Kim, Y.-N.; Bae, J.-Y.; Kim, J.-Y.; Lee, J.-Y.; Kim, Y.-C., Lifetime-Configurable Soft Robots Via Photodegradable Silicone Elastomer Composites. *Sci. Adv.* **2023,** *9* (34), eadh9962.
260. Wei, P.; Zhang, Z.; Cheng, S.; Meng, Y.; Tong, M.; Emu, L.; Yan, W.; Zhang, Y.; Wang, Y.; Zhao, J., Biodegradable Origami Enables Closed-Loop Sustainable Robotic Systems. *Sci. Adv.* **2025,** *11* (6), eads0217.
261. Baumgartner, M.; Hartmann, F.; Drack, M.; Preninger, D.; Wirthl, D.; Gerstmayr, R.; Lehner, L.; Mao, G.; Pruckner, R.; Demchyshyn, S., Resilient yet Entirely Degradable Gelatin-Based Biogels for Soft Robots and Electronics. *Nat. Mater.* **2020,** *19* (10), 1102-1109.
262. Jia, D.-Z.; Li, L.; Yang, Y.; Zhang, J.; Yang, T.-B.; Lin, H.; Huang, H.-D.; Zhong, G.-J.; Li, Z.-M., Recycling Thermoplastic Polyester with Dynamic Covalent Networks. *Macromolecules* **2025,** *58* (17), 9504-9514.
263. Zhou, W.; Liu, Y.; Nie, X.; Zhu, C.; Xiong, L.; Zhou, J.; Huang, W., Peptide-Based Inflammation-Responsive Implant Coating Sequentially Regulates Bone Regeneration to Enhance Interfacial Osseointegration. *Nat. Commun.* **2025,** *16* (1), 3283.
264. Ye, C.; Zhang, H.; Yang, Y.; Shan, Y.; Fu, J.; Gao, W.; Ren, J.; Cao, L.; Ling, S., Sustainable Silk Fibroin Ionic Touch Screens for Flexible Biodegradable Electronics with Integrated Ai and Iot Functionality. *Adv. Mater.* **2025,** *37* (22), 2412972.
265. He, K.; Cai, P.; Ji, S.; Tang, Z.; Fang, Z.; Li, W.; Yu, J.; Su, J.; Luo, Y.; Zhang, F., An Antidehydration Hydrogel Based on Zwitterionic Oligomers for Bioelectronic Interfacing. *Adv. Mater.* **2024,** *36* (8), 2311255.
266. Cao, C.; Ji, S.; Jiang, Y.; Su, J.; Xia, H.; Li, H.; Tian, C.; Wong, Y. J.; Feng, X.; Chen, X., Mitigating the Overheat of Stretchable Electronic Devices Via High-Enthalpy Thermal Dissipation of Hydrogel Encapsulation. *Adv. Mater.* **2024,** *36* (26), 2401875.
267. Kobayashi, S.; Makino, A., Enzymatic Polymer Synthesis: An Opportunity for Green Polymer Chemistry. *Chem. Rev.* **2009,** *109* (11), 5288-5353.
268. Mazzolai, B.; Laschi, C.; Margheri, L., Environmental Intelligence and Ecorobotics: Toward Environmental Sustainability. *Annual Review of Control, Robotics, and Autonomous Systems* **2025,** *8* (1), 25-47.
269. Goddard, M. A.; Davies, Z. G.; Guenat, S.; Ferguson, M. J.; Fisher, J. C.;

Akanni, A.; Ahjokoski, T.; Anderson, P. M.; Angeoletto, F.; Antoniou, C., A Global Horizon Scan of the Future Impacts of Robotics and Autonomous Systems on Urban Ecosystems. *Nature ecology & evolution* **2021,** *5* (2), 219-230.
270. Tan, Y. J., Compostable Soft Robots for Plant Monitoring. *Nature Sustainability* **2026**, 1-2.
271. Mazzolai, B.; Mondini, A.; Del Dottore, E.; Margheri, L.; Carpi, F.; Suzumori, K.; Cianchetti, M.; Speck, T.; Smoukov, S. K.; Burgert, I., Roadmap on Soft Robotics: Multifunctionality, Adaptability and Growth without Borders. *Multifunctional Materials* **2022,** *5* (3), 032001.
272. Su, J.; Jiang, Y.; Ye, D.; Huang, Y., Plasma-Jet-Assisted Maskless, Erasable, Extreme Wetting-Contrast Patterning on Stretchable Carbon Nanotubes Film. *Applied Physics Express* **2019,** *12* (11), 115503.
273. Linghu, C.; Liu, Y.; Yang, X.; Li, D.; Tan, Y. Y.; Mohamed Hafiz, M. H. B.; Rohani, M. F. B.; Du, Z.; Su, J.; Li, Y., Fibrillar Adhesives with Unprecedented Adhesion Strength, Switchability and Scalability. *National Science Review* **2024**, nwae106.
274. Abd Aziz, M. H.; Othman, M. H. D.; Tavares, J. R.; Pauzan, M. A. B.; Tenjimbayashi, M.; Lun, A. W.; Alias, N. H.; Ismail, A. F.; Rahman, M. A.; Jaafar, J., Self-Cleaning and Anti-Fouling Superhydrophobic Hierarchical Ceramic Surface Synthesized from Hydrothermal and Fluorination Methods. *Appl. Surf. Sci.* **2022,** *598*, 153702.
275. Aubin, C. A.; Choudhury, S.; Jerch, R.; Archer, L. A.; Pikul, J. H.; Shepherd, R. F., Electrolytic Vascular Systems for Energy-Dense Robots. *Nature* **2019,** *571* (7763), 51-57.
276. Katzschmann, R. K.; DelPreto, J.; MacCurdy, R.; Rus, D., Exploration of Underwater Life with an Acoustically Controlled Soft Robotic Fish. *Sci Robot.* **2018,** *3* (16), eaar3449.
277. Cianchetti, M.; Laschi, C.; Menciassi, A.; Dario, P., Biomedical Applications of Soft Robotics. *Nat. Rev. Mater.* **2018,** *3* (6), 143-153.
278. Zhang, X.; Jiang, L., Bioinspired Superwetting Interfacial Nanomaterials and Beyond: Bionic Ultralow-Energy-Consumption Processes. ACS Publications: 2026.
279. Miao, W.; Tian, Y.; Jiang, L., Bioinspired Superspreading Surface: From Essential Mechanism to Application. *Acc. Chem. Res.* **2022,** *55* (11), 1467-1479.
280. Guittard, F.; Amigoni, S.; Darmanin, T., Bioinspired and Biomimetic Wetting Properties. *ACS nano* **2025,** *19* (41), 36005-36026.
281. Ye, D.; Su, J.; Jiang, Y.; Yin, Z.; Huang, Y., Plasma-Jet-Induced Programmable Wettability on Stretchable Carbon Nanotube Films. *Materials Today Physics* **2020,** *14*, 100227.
282. Li, S.; Ma, J.; Han, J.; Fu, J., Biomimetic Self-Sensing Hydrogel Soft Robotics: Precise Structures for Integrated Actuation and Sensing. *Adv. Funct. Mater.* **2026**, e74884.
283. Lee, Y.; Park, J.; Choe, A.; Cho, S.; Kim, J.; Ko, H., Mimicking Human and Biological Skins for Multifunctional Skin Electronics. *Adv. Funct. Mater.* **2020,** *30* (20), 1904523.

284. Chen, Z.; Huang, Y.; Zhang, B.; Sun, D.; Yu, X., Deformable Materials and Structures in Wearable Haptic Interfaces. *Nat. Rev. Mater.* **2026**, 1-20.
285. Levin, M., The Multiscale Wisdom of the Body: Collective Intelligence as a Tractable Interface for Next-Generation Biomedicine. *Bioessays* **2025,** *47* (3), e202400196.
286. Bernth, J. E.; Ho, V. A.; Liu, H., Morphological Computation in Haptic Sensation and Interaction: From Nature to Robotics. *Advanced Robotics* **2018,** *32* (7), 340-362.
287. Rossiter, J. M.; Hauser, H., Soft Robotics-the Next Industrial Revolution? *IEEE Robotics and Automation Magazine* **2016,** *23* (3), 17-20.
288. Marcus, H. J.; Ramirez, P. T.; Khan, D. Z.; Layard Horsfall, H.; Hanrahan, J. G.; Williams, S. C.; Beard, D. J.; Bhat, R.; Catchpole, K.; Cook, A., The Ideal Framework for Surgical Robotics: Development, Comparative Evaluation and Long-Term Monitoring. *Nat. Med.* **2024,** *30* (1), 61-75.
289. Chen, X.-Y.; Lai, W.; Xiong, X.; Wang, X.; Wang, S.-M.; Li, P.; Han, W.; Du, Y.; Duan, W.; Du, W., Robotic Bronchoscopy System with Variable-Stiffness Catheter for Pulmonary Lesion Biopsy. *IEEE Transactions on Medical Robotics and Bionics* **2025,** *7* (1), 416-427.
290. Cha, J. M.; Hong, J.; Yoo, J.; Rha, D.-w., Wearable Robots for Rehabilitation and Assistance of Gait: A Narrative Review. *Annals of rehabilitation medicine* **2025,** *49* (4), 187-195.
291. Han, S.-H.; Choi, S.; Ko, C.; Lee, J. W.; Kong, K.; Rha, D.-W.; Kim, D. Y., Efficacy of a Soft Wearable Robot for Hip Assistance in Chronic Stroke Patients: A Randomized Crossover Trial. *IEEE Transactions on Neural Systems and Rehabilitation Engineering* **2025**.
292. Guo, W.; Katiyar, S. A.; Davis, S.; Nefti-Meziani, S., Overview: A Comprehensive Review of Soft Wearable Rehabilitation and Assistive Devices, with a Focus on the Function, Design and Control of Lower-Limb Exoskeletons. *Machines* **2025,** *13* (11), 1020.
293. Jiang, C.; Xiao, J.; Wei, H.; Wang, M. Y.; Chen, C., Review on Portable-Powered Lower Limb Exoskeletons. *Sensors* **2024,** *24* (24), 8090.
294. Chen, G.; Meng, X.; Qiao, J.; Zhang, Z.; Wu, W.; Xu, Y.; Hu, H., Design and Depth Control of a Beaver-Inspired Underwater Robot Based on Center-of-Mass Adjustment. *Ocean Eng.* **2026,** *352*, 124616.
295. Wang, P.; Lin, H. W.; Li, J.; Wang, J.; Shi, L.; Meng, M. Q.-H., Pierguard: A Planning Framework for Underwater Robotic Inspection of Coastal Piers. *IEEE Transactions on Automation Science and Engineering* **2025**.
296. İlman, M. M.; Huber, A.; Mishra, A. K.; Sen, S.; Wang, F.; Lin, T.; Jander, G.; Stroock, A. D.; Shepherd, R. F., In Situ Foliar Augmentation of Multiple Species for Optical Phenotyping and Bioengineering Using Soft Robotics. *Sci Robot.* **2025,** *10* (103), eadu2394.
297. Mishra, A. K.; Ramaswami, A.; Shree, V.; Ilman, M. M.; Ly, K. D.; Pritts, M. P.; Shepherd, R. F., Sensor Fusion of Touch & Vision in Soft Manipulators for Fruit Picking. *Nat. Commun.* **2026**.

298. O'Brien, K. W.; Xu, A.; Levine, D. J.; Aubin, C. A.; Yang, H.-J.; Xiao, M. F.; Wiesner, L. W.; Shepherd, R. F., Elastomeric Passive Transmission for Autonomous Force-Velocity Adaptation Applied to 3d-Printed Prosthetics. *Sci Robot.* **2018,** *3* (23), eaau5543.
299. Yuanyang, W.; Mahyuddin, M. N., Grasping Deformable Objects in Industry Application: A Comprehensive Review of Robotic Manipulation. *IEEE Access* **2025**.
300. Sun, Y.; Yap, H. K.; Liang, X.; Guo, J.; Qi, P.; Ang Jr, M. H.; Yeow, C.-H., Stiffness Customization and Patterning for Property Modulation of Silicone-Based Soft Pneumatic Actuators. *Soft robotics* **2017,** *4* (3), 251-260.
301. Majidi, C., Soft-Matter Engineering for Soft Robotics. *Adv. Mater. Technol.* **2019,** *4* (2), 1800477.
302. Gong, S.; Yap, L. W.; Zhu, B.; Cheng, W., Multiscale Soft–Hard Interface Design for Flexible Hybrid Electronics. *Adv. Mater.* **2020,** *32* (15), 1902278.
303. Hu, X.; Liu, Z.; Zhang, Y., Three-Dimensionally Architected Tactile Electronic Skins. *ACS nano* **2025,** *19* (15), 14523-14539.
304. Yap, H. K.; Ng, H. Y.; Yeow, C.-H., High-Force Soft Printable Pneumatics for Soft Robotic Applications. *Soft robotics* **2016,** *3* (3), 144-158.
305. Shami, Z.; Arslan, T.; Lomax, P., Wearable Soft Robots: Case Study of Using Shape Memory Alloys in Rehabilitation. *Bioengineering* **2025,** *12* (3), 276.
306. Zhang, Z.; Gao, Y.; Liang, Y.; Li, X.; Qiu, H.; Wang, Z.; Zhou, F.; Li, T., An Integrated Electrohydraulic Soft Robotic Fish with 3d Maneuverability and Autonomous Control. *IEEE Robotics and Automation Letters* **2026**.
307. Bliah, O.; Hegde, C.; Tan, J. M. R.; Magdassi, S., Fabrication of Soft Robotics by Additive Manufacturing: From Materials to Applications. *Chem. Rev.* **2025,** *125* (16), 7275-7320.
308. Laschi, C.; Wen, L.; Iida, F.; Abdulali, A.; Hauser, H.; Wang, Y.; Liu, K.; Ricotti, L.; Cianchetti, M.; Althoefer, K., Soft Robotics: What's Next in Bioinspired Design and Applications of Soft Robots? *Bioinspiration & Biomimetics* **2026,** *21* (1), 011501.