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A Review on Recent Trends of Bioinspired Soft Robotics: Actuators, Control Methods, Materials Selection, Sensors, Challenges, and Future Prospects

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Bioinspired soft robotics is an emerging field that aims to develop flexible and adaptive robots inspired by the movement and capabilities of biological organisms. This review article examines recent advances in materials, actuation mechanisms, sensors, and control strategies and discusses the challenges and future prospects of bioinspired soft robotics. Key innovations highlighted include pneumatic, elastomer actuators, variable-length shape memory alloy tendons, closed-loop control with soft sensors, and the incorporation of soft materials including shape memory polymers and conductive composites. Challenges in soft robotics such as achieving complex motion control, incorporating feedback systems, modeling soft material dynamics, and replicating biological muscle efficiency with artificial muscles are also discussed. Promising future directions are explored including the integration of biodegradable materials, machine learning-based control algorithms, and leveraging data-driven techniques for modeling and control. Building on progress in multi-functional materials, manufacturing techniques, and bioinspired design principles, soft robots hold considerable promise for expanding robot capabilities, enhancing versatility and adaptability, enabling applications from wearable assistive devices to search and rescue operations. This review provides a holistic perspective encompassing key drivers propelling innovations in the vibrant field of bioinspired soft robotics.

1. Introduction

Robots are versatile and programmable machines made for doing complex tasks with great precision.[1] Due to robots' ability to learn and adapt according to the task and execute them seamlessly with accuracy in a controlled manner. They have become popular in various sectors such as the food industry, agriculture, human–machine interaction, manufacturing, space exploration, military, and so on.[2] Soft robotics has brought light to a new category of robotics. It is a subdivision of robotics that concentrates on design, development, and application of robots made of soft, flexible, and compliant materials for performing environmental adaptive tasks. Soft robots are more adaptive and safer for human interaction, more robust and stable and low cost than traditional robots.[3] Bioinspired soft robotics draws inspiration from nature's most unique creatures. **Figure 1** shows how bioinspired soft robots have similar abilities like different animals such as earthworm, jellyfish, octopus, snail, etc. It explains how, many living organisms have inspired researchers and engineers to incorporate unique abilities like dexterity, compliance, flexibility, and adaptability into soft robots.[4] Soft materials used in soft robotics are elastomers, hydrogels, liquid metals, shape memory alloys, polymer foam, etc.[5] Soft technologies have expanded the horizon for robotics and unlocked new potentials such as: infinite degree of freedom, deformability, flexibility, self-healing. These characteristics can be found in biological organisms from which different soft robots are inspired, such animals are worms,[6] fish,[7] jellyfish,[8,9] copepod,[10] inchworm, earthworm,[11] snakes.[12] The next generation of robotics is moving toward soft robotics because of its uses in biomedical technologies, surgery, drug delivery[13–15] therapy to people with autism spectrum disorder,[16] in agriculture for crop harvesting,[17–19] underwater exploration,[20,21] interactive wearables,[22] military, search and rescue,[23] and many more where current rigid robots fail to work due to its inability to adapt to the unpredictable conditions of real world, human safety hazards, absorb impact shocks, conform to complex shapes, etc.

Bioinspired soft robotics is constantly working to replicate the behavior of living organisms like octopus, jellyfish, snail, etc. with the help of technological advancements[24,25] and teaching the robots to jump,[26] stretch,[27] grasp,[28] self-deploy,[29] self-heal,[30] grow, climb, and perform locomotion. Soft robotics uses shape memory alloy (SMA), pneumatic actuation, electroactive polymer actuation (EPA), liquid metals, hydraulics, etc. as actuation technologies[31] along with tactile sensors. Soft robotics is in its infancy and it must overcome many challenges to close the gap between real living organisms and soft robots. Efficiency, mechanical development, adaptability of electronic components

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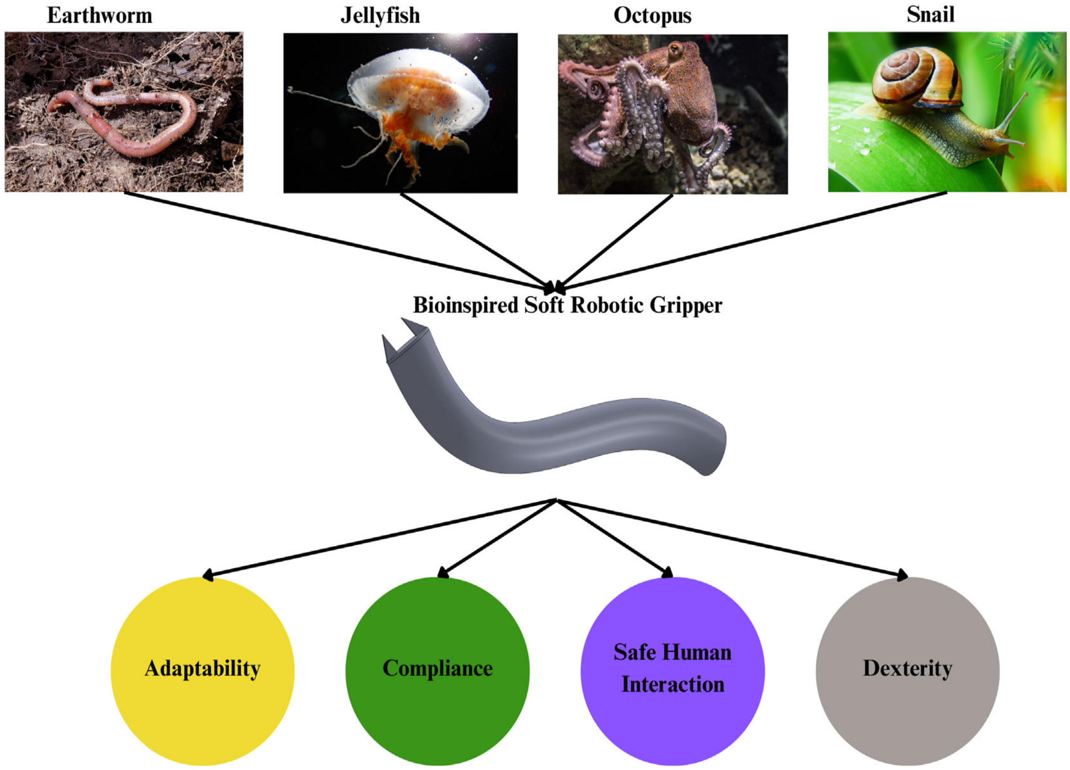

Figure 1. Bioinspired soft robotic gripper inheriting the abilities of different biological creatures.

to extreme environment, development of stretchable power sources,[32] controllers, sensing modules, integration of advanced algorithms with soft actuation and control systems are some of the challenges that need to be addressed in coming years.[33,34] Inclusion of biodegradable materials, renewable energy sources for sustainable approach toward bioinspired soft robotics,[35] machine learning methods for accurate control in unpredictable conditions[36] will have a great impact on this growing field of bioinspired soft robotics, helping it prevail over the boundaries of rigid linked robots and be on par with biological organisms.[37]

Nature has always excited our curious minds. Bioinspired soft robotics is a vast research field with a great potential. This article discusses the advances, limitations, and future direction for bioinspired soft robotics. The key features of this review article are as follows: 1) Highlighting the latest technologies in bioinspired soft robotics; 2) Discussing the challenges and exploring possible solutions; and 3) Future prospect of these robots.

Table 1 compares the contents of the recent related work on bioinspired soft robotics. Most review papers have covered a specific aspect of bioinspired soft robotics. But none of them have concentrated on all the aspects such as actuation, sensing, control technologies and material selection together. Most of the papers have discussed about different actuation systems but very few have explored the model-based and model-free control strategies for bioinspired soft robotics. Our article compiles all these technological advances along with the challenges and future directions of bioinspired soft robotics. **Figure 2** shows the topics covered in this article.

2. Bioinspired Soft Actuators

Actuators are foundational components of robots that use energy to produce motion. Conventional robots use motorized, cable joints or other rigid components that help them in rotational or reciprocal motion. In the search for enhanced efficiency, adaptability, flexibility, and safer human interaction, researchers have been led to design and fabricate actuators using soft materials. The inspiration is taken from living organisms to function the actuators like muscles in the animal body. These actuators have the ability to deform and change shape, contract, extend, bend like real body muscles.[24,38,39] The conventional actuators have finite degree of freedom whereas soft actuators theoretically have infinite degree of freedom.[37]

Bioinspired soft actuators have advanced astonishingly in recent years. Mimicking abilities such as camouflage like chameleons,[39] turtle-inspired swimming and walking,[40] octopus- like crawling, bionic movement mimicking frogs[41] by using different smart materials and control technologies in soft actuators. Recently, many new soft actuators have emerged based on materials such as pneumatic actuators (PA), hydrogel actuators (HA), biohybrid actuatosr (BHA), dielectric actuators (DEA), twisted and coiled yarns (TCY), shape memory alloys (SMA), liquid crystal elastomers (LCE), and ionic polymer–metal composites (IPMC).[25,38] These soft actuators can also be classified based on control technologies as follows: pneumatic actuation,[32,37,42] hydraulic actuation, electrical actuation,[43,44] chemical reaction stimulation[37] or other stimulations such as water, light, pH, heat, electric field, and magnetic field.[25]

Table 1. Survey of related papers.

References	Actuation System			Soft Sensor			Soft Materials			Control Methods				Challenges			Key Findings
	Variable Length Tendon	Electroactive Polymers	Fluid Elastomer Actuator	Bio-inspired	Bio-degradable	Shape Memory Alloy	Electroactive Polymer	Hydrogel	Bio-logical	Open loop	Closed loop	Model based	Model free	Modeling & Control	System Integration	Material	
[37]	×	×	✓	×	×	✓	✓	✓	×	×	×	×	×	×	×	×	Working principle of soft actuators, design and material selection in bioinspired soft robotics
[25]	×	×	×	✓	×	✓	✓	✓	✓	×	×	×	×	×	×	×	Advances in bioinspired soft actuator and sensor between 2017–2020
[20]	✓	✓	✓	×	×	×	×	×	×	×	×	✓	✓	✓	✓	×	Application of different modeling and control technologies and future direction of underwater soft robotics
[24]	✓	✓	✓	×	×	×	×	×	×	×	×	×	×	×	✓	✓	Inspiration for soft actuators, materials and creation of hybrid system with tissue engineering
[31]	✓	✓	✓	×	×	×	×	×	×	×	×	×	×	×	×	×	Recent development in field of soft grippers and their performance parameters
[32]	×	×	×	×	×	×	×	×	×	✓	✓	✓	✓	✓	×	×	Summary of recent advances and control strategies of pneumatic soft actuators
[38]	✓	✓	✓	×	×	✓	✓	✓	×	×	×	×	×	✓	✓	×	Soft material selection and their design strategies, comparison of popular actuation methods
This article	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	This article covers the recent technological advancement in the field of bioinspired soft robotics

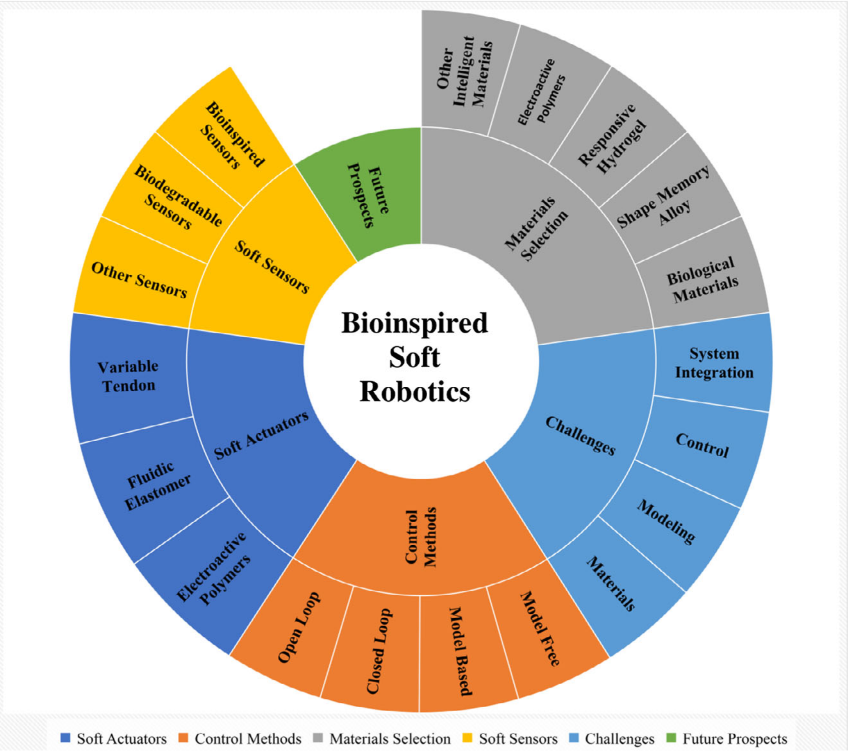

Figure 2. Overview of the topics covered in this review article.

2.1. Variable Length Tendon

Variable-length tendon (VLT) mimics the functionalities of tendons in living organisms. Its key feature is to replicate the flexibility and adaptability of biological muscles and tendons. VLT can be classified into tension cable and SMA.[44] Variable-length tendon has advantage over conventional actuation due to its enhanced dexterity, efficiency, force generation per length, and precise control over movement. Its application in bioinspired soft robots, locomotion, and grippers can revolutionize actuation mechanism.[40]

The characteristics of SMAs allow them to deform in response to stimuli like temperature, enabling the generation of motion without external motors or other components. SMAs formed in such a way that it is easy to integrate with soft structure.[45,46] In SMAs change of temperature controls the force generation.[24] Relatively small force generation,[47] overheating, poor efficiency[24] can be pointed out as disadvantage of SMA. Applications of SMA can be noticed in caterpillar-inspired GoQBot,[48] octopus-like arm structures,[49] soft turtle robot,[50] and so on.

Tension cables and piezoelectrics are also other techniques of actuation for soft robots. The use of tension cables have decreased over time due to the challenges of integrating hard cable with soft body.[44] Piezoelectric actuators use current to generate mechanical strain and they have similar advantages as SMA. SMAs have limitations but they can be overcome, for example, small strain can be addressed by spiral shaped SMA,[47] decreasing cross-sectional areas for higher thermal resistance for better response time[51] and using curved SMAs instead of conventional straight SMAs for larger deformation.[52]

2.2. Fluidic Elastomer Actuator

Fluidic elastomer actuators (FEA) use elastomeric materials and pressurized fluids (hydraulic or pneumatic) to inflate the chambers and generate locomotion. Elastomers that work similarly to SMA undergo change in volume in controlled manner to mimic the compliance and deformability of biological muscle.[44] The miniature inflatable chamber technology has made it possible to generate of force in small scale and precise locomotion.[53] One of the early versions of a fluidic actuator, called pneumatic artificial actuator, also known as McKibben actuator, is constructed of fiber braid that can produce high-intensity pressure and deform using pressurized air.[24]

FEA has found many applications in bioinspired soft robotics in driving mode of soft actuators, energy efficiency, controlled deformation, lightweight, and force generation per weight, which is scalable.[40] New generation of fluidic actuator coming in light is PneuNets (PN), this synthetic elastomer layered actuator deforms by pressurized gas and can hold its shape without any external energy sources.[47] Resilient quadrupedal soft robot,[54] snake-inspired soft robots,[55] compliant soft grippers[56] are some of the examples of PN architecture in bioinspired soft robotics.

FEAs are pressure-driven actuator which can be pneumatic or hydraulic. Hydraulic system is not as common as the use of pneumatic system in soft robotics field. These actuators can generate large forces and in the future, there are more possibilities of them to become lighter in size.[53] Pneumatic and hydraulic actuation methods are among the technologies used to replicate the movement of biological creature in soft robotics. Pneumatic actuation is preferred over hydraulic due to the easy access of air, eco-friendly to use, less time delay in response. Although pneumatics have their drawbacks, such as needing a continuous supply of air and high sealing requirements in extreme conditions[32,57,58] and hydraulics can generate more force than pneumatic actuators.[40] The basic principle behind hydraulic and pneumatic actuation is to pump the pressurized fluid into chambers that can produce desired deformation hence movement such as bending, twisting, expanding, etc.[53]

2.3. Electroactive Polymers

Electroactive polymer (EAP) actuators respond to electric stimulation which means they can change their size or shape when and electric field is applied. EAP is mainly classified into two categories: 1. Electronic EAP and 2. Ionic EAP.[47,59] There is also stimuli-responsive hydrogel actuator that swells when gaining water and shrinks as soon as water leaves. By this principle, it produces motion for soft robots.[60] This article discusses dielectric elastomer actuators (DEA) and ionic polymer–metal composites (IPMC) actuators.

2.3.1. Dielectric Elastomer Actuators

DEA works on the principle of electrostatic forces that are generated between electrodes embedded in a dielectric elastomer film. This leads to the contraction or extension of the body.[60] DEA's application in bioinspired soft robotics is possible because of their ability to produce distortion or large deformation, high energy density, long life, and fast response speed.[61,62] Rotary, multilayer stacked, diamond, rolled, bending, zipping, balloon, cone, hinge, planar, etc. are different types of DEAs.[61] Although DEAs bring a lot of positives to the table, it still has its limitations as well. Low yield stress without a rigid frame, complex design, and high operating voltage are major concerns in dielectric elastomer actuation technology.[24,38]

2.3.2. Ionic Polymer–Metal Composites

IPMC actuators require less operating input voltage (between 1 and 5 V) compared to DEAs. It is composed of ionic polymer which is sandwiched between two metal electrodes. Upon applying an electric field, the ions within the polymer move toward the oppositely charged electrode, causing the polymer to bend or deform. This feature of IPMC is utilized in soft robotics actuation.[38,60,63] The characteristics of IPMC have made it popular in wet environment usage and underwater soft robotics. IPMC is an exciting choice for bioinspired soft robotics actuation systems due to its capability of reaching large deformations against low electric field applied,[64] very quick response time of as good as 4 mm per 0.005 s,[44] and high durability. Though ionic EPAs like IPMC can show low mechanical coupling efficiency.[65,66] The applications of IPMC in inchworm-inspired soft robot body,[67] mimicking jelly fish,[8] underwater fish propeller using IPMC,[68] steerable fish[69] are suitable.

Table 2 discusses a detailed comparison of some vital characteristics of different soft actuation mechanisms. Strain is the deformation from the initial state in the direction of actuation and strain rate expresses the change in strain per unit time. Stress simply means the pressure exerted which is the ratio of output force to cross-sectional area. **Figure 3** highlights the range of Young's modulus, where it is clear that electromagnetic actuators have a higher range with SMA being close second. Work density refers to the work done per cycle by the actuator, while efficiency is the conversion of input energy into output. **Figure 4** shows that the SMA has a higher work density due to its ability to withstand high strain and stress. **Figure 5** shows that dielectric actuators are far more efficient than any other actuation mechanism.

3. Control Methods

Bioinspired soft robots are capable of doing complex tasks by interacting and adapting to the environment. However, control of soft robotics has always been a challenging task due to its flexible, deformable, adaptive, and compliant nature.[4,20] Their continuum property demands different a modeling technique than rigid-body robots. Unlike conventional rigid-body robots whose movements can be described by three translations and three rotations, soft robots have infinite degree of freedom. Because of nonlinear characteristics like hysteresis, compliance, infinite degrees of freedom, and unique design and modeling techniques, the control strategies used in conventional robots can't be implemented in soft robotics.[13,70] According to the task, environment, materials, and actuation system the control strategies may vary. Control methods used in bioinspired soft robotics can be classified into two categories: 1) Open loop control; and 2) closed-loop control.[47]

The most common control method in soft robotics is open loop control. Open loop control is generally used where minimum control effort is required.[34] Motion control of underwater star fish-like soft robot,[71] swimming eel-like robot with torque control algorithm,[72] control of granular material universal griper[73] uses different control methods. Open loop control tries to replicate muscle memory like a living organism without sensor feedback by predicting the movement based on the available knowledge about the system. Since there is no feedback mechanism to determine if the actuator has reached the targeted position. This limits the use of open loop method to only known environments and conditions.[74]

Closed-loop control is more robust and accurate compared to open loop control method. The closed-loop control approach in brittle star inspired underwater soft robot with crawling feature,[75] underwater soft robot with ability to swim[76] are examples of advancements in closed-loop control methods. Closed-loop approach is more accurate due to its feedback system having the ability to reject noise or disturbance.[40] Bioinspired soft robotics takes inspiration from biological creatures. Hence the impact of biological mechanisms can be seen in soft robots. If a human tries to grab something its neurons will act as sensors that will command the movement of arm. Then, for

Table 2. Comparison of different actuation mechanism in bioinspired soft robotics.

Actuation Mechanism	Strain [%]	Stress [MPa]	Work density [kj m^{-3}]	Frequency [Hz]	Efficiency [%]	Modulus [MPa]	Strain rate [% s^{-1}]	Advantages	Limitations	References
Shape Memory Alloy (SMA)	4–8	200	10^4–10^5	0.5–5	10	$28–75 \times 10^3$	10–50	Easy to fabricate and program Large deformation (300%)	Complex motion control	[25,45,60,175,176]
Pneumatic Actuation (PA)	10–40	1.16	1–200	1–5	49	0.1–100	10–70	Environment friendly Easy to access air Less time delay Lightweight	High sealing required Constant supply of air necessary	[31,32,40,60,175]
Dielectric Actuator (DEA)	1–1000	7.7	100–500	1–1000	90	0.1–3	10^2–10^5	High energy density Fast response time Greater force	High voltage required for actuation	[25,40,60,175,176]
Ionic Polymer-Metal Composites (IPMC)	0.5–10	3	1–10	0.1–2	1.5	25–2500	1–3	High actuation strain with respect to low applied voltage Bidirectional actuation Large bending displacement	Uncontrollable deformation Low electromechanical coupling efficiency	[25,40,60,175,177]
Hydrogel Actuator	10–20	.005	460	1	up to 80	–	2	Ability to mimic strength and energy density of biological muscle Low voltage operation and bistable	Slow response time Possibility of electrolysis above certain voltage Comparatively weaker mechanical properties	[64,175,176,178,179]
Liquid Crystal Elastomer (LCE)	10–50	.3–5.3	1–180	0.001–1	–	0.1–3	1–10	Powerful than ionic Longer operating time	Can't operate independently because it needs external high voltage amplifier	[25,40,60,180,181]
Hydraulically Amplified Self-healing Electrostatic Actuator (HASEL)	170	.3	64.4	20–50	21	–	2176	High force generation Simple fabrication	Fluid leakage can happen Requires high voltage to work	[40,60,182–184]
Electro-magnetic Actuator	15–25	–	–	High (up to 500 Hz)	–	0.3×10^2–3×10^5	–	Fast response Compact structure	Low efficiency Complex control	[25,182,184–186]

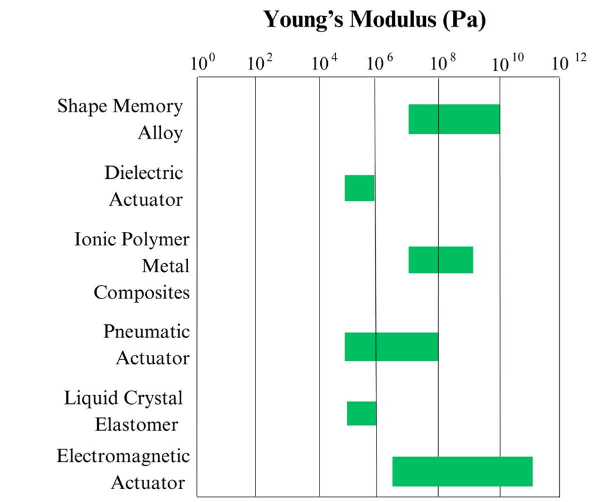

Figure 3. Overview of Young's modulus of different soft actuators.

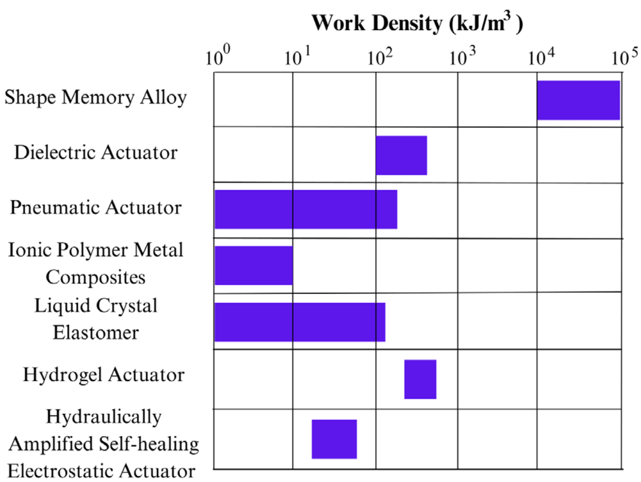

Figure 4. Work density of different soft actuators.

precise movement of the arm visual assistance is required from the eyes. Similarly closed-loop control can be divided into two parts: 1) First level closed-loop control; and 2) second level closed-loop control.[74]

The first level controls the deformation of the soft actuators where input is different stimuli such as water, pressure, temperature, electricity, etc., and the output of the actuator may be in terms of changes in length or angle.[74] First level closed-loop control in contrast to open loop control has a feedback path that compares output with reference with help of sensor.

Second level control takes the geometric parameters (length, angle) of the actuator as input and the output is the geometric parameter of the whole robot body. Second level control takes output of the first level which works as a mathematical model of kinematics and dynamics. Second level control includes kinematics or dynamics, on the contrary, first level has no relation to the kinematics and dynamics of robot body.[74] Forward and inverse kinematics are important in space control problems.

Control of soft robot also depends upon the modeling of the system. The precise control of robot in challenging environment requires different type of control strategies. Different model-based controllers that rely on analytical models or model-free controller which use machine learning techniques are implement in bioinspired soft robotics.[36,70] Basic principle in a layered control structure is that low-level controllers track the reference and drive the actuators, high level controllers use sensor feedback to estimate path and trajectory, meanwhile mid-level controllers involve kinematic and dynamic control.[20,22] The control of soft robotics has seen new heights thanks to the advancements in this field. Reinforcement learning (RL) is promising model-free control method that learns from trial and error with environmental experience. Also use of deep reinforcement learning (DRL) in the development of bioinspired soft robotics has enabled control of complex systems whether it is known or not.[20] There is recent work on DRL algorithm to mimic the muscle excitation patterns and movements of soft bodied animals. Soft tissues and muscles modeled by finite element method (FEM) are incorporated with a DRL algorithm for control of soft bodied robots.[77] FEM is also a popular open loop control strategy used for soft robot actuation.[74] One research uses deep Q-network (DQN) algorithm in soft robot fish for exploring underwater life. There are applications of deep Q-learning (DQL) which is union of deep learning and Q-learning method.[78] There are other algorithms such as deep deterministic policy gradient (DDPG), normalized advantage function (NAF), and advantage actor-critic (A2C) used to control soft robots in simulation environments. But there is a difference between simulation and real-world environment, this is where generative adversarial networks (GAN) can be used to narrow the gap between training environments and real-world applications.[20]

Kinematic model-based control requires a simple model because it considers soft robot without any force to perform position-based control. A human-inspired kinematics-based controller is used to control the tip position of a soft continuum arm used in daily interactive tasks like opening doors or pulling drawers. This project uses two control methods first, simplified Jacobian model and second, is Q-learning.[79] This finding implies that low-level controller focused on kinematics paired with high level planer can be as efficient as a complex model. On the contrary, dynamic model-based control utilizes a mathematical model to predict future behavior. Compared to kinematics-based control the dynamic model-based control is more accurate and versatile because dynamic approach takes the forces into consideration.[80] There have been many research works on dynamic model approaches, including model predictive control (MPC) based on piecewise constant curvature (PCC) model for continuum joint soft robots control,[81] trajectory tracking and interaction with the real-world environment and proportional integral derivative (PID) controller is used for regulating the robot's configuration,[82] application of curvature controller and cartesian regulation for achieving natural softness and adapting impedance of end effector[83] have had a great impact in the field of bioinspired soft robotics. The model-free controllers use data-driven techniques. In contrast to model-based control techniques, data-driven control learn from data collected from system operations. Data-driven techniques like reinforcement learning

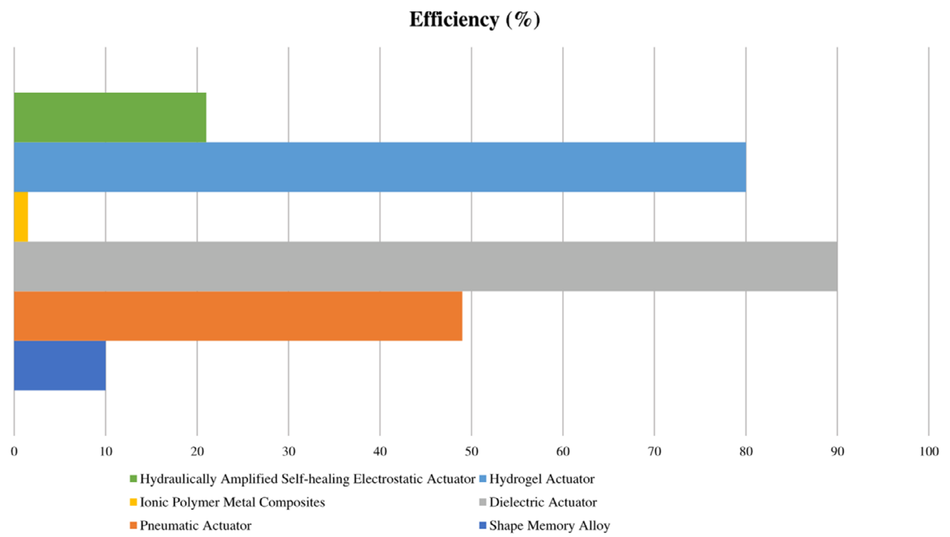

Figure 5. Comparison of efficiency of soft actuators.

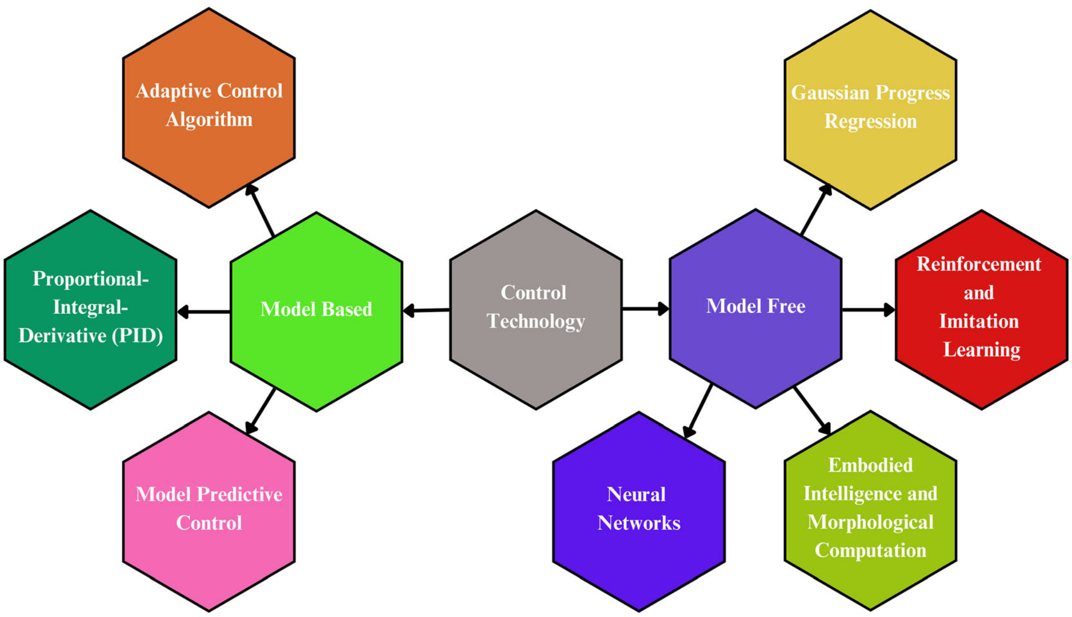

Figure 6. Overview of different control techniques of soft robotics.

(RL), neural networks, Gaussian process regression (GPR), Koopman operator, etc. are rapidly developing.[20,80] **Figure 6** gives an overview of different control techniques used in soft robotics based on models.

4. Material Selection

Soft robots with bioinspired designs have the capacity to match or perhaps exceed the extraordinary adaptability and multipurpose capabilities seen in living things. The design of such robots must seamlessly integrate sensing, passive mechanics, active movement, and control in order to achieve their full potential. To generate structures with global compliance and deformability, this integration deftly combines soft, stiff, and biological materials.[1,2] Developments in 3D printing, durable material interfaces, and creative systems-level design are just as important to this field's success as the creation of novel multifunctional materials.[37]

Although a lot of progress has been achieved in soft robotics in the last 10 years, soft bioinspired robotics is receiving more attention. This field offers fresh opportunities to create designed parts, apparatuses, and robots that can connect conventional robotics with living systems.[84,85]

Soft robots have utilized various materials, including rubbers, fabrics, papers, filaments, flexible electronics, and intelligent materials with a modulus of elasticity at least 1000 times lower than that of rigid materials.[86–91] Rubber polymers with high extensibility serve as common body materials, with mechanical characteristics dictated by elastic coefficients.[3] Intelligent material-driven mechanisms, especially those using various intelligent materials, are widely employed and can significantly influence the robot's maximum load, deformation, endurance, and overall performance.[92]

From **Figure 7** key materials used in soft bioinspired robotics include[2,9]: 1) Shape Memory Alloys (SMAs); 2) Electroactive Polymers: a) Dielectric Elastomers; b) Ionic Polymer–Metal Composites; 3) Responsive Hydro-gels; 4) Other Intelligent Materials (shape memory polymers, magnetorheological materi-als); 5) Biological Materials: a) Muscle cells; b) Plant fibers; c) Carbon-based materials; and d) Liquid crystalline polymers

Among these, SMAs, EAPs, and muscle cells are most prevalently utilized for actuation.

4.1. Shape Memory Alloy

SMAs exhibit shape memory and superelasticity through solid–solid phase transformations induced by temperature or magnetic field changes. This makes it possible to apply linear actuation with reversible contraction and elongation.[10] Based on how they function, SMAs may be divided into two types: magnetic control and temperature control. In the creation of soft robots, the temperature control type is more frequently employed as it produces force and deformation upon heating. The two phases of temperature-controlled SMAs—the high-temperature austenite phase and the low-temperature martensite phase—each have distinct deformation properties. The phase transition occurs based on the temperature difference, with martensite showing deformation at lower temperatures and austenite exhibiting the opposite behavior.[92]

4.2. Electroactive Polymer

Electroactive polymers (EAPs) are smart materials that change shape or size in response to electrical stimulation. The two main types of EAPs used in soft robotics are dielectric elastomers (DEs) and IPMCs.[59]

4.2.1. Dielectric Elastomer (DE)

DEs are composed of elastomeric materials like silicones or acrylics that are sandwiched between two compliant electrodes.[61,62] When a high voltage is applied, electrostatic forces squeeze the elastomer, causing it to expand in area and contract in thickness up to 480% strain.[61] Key properties that make DEs suitable as soft robotic actuators include high energy density, fast actuation speed, low cost, customizability, and noiseless and shockless operation.[62,63] DE transducers have been implemented in soft grippers, crawlers, swimmers, and manipulators.[61,66] However, issues like high driving voltages, electromechanical instability, and viscoelastic creep still need to be resolved before widespread adoption.[62] Recent work has focused on new dielectric materials, prestraining methods, and stacking geometries to improve actuation strain and efficiency.[61]

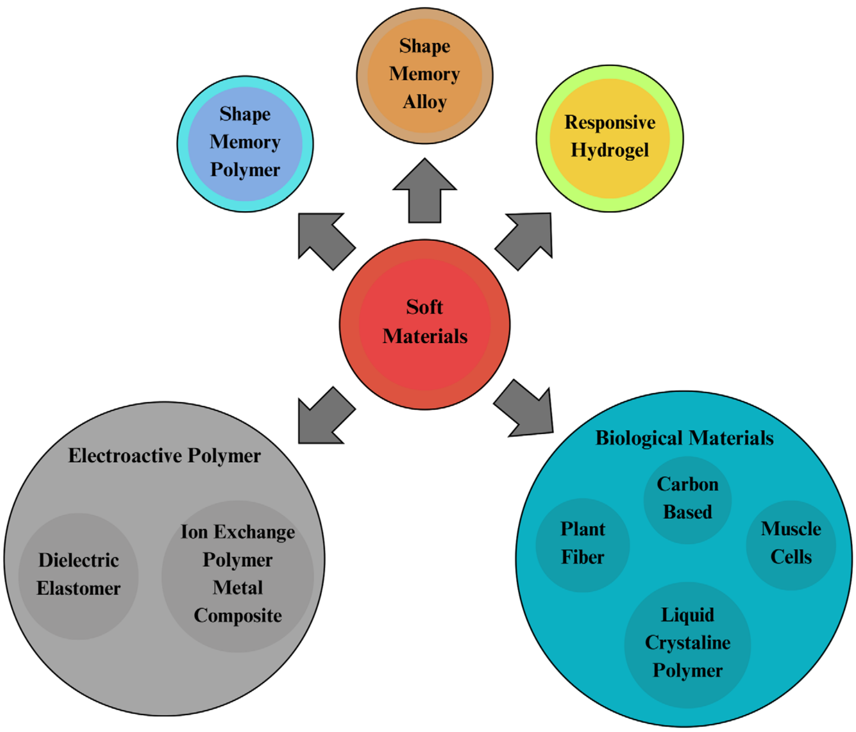

Figure 7. Different materials used in bioinspired soft robotics.

4.2.2. Ion Exchange Polymer–Metal Composite

IPMC actuators contain an ion exchange membrane (usually Nafion) plated with noble metal electrodes, like gold or platinum. When an electric field is applied, mobile cations migrate, causing bending toward the anode via osmotic swelling.[63,67] Under 3 V activation and in a hydrated state, IPMCs can achieve over 220% strain but with low force output (1–5 MPa).[59] Properties such as low operating voltage, biocompatibility, chemical stability, and resilience have enabled bioinspired underwater soft robots to achieve maneuverable propulsion and manipulation.[66,68] However, further optimization is needed to address issues such as dehydration, poor force production, and efficiency loss over repetitive cycles.[63,69] Recent focus has shifted to improving ion mobility and electromechanical efficiency using novel nanocomposite structures.[63,65] Overall, IPMCs remain a highly versatile and adaptive EAP for soft transduction in wet environments.

4.3. Responsive Hydrogel

Hydrogels undergo swelling/deswelling transitions in response to environmental stimuli.[9] Responsive hydrogels undergo phase transformation in response to external factors such as temperature, pH, light, or specific chemical molecules. For instance, thermosensitive hydrogels exhibit changes in hydrophilicity and hydrophobicity based on the temperature, while pH-sensitive hydrogels change their volume and morphology in response to acidity or alkalinity.[92]

4.4. Other Intelligent Materials

Other intelligent materials, such as shape memory polymers (SMP) and magnetorheological materials, offer unique properties. SMP can eliminate deformation through external factors like heat, light, electricity, or magnetism, and some SMP materials can be directly formed by 3D printing. Magnetorheological materials exhibit reversible changes in mechanical, electrical, and magnetic properties under the influence of a magnetic field. Liquid metals are pure metals or alloys of metals that show the characteristics of a low melting point, low toxicity, low viscosity, high conductivity, and high flexibility, as well as good thermal conductivity. Common liquid metallic elements include mercury (Hg), gallium (Ga), and cesium (Cs), among which gallium is more popular due to its low melting point and high boiling point.[93,94] Liquid metals flow-ability, softness, conductivity changes with ratio contents mixture. For instance, increasing oxide content will increase the electroconductivity of material.[93,95] Liquid metals are innovatively used in soft humanoid robots,[96] wheeled robot,[97] shape transformable nanomachine,[98] artificial muscle,[99] biomimetic robotic jellyfish,[100] etc. Gallium-based alloys are non-toxic and bio-compatible which will be vital in healthcare sector as well.

4.5. Biological Materials

Using a variety of biological materials, such as muscle tissue, plant fibers, carbon-based materials like graphite, graphene oxide (GO), and carbon nanotubes (CNT), as well as hydrogel materials like poly(N-isopropylacrylamide) (PNIPAM), liquid crystal elastomers (LCE), DE, and IPMC,[101–109] researchers have developed soft bioinspired actuators and sensors in recent years. Below is a discussion of these materials and the underlying mechanics.

4.5.1. Muscle Cells

Muscle tissue, featuring high strain density, self-healing properties, and electrical activation, is a crucial component for efficient actuation in soft robotics. Muscle cells naturally offer high actuation strain and self-healing ability. The direct integration of such contractile units from cardiac or skeletal muscles facilitates untethered biohybrid systems well-suited for biomedical applications.[9] Soft robotic systems directly utilize living cells, especially cardiac and skeletal muscle cells, which have led to the development of the field of miniature soft biohybrid robots. These biocompatible robots have unique sensing and actuation capabilities and show potential for use in medical applications such as medication treatment, surgery, and disease diagnosis.[110] Bio-hybrid micro systems can sense and respond, making them appropriate for untethered applications and environment-adaptive.[25]

4.5.2. Plant Fibers

Plant fibers, which are well-known for their capacity to expand and contract in response to variations in moisture, aid in actuation. These processes are comparable to those found in a variety of plant moving parts, such as the opening of a pine cone. Actuators that utilize these characteristics of the material are known as hygromorphic bio-composite (HBC) actuators. HBCs are inexpensive, easily accessible, and eco-friendly, but their primary disadvantage for composite reinforcement is that their high water absorption shortens their lifespan. Furthermore, the creation of high-performance composites is impeded by inadequate understanding and investigation of their mechanical behavior.[103,111,112]

4.5.3. Carbon-Based Materials

The word graphene describes a mono layer configuration of carbon atoms that resembles a honeycomb-shaped hexagonal lattice. Flexible graphene paper with a Young's modulus of 23–42 GPa and a tensile strength of 15–193 MPa, depending on the production procedure, is produced by stacking graphene layers. High electrical conductivity is exhibited by graphene, which is produced when graphite oxidizes and graphite oxide exfoliates GO layers. Conversely, GO serves as an electrical insulator. Bio-inspired robotics use graphene's electrical properties for sensing purposes. When graphite is exposed to potent oxidizing chemicals, graphite oxide is created. The Staudenmaier, Hummers, and Modified Hummers methods are often used for this oxidation.[113–115] Even though GO paper has exceptional mechanical strength, flexibility, electrical and thermal conductivity, and surface area, warming can lead to individual layers rupturing and delaminating, which can cause irreversible damage to the material's layered structure and layer wrinkling. Additionally, graphene's uses are limited by its short life cycles and low actuation strain.[113,116]

4.5.4. Liquid Crystalline Polymers

Liquid crystalline elastomers (LCEs) can reorder their orientation and exhibit shape transformations when activated.[9] Furthermore, LCEs have the capability to autonomously organize into a homogeneous material, undergoing mechanical transformations into various spatial orientations and geometries. However, the activation of LCEs necessitates elevated temperatures exceeding 100 °C. Additionally, these materials face challenges due to suboptimal mechanical properties, and their application is restricted by low blocking stress, which falls below 500 kPa.[117]

Table 3 compares some of the key materials used in bioinspired soft robotics. **Figure 8** shows the comparison between the strain capability and durability/life cycle of some soft materials. Among the soft materials there are SMS, DE, IPMC and muscle cells.[25,51,61,63,66,68,92] While various material options exist, such as SMAs, DEs, and IPMCs, that appear most promising for soft robotic actuation based on strain capabilities, configurability, and reliability.[8–10] Further development of nanocomposites using novel multi-functional constituents may help overcome limitations of existing technologies.[8]

5. Soft Sensors and Sensing for Control

Effective control of soft robots relies on integrated sensing and feedback systems. Recent progress has focused on multimodal, stretchable, and biodegradable soft sensors to achieve comprehensive environmental perception and proprioception.[34] Recent progress has resulted in the development of integrated soft sensing systems and innovative sensor materials designed to replicate biological sensory capabilities.[25,34] Numerous soft sensors have been created to measure essential parameters necessary for controlling soft robots. For instance, flexible and stretchable strain and pressure sensors enable soft robots to perceive touch, contact, and interactions with their external environments, akin to natural skin.[5] Examples include resistive and piezoresistive soft sensors that utilize conductive composites or liquid metals to convert pressure or strain into measurable electrical signals.[25] Similarly, soft optical sensors leveraging changes in light transmission can identify deformation for proprioceptive feedback.[34] This section delves into recent trends and insights derived from key papers in the field.

5.1. Bioinspired Soft Sensors

Bioinspired refers to designs, materials, or technologies that draw inspiration from biological systems and processes found in nature. This method involves using the structures, activities, or methods of biological things as a model to tackle challenging engineering problems and advance current technologies. Bioinspired advances in soft robotics take advantage of the adaptability and efficiency of natural systems, resulting in the creation of sophisticated materials and robotic designs that improve performance and functionality[34]: 1) Bio-mimicry is crucial in soft sensor design to replicate biological sensory features. Artificial tactile, optical, and chemical soft sensors aim to emulate natural senses using intelligent layouts and soft, active materials.[34] Drawing inspiration from organisms like cephalopods and plants, there is a focus on encoding external mechanical

Table 3. Comparison of properties for some key soft robotic materials.

Serial No.	Material	Strain capability	Response time	Stimulus type	Durability/Life cycles	References
1	Shape Memory Alloy (SMA)	<10%	Slow (secs)	Temp., Magnetic Field	High (>10^6)	[51,52,92]
2	Dielectric Elastomer (DE)	380–480%	Fast (ms)	Electric Field	Medium (10^4–10^5)	[61,64,66]
3	Ion Exchange Polymer–Metal Composite (IPMC)	>200%	Fast (ms)	Low Voltage, Wet	Low(10^2–10^3)	[63,68,69]
4	Muscle Cells	≈40%	Fast (ms)	Electrical, Chemical	100–200 (ex vivo)	[25,102,110]

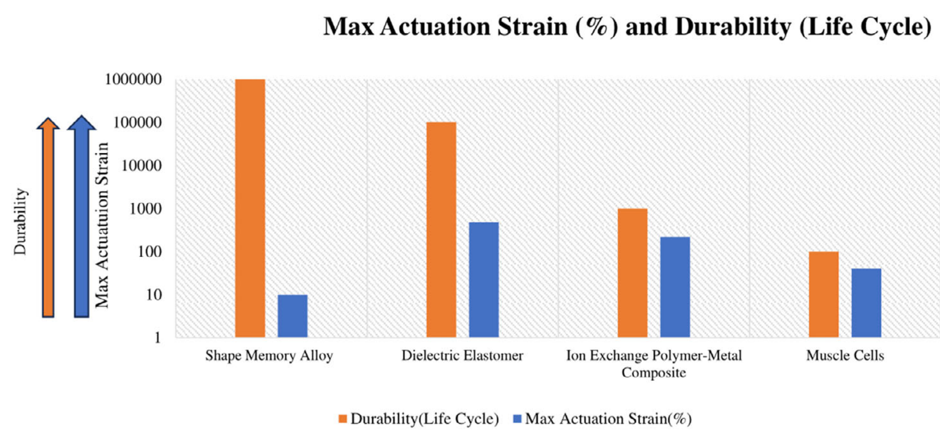

Figure 8. Comparative strain capability and durability of different soft materials.

information through touch sense and mechanosensation.[118] The integration of sensing and the soft body in soft robots necessitates innovative, flexible, and deformable strategies to achieve comprehensive exteroception and proprioception capabilities; 2) Artificial tactile sensing relies on mimicking the intrinsic characteristics of natural touch, utilizing intelligent layouts, and incorporating soft active materials.[24] Various materials, including conductive polymers, liquid metals, graphene, and stretchable epidermal electronics, contribute to the advancement of soft sensing technologies. Two case studies are examined, highlighting three-axial force sensing using textiles and soft materials for capacitive transduction in the first case.[119] The second case explores bending and pressure detection in a soft body, drawing inspiration from plant mechanoperception and employing stretchable materials and textiles[120]; and 3) Despite the advancements, integrating sensing devices into soft robots poses challenges related to decoupling mechanical solicitations and addressing the deformations of the soft body. The pursuit of multimodality and functional integration emerges as critical aspects for future developments.[121]

5.2. Biodegradable Sensors

Materials that may naturally break down into simpler organic compounds by microbes such as bacteria and fungi are known as biodegradable materials. This reduces the impact of the material on the environment. Numerous settings, including both anaerobic (without oxygen) and aerobic (with oxygen), can support this activity.[122]

Because biodegradable sensors in soft robotics include environmental factors in robotic design, they represent a substantial step forward in the development of sustainable technology. Many biodegradable materials and their uses in sensor technology are highlighted in recent research, emphasizing their potential to cut down on electronic waste without sacrificing functionality. Biodegradable sensors, which incorporate materials that offer crucial mechanical qualities and safely decompose in the environment, are developing as a game-changing breakthrough in bio-inspired soft robotics. These sensors are in line with the rising need for sustainable technologies by drastically reducing electronic waste and its negative effects on the environment.[123] Conductive coatings made from graphene and carbon nanofibers combined with biodegradable vitrimers offer flexibility and recyclability, crucial for soft robotics applications.[124] Besides, biodegradable materials enable soft robots to adapt to environmental stimuli, enhancing their functionality in applications like drug delivery and sensing.[125] Biodegradable micro robots are designed for biomedical applications, ensuring no toxic residues remain post-operation, which is vital for in vivo applications.[126] When together, these revelations highlight the potential of biodegradable sensors in enhancing the sustainability and functionality of soft robotic systems.

5.2.1. Pressure Sensors

A piezoresistive pressure sensor using Ag nanowires has been developed on a paper-based platform, exhibiting high sensitivity ($1.5\,kPa^{-1}$) within the pressure range of 30 Pa to 30 kPa. Challenges in achieving full biodegradability were acknowledged due to Ag nanowire degradation in humid conditions. The substitution of non-biodegradable components, such as Ag nanowires, poses difficulties due to rapid degradation in humid conditions.[127]

5.2.2. Implantable Biodegradable Sensors

A thin Fe/Zn bi layer structure has been employed as electrodes for a capacitive sensor with a sensitivity of $0.06\,kPa^{-1}$. Although exhibiting partial degradation within 18 days, the study emphasized the need for accelerated degradation in practical applications. Balancing degradation rates while preserving sensor performance is crucial for the practical implementation of implantable biodegradable sensors.[128]

5.2.3. Stretchable Pressure and Strain Sensors

Stretchable capacitive sensors, utilizing silk fibroin sheets with Ag nanowires, demonstrated high sensitivity (1.8×10^{-2}) at low pressures up to 20 kPa. However, challenges persist in achieving complete degradation of materials like Eco flex under natural conditions. Striking a balance between stretch ability and degradation rates is essential for creating sustainable and functional stretchable pressure and strain sensors.[129]

5.2.4. Temperature Sensors

A deformable temperature sensor has been developed with serpentine-shaped Mg traces encapsulated in Eco flex, exhibiting a sensitivity of $0.2\%\,K^{-1}$. The use of biodegradable materials contributes to sustainability. Exploring alternatives like natural wax composites for temperature sensing further enhances the eco-friendly design of sensors.[130]

5.2.5. Humidity Sensors

Humidity sensors, based on interdigitated Zn electrodes and biodegradable hydrogels, demonstrated a significant relative impedance change of two orders of magnitude between 10% and 80% relative humidity. The utilization of biodegradable substrates like hydrogels enhances the ecofriendliness of humidity sensors, providing valuable insights into environmental conditions.[131]

The development of biodegradable sensors involves intricate material choices and design considerations. Challenges persist in ensuring complete biodegradability and managing degradation rates, especially under practical conditions. Future advancements should prioritize sustainability without compromising sensor performance.

5.3. Other Sensors

Furthermore, there is a recognized trend toward integrating sensing data with data-driven learning algorithms. Researchers have applied learning algorithms in haptic identification,[132] developed neural network and regression models for closed-loop control,[133] utilized long short-term memory networks for real-time kinematics and force modeling,[31] and developed a convolutional neural network (CNN) model for object identification in conjunction with a triboelectric tactile sensor to construct a tactile feedback smart glove.[134] Using several machine learning techniques, soft optoelectronic sensory foams with proprioception are created.[135]

Various sensor types play a significant role in the sensing capabilities of bio-inspired soft robotics. Photoreceptors, drawing inspiration from the human eye and arthropod compound eyes, are designed with tunable soft lenses that alter focal length through mechanisms such as pH changes, electrowetting, and dielectric actuation. Curved image sensors, resembling retinas, have been fabricated to minimize aberrations and achieve a wide field of view.[136–138] Chemo-receptors emulate gas and humidity sensors based on beetle photonic structures and human skin, exhibiting color changes or wrinkling. These sensors can detect volatile organic compounds (VOCs) and humidity with high sensitivity down to 0.54 nm or 1.74 $g\,mL^{-1}$ through hydrogen bonding and molecular interactions.[139–143] Mechanoreceptors include strain sensors incorporating microcracks, self-healing hydrogels, and hierarchical structures for heightened sensitivity. Dual strain/pressure sensors utilize interlocking micro/nanostructures and capacitance changes. Pressure-only sensors, inspired by plant leaves, sea sponges, and human mechanoreceptors, are also being developed. Additionally, flow sensors mimic hair cell neuromasts found in fish and amphibians.[144]

The examination of transduction mechanisms and the structural and functional patterns of bioinspired sensors is crucial for comprehending the behavior principles of these sensors and their sensing capabilities: 1) Structural Motifs: Biological sensory systems have developed specialized structures, such as fingerprints, domed microstructures, porous networks, whiskers, hierarchical micro/nano features, and crack-like slits, to enhance sensitivity, signal amplification, response time, and detection ranges[145]; 2) Flexible Mechanosensors: Bio-inspired flexible sensors strive to replicate these structural motifs using materials like conductive composites, liquid metals, ionogels, and elastomers. This replication has resulted in improved pressure sensitivity, proprioception, texture detection, and other enhanced capabilities[25]; and 3) Functional Motifs: Biological sensory functionality emerges from mechanoreceptors, ion channels, and sensory neurons responsible for signal transduction and propagation. Flexible sensors imitate these functionalities through piezoelectric, triboelectric, piezoresistive, and capacitive effects, along with the incorporation of artificial neuron systems.[24]

Regarding current trends, there is a notable shift toward enhancing the integration of flexible sensors with soft bodies, aiming to advance toward closed-loop autonomous systems. Additionally, there is a growing demand for multifunctional sensing to achieve comprehensive environmental perception.[34]

Table 4 compares some of the key aspects and metrics of different sensors while **Table 5** compares some key sensor

Table 4. Comparison table of key aspects and metrics for the different bio-inspired sensors.

Serial No.	Sensor Type	Transduction Mechanism	Key Properties	Performance Metrics	References
1	Photo receptors	pH tuning, electrowetting, dielectric actuation	Soft, tunable lenses	Focal length variation: 0.246–0.362 mm; Field of view change: 30–80°	[187]
2	Chemoreceptors	Molecular interactions, hydrogen bonding	Hydro gel swell-ability and instability	Humidity range: 10–97% RH; VOC detection limit: 1.74 g mL	[188,189]
3	Strain Sensors	Piezoresistivity, micro cracks, self-healing	Stretch ability, conform-ability	Gauge factor: 107–1129%; Strain range: 0.25–2000%	[190,191]
4	Pressure Sensors	Capacitance change, interlocking nanostructures	Sensitivity, linearity	Pressure range: 0.4 Pa–25 kPa	[192,193]
5	Flow Sensors	Pillar deflection, optical diffraction	Sensitivity, dynamic range	Detection threshold similar to natural system	[191,194]

Table 5. Key sensor performance metrics and transduction mechanisms inspired from the biological world.

Sl. No.	Sensor type	Sensitivity	Frequency response	Transduction mechanism	Biological analog	Transduction mode	Stimulus-Response	Frequency bandwidth	Output signal	References
1	Piezoresistive	High	Static/Low frequency	Resistance change	Slow adapting receptors	Static compression	Low	Resistance change	Slow adapting receptors	[123]
2	Capacitive	Medium	Static/Low frequency	Capacitance change	Slow adapting receptors	Static compression	Low	Capacitance change	Slow adapting receptors	[195,196]
3	Piezoelectric	Medium	Dynamic/High frequency	Piezopotential	Fast adapting receptors	Dynamic compression	High	AC voltage	Fast adapting receptors	[197]
4	Triboelectric	Medium	Dynamic/High frequency	Tribocharge	Fast adapting receptors	Frictional slide	High	AC current	Fast adapting receptors	[198]
5	Iontronic	Ultrahigh	Wide frequency range	Ion flow	Ion channels	Ion flux	Wideband	Ionic current	Ion channels	[199]

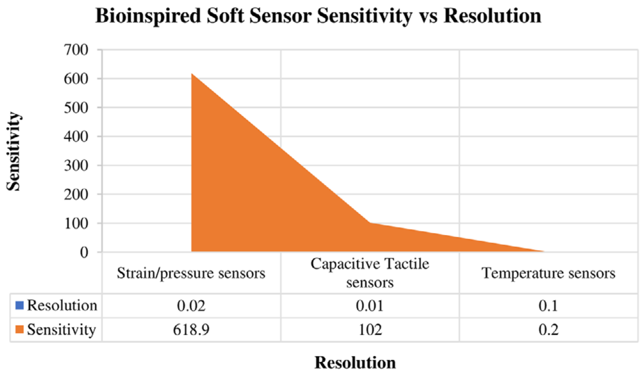

Figure 9. Sensitivity versus resolution for different bioinspired soft sensors.

performance metrics and transduction mechanism inspired from the biological world. **Figure 9** shows graph that gives a visual comparison between the resolution and sensitivity of 3 sensors where we can see that the sensitivity of a sensor decreases with the increase in resolution. Strain/pressure sensors using interlocking micro/nanostructures like hierarchical structures (sensitivity up to 618.9, resolution 0.02% strain).[119] Capacitive tactile sensors using textiles (sensitivity up to 102, resolution 0.01 kPa).[130] Temperature sensors using magnesium traces (sensitivity 0.2% K^{-1}, resolution 0.1 °C).[144] **Figure 10** demonstrates the rise in research interest in various categories of sensors. The rising interest in research is very significantly visible in sensors like mechanoreceptors, photoreceptors, and chemoreceptors over the years.[25,136,137,139,140]

6. Challenges

6.1. Control of Soft Robots

Compared to stiff robots, soft robots are more difficult to operate due to their flexibility, deform-ability, and continuous nature.[4,20] Besides, infinite degrees of freedom, non-linear characteristics like compliance and hysteresis make conventional control methods inapplicable.[13,70] There are also challenges regarding the complexity of closed-loop control with feedback systems but it is also needed for precision. Possible solutions can be data-driven and model-based control approaches, reduced order dynamic modeling, machine learning for control policy optimization.[81,82,146–148] Data-driven approaches like neural networks to learn complex control policies mapping states to actions, avoiding hand-engineering.[81] Researchers implemented model order reduction to rapidly simulate different gaits for a soft-legged robot.[146] Leverage differentiable simulators to train control policies in simulation and transfer them to real robots[71]

6.2. Modeling and Dynamics

Accurately modeling soft body dynamics with factors like variable stiffness poses difficulties.[20,80] The balance between model complexity and real-time control also needs to be managed. Softness necessitates new modeling approaches beyond traditional robotics control theory.[149] Reducing computational cost of models and simulations is important for efficient control implementation.[150] Reduced order methods like model order reduction and Koopman operator framework to capture dominant dynamics can be implied to overcome the issue.[146,147] Data-driven and learning-based approaches can also be a solution for tackling the limitations.[36]

6.3. Materials Requirements

Achieving the demanding mechanics, processability, costs, shelf life, and degradability requirements with sustainable materials is challenging. Enhancing stretchability without compromising strength or acceleration degradation is also difficult. Managing swelling and stability in ambient environments is a significant challenge. Replicating highly efficient muscle actuation from biology with artificial muscles remains difficult.[146] Continued materials research needed to improve actuation.[151,152] Design optimization processes still in early stages due to developing material models.[153] Replicating efficient muscle actuation from biology with artificial muscles remains difficult.[154,155] Continued materials research is needed. Power consumption and storage is a notorious issue limiting progress of mobile soft robots.[156] To solve the issues continued research into novel

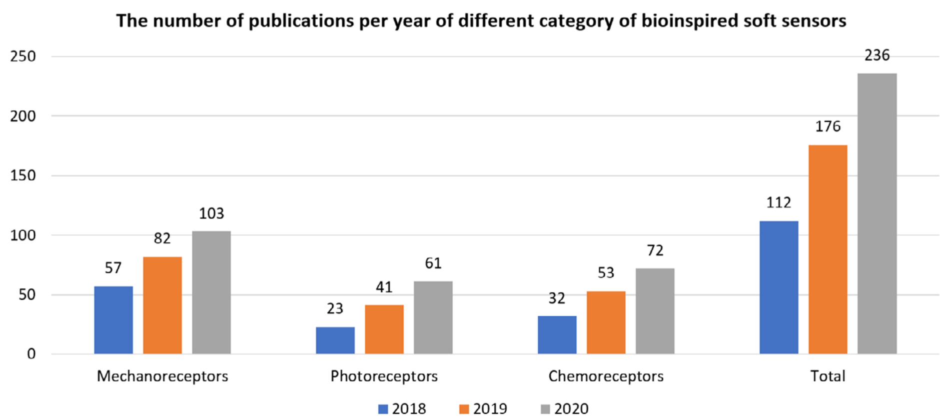

Figure 10. Recent trends in various category of soft sensors.

smart materials like dielectric elastomers, ionic polymer metal composites, SMAs, self-healing materials, biodegradable materials has to be made.[13,30,53,117] Materials sustainability through recycling and biodegradability should be emphasized.[157–159]

6.4. Sensors and Sensing

Integrating sensing devices seamlessly into deformable soft bodies.Decoupling multiple mechanical signals like pressure and strain.[121] Miniaturization of sensors while preserving performance. Some of the key possible solutions can be microfluidic sensors, flexible and stretchable electronics, and skin-inspired composites. A paper-based electrical respiration sensor has been developed as wearable. Besides, a flexible pressure sensor using electrospun nanofibers has been fabricated for a soft sensing suit.[127–131]

6.5. System Integration

Combining sensing, actuation, mechanics, and control elements in a unified system. Interfacing rigid components like electronics with soft materials.Coping with body deformations affecting functionalities.[1] Significant progress still required in creating untethered continuum arms that can generate desired force profiles for advanced control schemes.[147,160] Onboard computation for control still faces barriers from system weight and power constraints.Smoothly integrating sensors, actuators, computation, and energy components into a unified system is challenging but critical.[148] Onboard computation for control still faces barriers from system weight and power constraints. Better characterization of interface mechanics between hard and soft components, compliant hybrid electronics, wireless and energy harvesting solutions to untether soft systems can be implemented to eliminate the existing limitations.[137,144,148] Researchers has developed an anthropomorphic robotic torso ECCE integrating bio-inspired muscles, compliance and sensing.[148]

6.6. Computational Complexity

Efficient control implementation hinges on reducing the computational cost of models and simulations, particularly for computationally intensive models like Cosserat rods.[161] This necessitates the development of numerical methods that enable real-time control.[162] Promising solutions lie in model order reduction methods, graph neural networks, and machine learning-based approaches.[81,82,147,153]

6.7. Behavioral Complexity

While achieving the behavioral diversity and dexterity of humans and animals remains elusive,[163,164] leveraging imitation learning from human/teacher demonstrations holds promise for simplifying the acquisition of real-world skills.[163,164] However, differences in embodiment between robots and biological systems pose significant challenges. Promising long-term solutions lie in mimicking bio-mechanics and control principles from neuroscience and biology[13] alongside Sim2Real approaches powered by differentiable simulators.[71]

7. Future Prospects

Bioinspired soft robotics combines biology with engineering to mimic the adaptability, robustness, and flexibility of biological creatures. This field has huge potential to revolutionize various industries, such as healthcare, disaster relief, underwater exploration, space exploration, human–machine interaction, manufacturing, and many more, as shown in **Figure 11**. Bioinspired soft robotics is not a new concept; there have been some research works in recent years, yet there is room for more improvement in soft robotics technologies. The current research in this field aims to dethrone conventional rigid-body robots by developing new designs, modeling, materials, and controlling technologies.[20] The main idea behind soft robotics is to be able to replicate the characteristics of biological organisms such as muscles, tendons, sensory systems, and the nervous system. Because of this, the compliant, flexible, infinite degrees of freedom, and adaptive nature make controlling soft robots very challenging. The new model-free reinforcement learning for complex tasks without any mathematical model of the system is the future of soft robotics. The introduction of artificial intelligence and machine learning to learn from experience and predict future behavior will create opportunities in the application of soft robotics in complex tasks and uncertain environments.[38] The characteristics of soft materials are different from those used in rigid-body robots. Therefore, it can be a great addition to be able to estimate the performance and lifetime of soft actuators by applying prognostic methods.[36,165,166]

Soft materials are one of the main components of bioinspired soft robotics. Hence, the search for new advanced materials is very important in overcoming existing challenges. Recent research is exploring new soft materials with variable controlled stiffness, suitable for unpredictable environments, taking advantage of their morphology in actuation, sensing, and control to solve the current challenges in bioinspired soft robotics.[20] In the future, moving toward more data-driven approach, using data processing algorithms and computational modules with intelligent soft materials.[34] Another direction is using organic living tissues for bioinspired soft robotics. These living tissues embedded in soft robotics might be able to help replicate the actual muscle actuation and sensory features. This inspiration from biological creatures can lead to a better control and interaction with the real-world environment.[20]

A direction that will take bioinspired soft robotics to the forefront is miniaturizing actuators, power supply and sensory circuits. Soft robots free of any kind of rigid components are the future goal.[44] Integration of the flexible power sources, flexible driving components and controllers should be explored. This will be a step toward rigid component-less soft robotics.[32,167]

Negative impact on environment due to technological advancement cannot be denied. Sustainable energy sources, biodegradable materials, recycling are the solutions to this. Nature has the best examples for sustainable and biodegradable resources. Bioinspired soft robotics takes those inspiration to integrate with robotics technology for a better future. Bioinspired soft

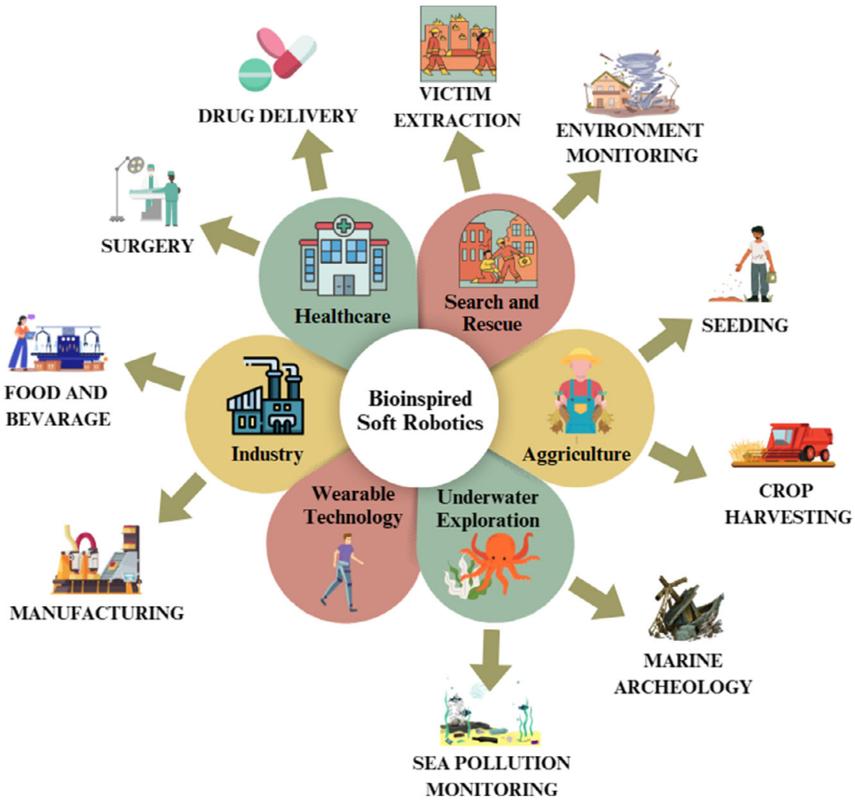

Figure 11. Applications areas of bioinspired soft robotics.

robotics is now at a stage where we can think of implementing more sustainable and greener technology.[35] In robotics, a major problem is what happens to the product after end of its life cycle. Current conventional robots are already moving toward a more sustainable approach and integrating a recycle loop.[168] Biodegradable and biocompatible materials can be used in bio-inspired soft robotics. Different natural and synthetic biodegradable polymers such as chitosan, gelatin, cellulose, polylatic acid, polyethylene glycol, polyarcylic acid, etc. can be used in the development of soft robotics.[125,169,170] Research of new materials or modification of existing materials for better durability, long life cycle, recycling and waste reduction can help in mitigating greenhouse emission and environment pollution. Design, fabrication, and manufacturing of soft actuators, soft sensors, electronics, and other components of bioinspired soft robots should use biodegradable, renewable, low cost.[35,171] Self-healing polymers can also solve the sustainability issues in soft robotics as their self recovery property means less wastage.[30,172] Application of renewable energy sources like the wind power, solar power, vibration, etc. is an eco-friendly approach for bio-inspired soft robotics. A suitable example for this is sunlight driven soft robot.[159] Another important technology, microbial fuel cells make use of microbially catalyzed anodic and cathodic electrochemical reactions to produce energy without any external power source. Research on this technology may unlock new potential for bioinspired soft robotics.[35]

New technologies will take bioinspired soft robotics to new heights in the application fields. The application of bioinspired soft robotics in underwater exploration is growing with recent innovations. Development of acoustically controlled soft robot fish,[78] legged robot named SILVER-2[158] has broadened the scope of marine research, ocean exploration and interaction with underwater animals. The introduction of soft grippers for automatic crop harvesting in agriculture can solve problems like hygiene, damaging crops, adapting to unstructured real-world environment.[17,18] Bioinspired soft robotics can become the new standard in healthcare by introducing likes of micro-motors.[15,173,174]

Soft robotics has room for a lot of growth in the commercial market. However, unique functionalities alone cannot make bio-inspired soft robotics successful commercially. There has been great advancement in the field of bioinspired soft robotics. Going forward, the aim for manufacturing soft robotics should be inexpensive and mass production. This can help bioinspired soft robotics gain success commercially.[157]

8. Discussion

This review has highlighted significant advances across key enabling areas that are driving progress in bioinspired soft robotics. Innovations in soft materials, fabrication approaches, actuation mechanisms, sensing and control strategies are helping bridge the gap between traditional rigid robots and highly flexible natural organisms. However, there remain considerable gaps to be addressed before soft robots can match the versatility and robustness exhibited by living creatures. Many research challenges persist in effectively translating bioinspired design concepts into fully realized functioning soft robotic systems.

A primary bottleneck is the availability of suitable soft multifunctional materials. Replicating the integrated properties of biological muscle, skin and sensory organs with artificial substitutes continues to be an open materials science challenge. Balancing critical mechanics like strength, conductivity, bio-compatibility, and degradability demands substantial interdisciplinary materials research. The processability and scalable manufacturing of these materials also pose difficulties. Additionally, soft actuation mechanisms have yet to achieve the efficiency, speed and power density observed in natural muscle. Alternatives to pneumatic and hydraulic approaches need to be explored to progress toward fully soft robotic architectures without rigid components. Considerable work remains in improving existing electroactive and variable-length polymer actuators.

Effective closed-loop control of infinite degree of freedom soft continuum structures is non-trivial, necessitating sensing and models that account for material nonlinearities. Soft proprioception and exteroception together enable natural movement, but integrating flexible sensors into bodies without compromising mechanics or decoupling strains remains an ongoing pursuit. Along with advances in materials and components, progress toward autonomous functionality relies on innovations in modeling and controls tailored to soft bodies. Bridging these gaps calls for perspectives and collaborations spanning material science, mechanics, mechatronics, bio-mechanics, and biological inspiration. There is a need to coalesce principles from these areas into integrated soft robotic platforms. Exciting near future possibilities include hybrid systems combining soft and rigid elements, machine learning-based modeling and control, and drawing concepts from synthetic biology to integrate biological components for sensing, actuation, control and energy harvesting.

While challenges exist, the vibrant progress across the many constituent disciplines of bioinspired soft robotics paints an optimistic outlook for the coming years. With innovations in multifunctional materials, manufacturing techniques and bioinspired design, soft robots hold the potential to match and even surpass natural organisms in many aspects of movement, resilience, adaptation and autonomy. By effectively addressing the identified gaps in an interdisciplinary fashion, it is destined for greater advancement.

9. Conclusion

The nature of soft technologies and materials makes them more adaptive, robust and safer for interaction. Discovery of new actuation and control technology, algorithms, materials, modeling, and design is playing a pivotal role in advancement of bioinspired soft robotics. Unparalleled features like infinite degree of freedom, deform-ability, flexibility, adaptiveness, self-healing of different biological creatures like fish, jellyfish, copepod, inchworm, earthworm, snakes have helped in developing new technologies for soft robotics. The next generation of robotics is moving toward bioinspired soft robotics because of its variety of application where rigid-body robots fail. For example biomedical, surgery, drug delivery, therapy to people with autism spectrum disorder, agriculture for crop harvesting, underwater exploration, interactive wearable, military, search and rescue and many more.

This review article focuses on the recent advancement of actuation system, control methods, sensors, materials and the challenges related to them. The progress of soft technologies is pushing the boundaries of bioinspired soft robotics. New research and development of new technologies is adding to the vast sea of bioinspired soft robotics, yet there are still many major challenges that stands in the path of bioinspired soft robotics reaching its full potential.

The flexible and continuum nature of soft robots makes the modeling and controlling a difficult task for engineers. Because of this model-free control strategies such as reinforcement learning, Q-learning, adaptive control is becoming popular in soft robotics. Integration of sensor, power system or control circuits can be challenge which is why search of new materials is important to move toward soft robot without any rigid components. Bioinspired soft robotics can make use of the renewable energy sources such as solar, wind, vibration, microbial fuel cells etc. for driving the system. The integration of renewable energy sources with biodegradable materials will be a step toward greener approach.

Bioinspired soft robotics was made by keeping safer human interaction, sustainability, adaptability and efficiency in mind. In future bioinspired soft robotics can move toward inclusion of only biodegradable and soft components. Addition of embedded sensory and power source circuit will be a leap in the right direction for bioinspired soft robotics. Another focus of bioinspired soft robotics should be the commercial market.

Our article represents the existing sensor, material, actuation, control technologies and their advancement. Also, we discuss the current challenges and possible solution in the field of bioinspired soft robotics. Bioinspired soft robotics is still a new concept and it has the potential to overtake rigid-body robots.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Abhirup Sarker: Conceptualization (lead); Writing—original draft (lead); Writing—review & editing (lead). **Tamzid Ul Islam**: Conceptualization (lead); Writing—original draft (lead). **Md. Robiul Islam**: Supervision (lead); Writing—review & editing (supporting).

Keywords

bioinspired, control methods, materials selection, reinforcement learning, soft actuators, soft robotics, soft sensors

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