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Perspective

Leveraging biomimetic materials for bioelectronics

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PROGRESS AND POTENTIAL Biomimetic materials, inspired by nature's intricate designs and functions, are revolutionizing bioelectronics and driving transformative advancements in medical technology. By emulating the structures, properties, and behaviors of natural systems, these materials enable the development of devices that integrate seamlessly with living tissues, enhancing signal acquisition, transduction, and analysis. This seamless integration is pivotal for creating advanced medical implants, wearable biosensors, and neural interfaces, offering substantial societal benefits through improved diagnostic and therapeutic solutions.

SUMMARY

The exploration of biomimetic materials for bioelectronics is driving transformative advancements in medical technology and beyond. Drawing inspiration from nature's intricate designs, these materials hold immense potential for creating bioelectronics that integrate seamlessly with living tissues. This work highlights three key biomimetic strategies in the current bioelectronics community: structural design, material properties, and natural processes. We demonstrate how these approaches significantly enhance the bioelectronic performance in the aspects of bio-signal acquisition, transduction, and analysis, addressing critical challenges in current biomedical technologies. By incorporating these principles, biomimetic materials and technologies are poised to revolutionize the conventional medical model, fostering the development of more intelligent, efficient, and biocompatible bioelectronic devices.

INTRODUCTION

Since ancient times, humanity has harbored a deep sense of reverence and curiosity for nature. From early observations to modern research, our understanding of the material world has continually progressed.[1–3] In recent decades, advancements in biology have revealed the molecular foundations of life, enabling us to explore cellular and subcellular processes in unprecedented detail. The rapid progression of science and technology has not only enhanced our understanding of the complexity of life but also enabled us to apply the principles of natural biological design to develop innovative systems.[4,5]

Over millions of years of evolution, natural biological structures have achieved sophisticated efficiency and balance. These structures exhibited unique properties, including multifunctionality, strength, toughness, and biocompatibility, which enable exceptional performance in complex environments.[6] Additionally, organisms possess complex behavioral characteristics, allowing them to dynamically respond to environmental changes, self-heal, and regenerate.[7] These traits not only demonstrate biological adaptability but also offer a wealth of inspiration and practical guidance for producing innovative designs.

Biomimetic materials are those engineered to mimic the structure and function of biological systems, while bioelectronics refers to the study and application of electronic systems and devices in biological environments. The study of biomimetic materials, particularly their application in bioelectronics, exemplifies the fusion of natural wisdom with modern technology.[8–13] As our understanding of these biological processes deepens, we begin to incorporate biomimetic structures into bioelectronic design paradigms. This approach bridges the gap between electronic devices and the biological world, enhancing the functionality of bioelectronics and their adaptability to biological tissues.[14–18]

In this invited perspective, we explore the latest advancements in biomimetic materials for bioelectronics, focusing on three key pathways: structural biomimetic materials, property biomimetic materials, and behavior biomimetic materials (Figure 1). For structural biomimetic materials, we examine how biologically inspired structures can be incorporated into bioelectronic device design to optimize performance and facilitate seamless integration with biological systems, ultimately enhancing diagnostic and therapeutic outcomes. For property biomimetic materials, we focus on how replicating mechanical, biogenic, and neuromorphic properties from natural substances can enhance electronic biocompatibility and signal transmission efficiency. Finally, we explore the behavior of biomimetic materials inspired by the dynamic characteristics of living organisms,

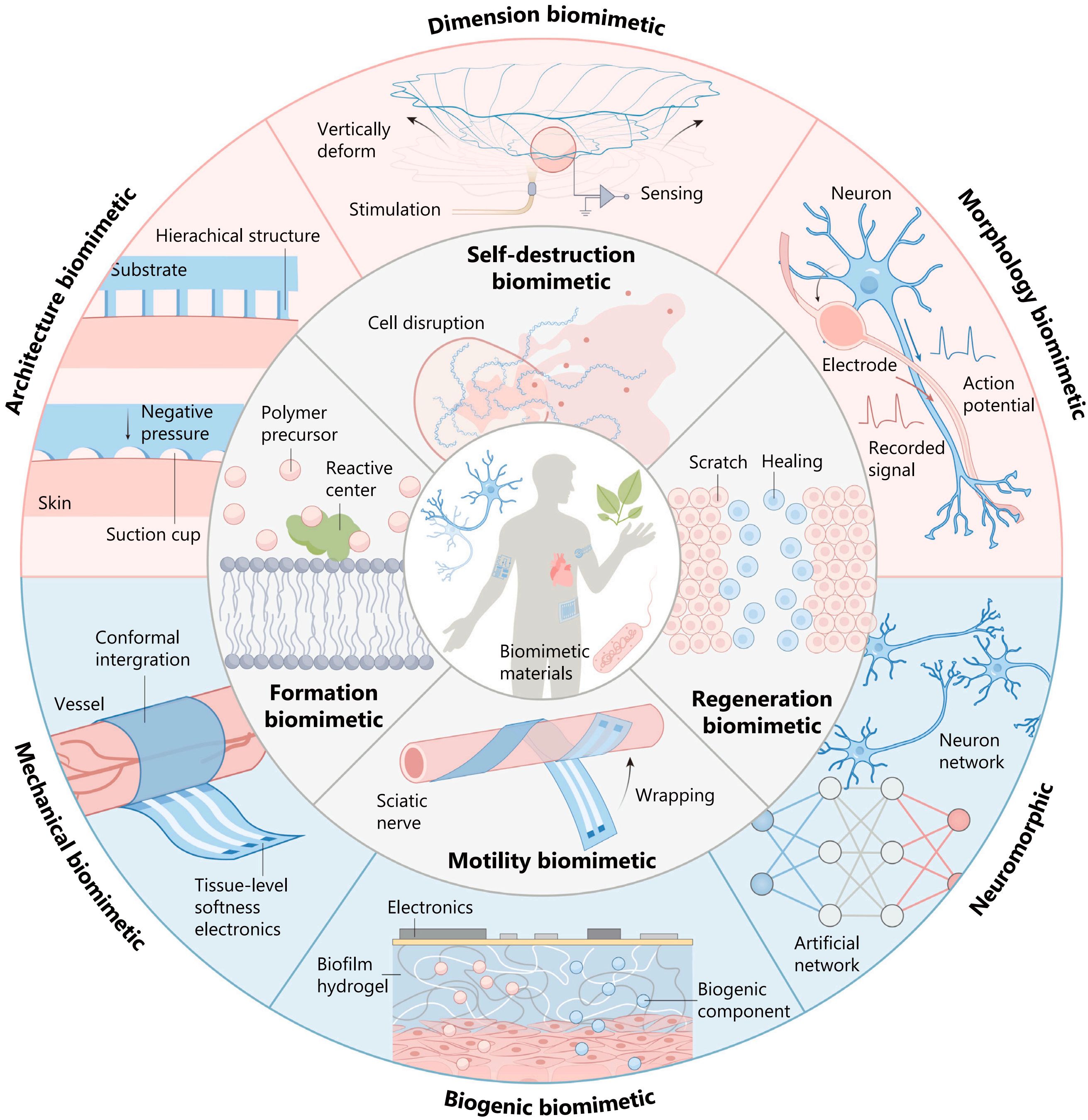

Figure 1. An overview of biomimetic strategies for bioelectronics

A detailed schematic of biomimetic material strategies in bioelectronics, emphasizing perspectives on structural, property-based, and behavioral biomimetics. Structural biomimetics involve adaptations in dimensions, architecture, and shapes inspired by natural designs, replicating intricate forms found in nature to improve integration and performance. Property-based biomimetics focus on improving material performance and functionality by emulating mechanical, biogenic, and neuromorphic properties. Behavioral biomimetics replicate biological processes such as self-destruction, regeneration, motility, and functional dynamics, illustrating how bioelectronic devices can mimic the adaptive and responsive behaviors of living organisms.

leading to the development of smart materials capable of self-assembly, actuation, healing, and degradation. These advancements could provide new avenues for integrating sophisticated functionalities into bioelectronic devices.

STRUCTURAL BIOMIMETIC MATERIALS

Observing biological structures in nature provides intuitive insights into material systems. By designing and fabricating

Table 1. Summary of biomimetic methods and materials for bioelectronics

Biomimetic methods	Bioelectronic device	Functionalities	Application scenarios	Materials used	Reference
Dimension biomimetics	3D nanowire transistors	monitor cellular electrical and mechanical responses	cell studies	Si, PDMS, SU-8	Gao et al.[19]
Dimension biomimetics	voids-guided crack electronics	high sensitivity, durability	mechanical sensing	Ag NWs, PDMS, PEIE, Pt	Miao et al.[20]
Dimension biomimetics	micro-lattice 3D mesosurfaces	construction of 3D electronics with desired curvature	temperature sensing, optogenetics, cell behaviors	Si, PI, Au, Ti	Cheng et al.[22]
Dimension biomimetics	3D kirigami electronics	record neural organoids and assembloids in suspension	electrophysiological recording, optogenetics	Au, Ti, Pt, SU-8	Yang et al.[24]
Morphology biomimetics	neuron-like flexible electronic devices	long-term unit recording of brain neurons	electrophysiological recording, regenerative medicine	Pt, Cr, Au, SU-8	Yang et al.[29]
Architecture biomimetics	adhesive electronics with octopus-like suckers	attachable electronic devices with conductivity and stretchability	mechanical sensing, electrophysiological recording	CB, P3HT, PDMS	Kim et al.[32]
Architecture biomimetics	complexly architected electronic skin	modulus/curvature measurements of an object	tactile system, mechanical sensing	Au, Cr, PI, PDMS, Ecoflex	Liu et al.[38]
Mechanical biomimetics	hydrogel-based microelectronics	integrate with curved tissue surfaces while reducing immune responses and mechanical mismatches	electrical neuromodulation	PEDOT:PSS, ionic liquid, PTPE	Liu et al.[40]
Mechanical biomimetics	dynamic noise-free bioelectronics	selectively record high-frequency bio-signal through hydrogel dynamic bonds	electrophysiological recording, mechanical sensing	chitosan, gelatin	Park et al.[43]
Biogenic biomimetics	bacteria-enabled living biointerface	treat skin inflammation while monitoring the recovery process	inflammatory healing, electrophysiological sensing	*Staphylococcus epidermidis*, protein, polysaccharide	Shi et al.[45]
Neuromorphic biomimetics	artificial afferent nerve system	collect and process pressure information, converting it into action potentials, and integrating these signals via a synaptic transistor to distinguish complex tactile inputs	neurorobotics, neuroprosthetics	CMOS, CNT, Au	Kim et al.[46]
Neuromorphic biomimetics	modular neuromorphic biosensor chip	on-chip learning and retraining, classifying health conditions from biomarkers using ion-selective sensors and error signal feedback to adjust conductance within its neuromorphic circuit	point-of-care medical diagnostics	OECT, Au, Cr, PEDOT:PSS	van Doremaele et al.[47]

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Table 1. *Continued*

Biomimetic methods	Bioelectronic device	Functionalities	Application scenarios	Materials used	Reference
Neuromorphic biomimetics	organic artificial spiking neuron	spiking behavior responsive to changes in ionic and biomolecular concentrations, mimicking biological neuron functionalities to interface with biological membranes for real-time signal processing	neurorobotic systems, biointerfacing technologies, and neuromorphic computing devices	PEDOT, polymeric thieno [3,2-b] thiophene derivative	Sarkar et al.[48]
Formation biomimetics	genetically targeted conductive polymer systems	modulates neuronal activity of selective targeted cell	neural interfaces, therapeutic modulation	PANI, PEDOT	Liu et al.[53]
Motility biomimetics	soft robotic peripheral nerve cuffs	provides high-resolution neural recordings via adaptive grasping and wrapping around nerves	nerve activity monitoring, prosthetics control	PPy, PEDOT, Au, Parylene C	Dong et al.[56]
Regeneration biomimetics	self-healing multilayer thin-film pressure sensors and actuators	autonomous healing and realignment; pressure sensing	wearable electronics, underwater robotics	PDMS, PPG	Cooper et al.[60]
Decomposition biomimetics	biodegradable electronic bandage	electrostimulation for gene transfection and healing factor secretion	wound healing, tissue repairs	PCL, Mg/Mo GelMA, chitosan, DNA plasmids	Wu et al.[64]

PDMS, polydimethylsiloxane; NWs, nanowires; PEIE, polyethylenimine; PI, polyimide; CB, carbon mesoporous; P3HT, poly(3-hexylthyophene); PEDOT:PSS, poly(3,4-ethylenedioxythiophene):-poly(styrenesulfonate); PTPE, perfluoropolyether; PANI, polyaniline; PPG, polypropylene glycol; PPy, polypyrrole; PCL, polycaprolactone; GelMA, gelatin methacryloyl; CMOS, pseudo-complementary metal-oxide semiconductor; OECT, organic electrochemical transistor.

structural biomimetic materials that emulate the dimensions, shapes, and architectures of biological structures, we gain valuable insights and practical applications for bioelectronics. These biomimetic structures not only inspire innovative designs but also facilitate seamless integration with biological systems, enhancing both the stability and functionality of the devices.

Dimension biomimetics

Biological structures, ranging from cellular three-dimensional (3D) constructs to entire organisms, display intricate multidimensional characteristics. These organisms possess remarkable abilities to perceive and respond to their surrounding environments with exceptional sensitivity and promptness. Dimension biomimetics, inspired by the multidimensional structures in biological systems, from cellular structures to entire organisms, are essential in replicating those biological features. This principle focuses on incorporating unique macroscopic spatial properties and overall geometric dimensions found in nature to optimize the functionalities of bioelectronics, achieving crucial characteristics like high stretchability, sensitive detection, and multi-channel sensing.

For instance, the replication of natural organisms has led to the development of 3D nanowire transistors that mimic the winding microfibers within cells (Table 1).[19] Additionally, sensors with micro/nano void structures emulate the bending microcracks in insect wings,[20,21] and micro-lattice electronic systems are inspired by the 3D porous microstructures of organisms, providing superior mechanical and electrical performance.[22]

Moreover, developing highly compatible 3D biomimetic materials allows for excellent adaptation to the curved morphology of tissues, achieving seamless mechanical integration at the bioelectronic-tissue interface. Recently, the art of kirigami—paper cutting and 3D unfolding—has been utilized to design bioelectronics that conform to complex shapes, such as the brachial artery, facilitating pulse wave monitoring through advanced wearable sensors.[23] Recently, the honeycomb-inspired kirigami design, which mimics the microstructure network of 3D honeycombs, has demonstrated enhanced flexibility and compatibility with cortical organoids. Furthermore, honeycomb-inspired Kirigami-based electronics (KiriE) have expanded their applications to include recording electrical activities in neural organoids.[24] By leveraging the honeycomb-like kirigami microstructures, these devices can spontaneously transform from ultra-thin 2D patterns into 3D spiral microelectrode arrays. This design enables seamless integration and long-term recording of neural activities from human cortical organoids (hCOs) in suspension while preserving their 3D self-organization and differentiation (Figures 2A and 2B). KiriE also demonstrates compatibility with optogenetic and pharmacological operations, facilitating studies of corticostriatal circuitry in both assembled hCOs and human striatal organoids (hStrOs) (Figure 2C).[25] By employing optogenetic stimulation of the cortex, simultaneous increasement in neural activity were observed in both hCO and hStrO neurons. This indicates that KiriE is capable of detecting connectivity and electrical properties during the development of functionally integrated organoids (Figure 2D). In addition, the 3D network structure formed between cells in biological tissues also inspired the next generation of soft bioelectronics.

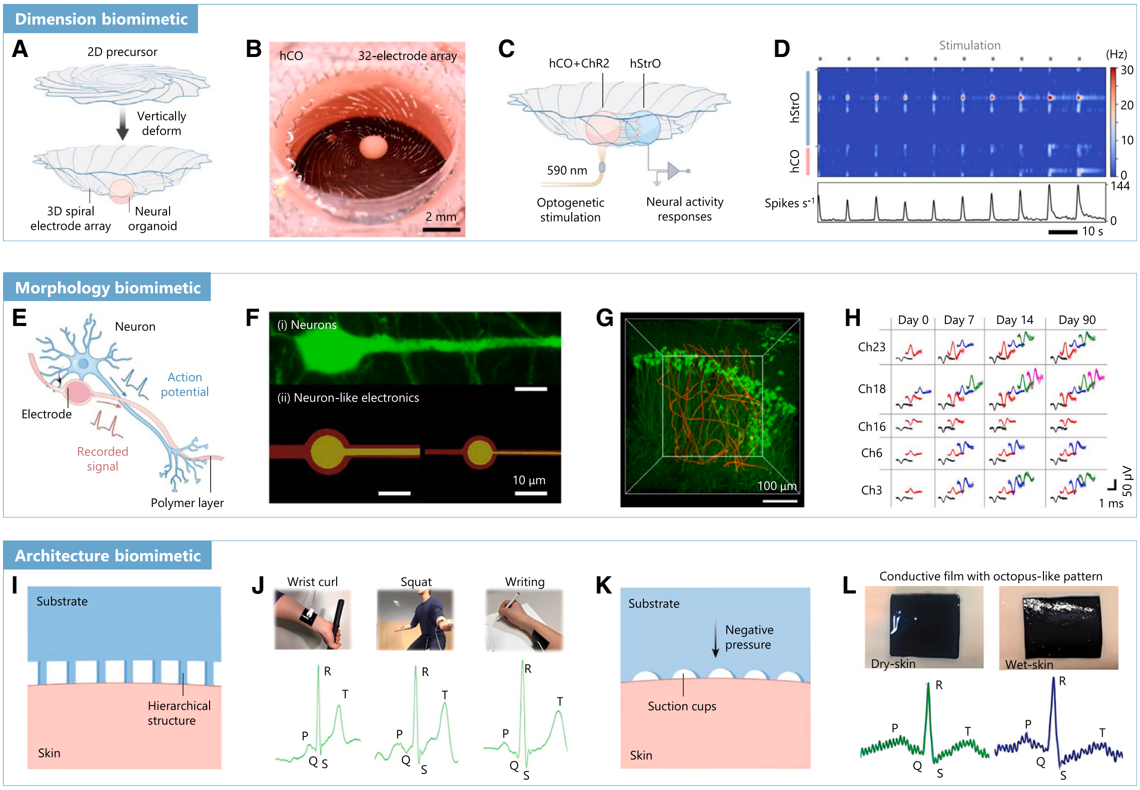

Figure 2. Structural biomimetic materials for bioelectronics

(A) Design concept of the vertically deformable KiriE, transitioning from a 2D precursor and its integration with neural organoids.
(B) Image of a spherical hCO integrated with KiriE during differentiation.
(C) Design of assembloid circuit connectivity, evaluated via optogenetic stimulation and KiriE recording.
(D) Heatmap showing assembloid neural activity at day 167 of differentiation, represented by firing rates.[24]
(E) Schematics of the neuron-morphology-inspired NeuE design at the subcellular level.
(F) Fluorescence microscopy images comparing (i) neuron morphology and (ii) NeuE.
(G) 3D interfaces between NeuE (red) and neurons (green) post implantation.
(H) Evolution of spike patterns from clustered single units over 3 months following injection.[26]
(I) Hierarchical architecture that enhances adhesion to skin surfaces via van der Waals forces.
(J) Hierarchically structured conductive dry adhesives designed for ECG sensing in dynamic environments.[27]
(K) Micro-sucker architecture provides strong adhesion to skin surfaces through negative pressure.
(L) Conductive film with an octopus-like pattern for stable ECG signal acquisition in wet conditions.[28]

Researchers have developed the macroporous nanowire nanoelectronic scaffolds (nanoESs) that mimic natural tissue scaffolds, supporting 3D cultures of neurons, cardiomyocytes, and smooth muscle cells. NanoESs also enable real-time monitoring of local electrical activity within 3D nanoES/cardiomyocyte constructs.[26]

Morphology biomimetics

Biological structures display a wide range of morphological diversity and distinct functionality. The morphology biomimetics emphasizes mimicking biological elementary geometries, such as curvatures and shapes, to enhance bioelectronic functional performance and biological interface interaction. The dendritic morphology of neurons, for example, illustrates how branching structures facilitate efficient signal transmission. Integrating these morphological characteristics into biomimetic material design can significantly enhance device performances, including recording sensitivity, conformability, and biocompatibility. For example, by replicating the dendritic morphology of neurons, neuron-like electronic devices (NeuEs) can be developed with enhanced signal processing capabilities (Figures 2E and 2F).[29] The neurite-sized diameter of NeuEs offers flexibility that closely matches that of neurons, enabling the formation of structurally and functionally stable interfaces with neuronal and glial networks post-implantation into the brain. This allows for long-term unit recordings (Figures 2G and 2H). Additionally, this biomimetic morphological feature promotes the migration of endogenous neural progenitor cells and the development of new neurons, accelerating tissue healing. Consequently, the NeuE holds significant potential as an electroactive platform in non-transplant regenerative medicine.

Complex curvature, as a fundamental biological geometry, such as curved skin surface topography and textures, plays a pivotal role in inspiring morphology biomimetics. These morphology biomimetic devices perform seamless bioelectronic-tissue integration and functional conformity. Soft electrode systems with fractal mesh geometries, for instance, are designed to conform closely to the intricate topography of the auricle, enabling prolonged high-fidelity electroencephalogram (EEG) recordings while minimizing mechanical stress and ensuring biocompatibility.[30] Similarly, van der Waals thin films draw upon nanoscale curvature principles to create ultra-conformal and stretchable interfaces with biological tissues. The sliding and rotation of staggered nanosheet structure allow the bioelectronic device to mimic dynamic surface textures with natural adaptability. This biomimetic approach not only minimizes stress and irritation at the bioelectronic interface but also contributes to the stable signal acquisition, even under continuous mechanical deformation.[27]

Architecture biomimetics

The intricate hierarchical and networked architectures found in the surface morphologies of organisms offer valuable inspiration for biomimetic designs.[28] Architecture biomimetics replicate complex multi-scale, hierarchical micro/nano-structures found in nature, emphasizing the interplay between different layers to achieve functional synergy. Designing these hierarchically layered and networked structures in biomimetic materials offers tremendous potential to provide the functionality of bioelectronic devices.[31] Many biomimetic designs have been inspired by naturally occurring hierarchical architectures, such as those found in geckos, which feature micro and nanopillars. This multi-scale and layered structures enables rapid attachment to various surfaces through van der Waals forces as a strong adhesive layer. By mimicking this biological architecture, researchers have developed hierarchically structured and conductive dry adhesives that demonstrated adhesion on rough skin surfaces. These adhesives also offer superior conductivity and flexibility, allowing for stable bio-signal recording in dynamic environments (Figures 2I and 2J).[32] Furthermore, naturally occurring architectures can inspire novel biomimetic strategies that enhance adhesive properties in wet environments. For example, the suction cup structures of octopuses can offer robust adhesion even in wet environments. Inspired by this, researchers have developed soft and stretchable electronic devices that maintain stable interfaces with human skin under both wet and dry conditions, ensuring a stable contact interface for electrocardiogram (ECG) monitoring (Figures 2K and 2L).[33] In addition to enhanced adhesive properties, the microscale junction architectures in natural organisms also provided precise on-demand release mechanisms.[34,35] To replicate these layered and hierarchical structures, researchers have utilized sodium carboxymethyl cellulose-based aerogels, employing laser patterning and chemo-mechanical force to facilitate the growth of carbon film patterns and their instantaneous stratification. This technique offers a sustainable manufacturing pathway for carbon-based biomimetic electronic devices.[36]

Additionally, imitating the architectures of organisms can endow mechanical sensors with high sensitivity and perceptual abilities akin to those found in biological systems. For instance, adopting the hierarchical micropatterns of beetle elytra, an interlocking nanofiber sensor can detect ultralow pressure, shear force, and torsional force.[37] Similarly, human skin's ability to perceive various mechanical stimuli is attributed to its layered distribution of mechanoreceptors, such as Merkel cells and Ruffini endings.[38] By mirroring this layered structure, 3D-architected artificial skin can decouple the measurements of normal force, shear force, and tensile strain, enabling it to discern an object's modulus and curvature through tactile interaction. These architectural biomimetic strategies demonstrate the potential of multi-scale and hierarchical designs to drive the development of highly efficient and reliable bioelectronic devices, opening new avenues for future innovations. General trends in structural biomimetic materials highlight the integration of hierarchical architectures inspired by nature to improve adaptability and device-tissue interfaces. Challenges remain in fabricating complex 3D biomimetic structures with high resolution and scalability.[39] Future research efforts include exploring dynamic structural materials that can adapt to changing biological environments and creating self-evolving architectures inspired by cellular growth and regeneration processes.

PROPERTY BIOMIMETIC MATERIALS

Over millions of years, nature has refined an array of unique adaptations that enable organisms to thrive in diverse environments. By harnessing insights from these biological properties, we can design advanced bioelectronic materials that enhance functionality and drive progress within the field of medical technology and beyond.

Mechanical biomimetics

Mechanical biomimetic materials, inspired by the intricate mechanical characteristics of living organisms such as softness, adhesiveness, and viscoelasticity, establish exceptional interface performance between bioelectronic devices and dynamic biological tissues. This enhances the conformability, biocompatibility, and long-term stability of devices when integrated with complex biological surfaces.

Biological structures frequently exhibit soft mechanical characteristics, allowing them to adapt to dynamic environments. Bioelectronic devices can be specifically designed to emulate these soft mechanical properties, conforming to curved tissue surfaces while enhancing biocompatibility. For instance, hydrogel-based bioelectronic devices replicate tissue softness, achieving seamless integration and long-term stability with curved tissue surfaces while reducing immune responses and mechanical mismatches (Figures 3A and 3B).[40] Furthermore, adhesion is vital for the survival of many organisms, exemplified by the footpads of geckos and the adhesive proteins of mussels. By mimicking these adhesion mechanisms, polymer-based bioelectronics with diverse functional chemical groups can form strong chemical bonds, enabling tight adhesion to wet biological tissues such as the heart and kidney. This enhances the reliability and quality of data collection, ensuring consistent device performance.[41] Viscoelasticity that combines elastic and viscous properties, enables materials to deform and recover over time when subjected to stress.[42] By mimicking the adhesive bonds found in spider footpads, researchers developed the damping materials that efficiently isolate low-frequency mechanical noise.

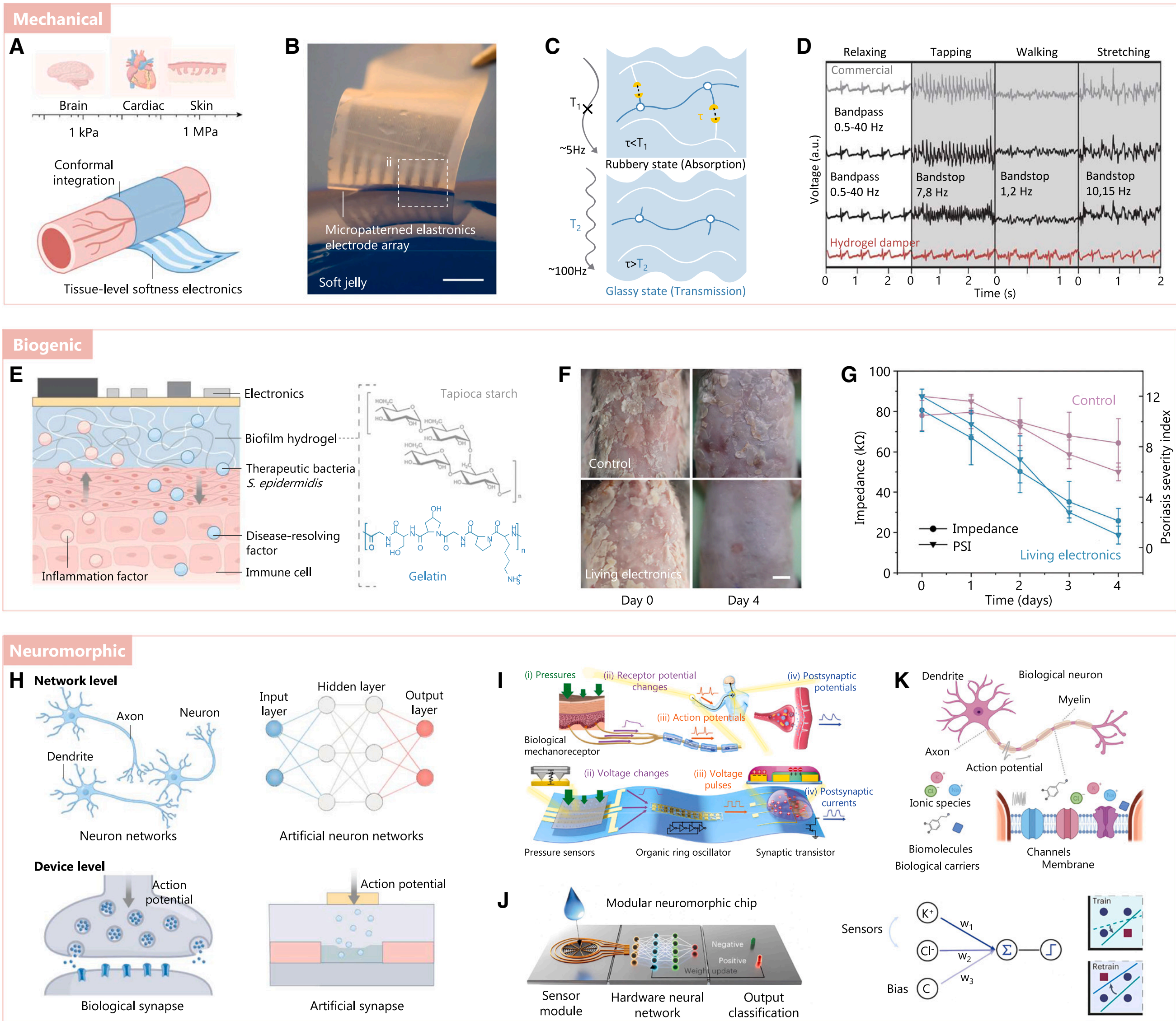

Figure 3. Property biomimetic materials for bioelectronics

(A) Comparison of biological tissue with biomimetic electronic materials designed to match tissue-level softness.
(B) A freestanding micropatterned hydrogel electrode array applied to soft jelly.[36]
(C) Working mechanism of a hydrogel damper, demonstrating its ability to absorb and transmit mechanical signals.
(D) Comparison of ECG signals between a commercial electrode, bandpass filter, and a hydrogel damper in a noisy environment.[39]
(E) Bacteria-based hydrogel living biointerface used for psoriasis treatment and inflammation monitoring.
(F) Photographs illustrating psoriasis treatment with living electronics at day 0 and day 4.
(G) Monitoring of skin impedance via living electronics throughout psoriasis recovery.[41]
(H) Schematics of neuromorphic biomimetic materials for bioelectronics, emphasizing network- and device-level integration.
(I) An artificial afferent nerve constructed from flexible organic electronics, designed to mimic the human sensory nerve system.[42]
(J) A neuromorphic chip featuring sensor modules and neural networks for dynamic information processing.[43]
(K) Illustration of a biological neuron transmitting action potentials through ion exchanges across its membrane, efficiently traveling along the axon via specialized ion channels in an aqueous electrochemical environment.[44]

This approach, rooted in mechanical biomimetics, leverages the viscoelastic cuticular pad in spiders, which transitions between a rubbery and glassy state around 30 Hz. This selective damping mechanism, driven by hydrogen bonds between chitin and protein chains, allows spiders to filter low-frequency vibrations while transmitting higher frequencies. Inspired by this principle, gelatin-chitosan hydrogels mimic these transitions, absorbing low-frequency vibrations via bond dissociation and elastically transmitting high-frequency signals. This innovation allows bioelectronics to capture electrical and high-frequency mechanical signals reliably even during motions (Figures 3C and 3D).[14,43] Such biomimetic approaches allow for the fine-tuning of mechanical properties, enhancing the integration, stability, and performance of bioelectronics in complex and dynamic environments.

Biogenic biomimetics

In nature, biogenic materials that incorporate living cells or bacteria, excel in immune regulation and regeneration. Natural biofilms facilitate nutrient exchange with surrounding environment, enhancing bacterial survival and community regulation.[44] Inspired by these natural systems, biogenic biomimetics mirror the chemical composition and functional characteristics of biofilms, bacteria, or living cells, offering promising solutions for bioelectronic devices in immune modulation, tissue repair, and functional integration. For instance, researchers developed a living hydrogel that replicated the main chemical components of biofilms, supporting the growth and functional expression of *Staphylococcus aureus*. This hydrogel functions as a living biointerface, bridging bioelectronics and tissue through its biogenic capabilities (Figure 3E).[45] By modulating the immune microenvironment and promoting epithelial repair, this living biointerface can actively treat inflammatory conditions like psoriasis (Figure 3F). Additionally, the active biointegrated living electronics integrate skin impedance monitoring to measure the progression of psoriasis skin lesion recovery. Changes in impedance correlate with improvements in the psoriasis severity index, reflecting reductions in inflammation, erythema, and epithelial regeneration (Figure 3G). Furthermore, the living electronics also include temperature and humidity sensors to provide complementary information of the skin's microenvironment. Together, these features enable precise tracking of therapeutic outcomes while simultaneously administering bacteria to modulate immune responses and treat skin inflammation. This approach provides a novel strategy for non-invasive and effective method of managing and healing inflammatory conditions.

Neuromorphic biomimetics

Neuromorphic biomimetics, by emulating the signal transmission and sensory mechanisms of biological neural systems, can enhance the interaction between electronics and biological environments at both the network and device levels (Figure 3H). This biomimetic method advances the capabilities of bioelectronic devices in signal processing, data classification, and environmental adaptation. A notable advancement in this area was made in 2018 with the development of an artificial afferent nerve based on flexible organic electronics designed to replicate the human sensory nerve system.[46] This device can process and convert pressure information into electrical signals, which are integrated and interpreted by a synaptic transistor (Figure 3I). Such technology has the potential to significantly enhance the sensory capabilities of robotic and prosthetic systems, allowing for more sophisticated interactions with various environments. More recently, researchers developed a neuromorphic biosensing platform capable of autonomous and complex classifications, such as detecting genetic disorders from biological samples.[47] This platform integrates ion-selective sensors, organic neuromorphic devices, and an output layer for real-time data classification, streamlining the integration of sensor data and processing in wearable and implantable devices (Figure 3J). Additionally, Sarkar et al. introduced an organic artificial neuron, designed to operate in liquid environments, making it ideal for direct interaction with biological systems.[48] This compact device can respond to variations in the concentrations of biological species, replicating neuronal behavior and enabling real-time interactions with cellular structures for medical diagnostics and treatment (Figure 3K). The neuron-like device demonstrated its ability of functioning synergistically with biological systems in real time, maintaining performance over prolonged periods (>105 spiking cycles), a significant improvement indicating potential for long-term applications in biohybrid interfaces. The device's firing frequency can be precisely modulated (6–40 Hz), with changes in capacitance affecting the firing rates, highlighting the precise control over its neuromorphic functions. These innovations underscore the significant potential of neuromorphic biomimetics in creating devices that are both biocompatible and seamlessly integrated with biological systems. They pave the way for electronic systems that are precisely tuned to individual physiological conditions, offering substantial opportunities for personalized medicine and advanced therapeutic interventions.

Enhanced by advanced organic materials and flexible electronics, neuromorphic biomimetics revolutionizes bioelectronics by seamlessly integrating biological sensory and neural functions with electronic systems. By enabling seamless integration and interaction with biological systems, neuromorphic biomimetics continues to propel the field forward, revolutionizing the interface between technology and biology.[15] Recent advances in this field revealed promising pathways for advanced prosthetics and neurorobotic applications through the development of artificial nerves. These artificial nerves can effectively process and respond to sensory information, enabling the autonomous performance of complex tasks such as disease detection and dynamic responses to environmental stimuli. Moreover, the ability of these neuromorphic systems to adapt to biological environments highlights their potential for creating effective biohybrid interfaces. Neuromorphic systems mimic the dynamic ion-exchange mechanisms of neuronal membranes, enabling seamless electrical signal transmission across the bioelectronic interface. This adaptability can minimize immune responses and mechanical mismatches, creating biohybrid interfaces that maintain stable functionality *in vivo*. For example, these systems allow for the continuous monitoring of neural activity with high fidelity, ensuring precise signal integration over extended periods. Biohybrid interfaces enable real-time integration of biological signals into computational systems, which is critical for medical diagnostics. For instance, neuromorphic biosensors can autonomously classify biomarkers, reducing diagnostic time from hours to minutes. In personalized medicine, these interfaces allow prosthetics to adjust to individual neural patterns, enhancing motor control. Additionally, their biocompatibility ensures reliable therapeutic interventions, such as localized neuromodulation for treating neurodegenerative disorders. These interfaces could have a profound impact on medical diagnostics, personalized medicine, and therapeutic strategies. The progress in this field suggests a promising future where electronic devices are not only biocompatible but also integrable with biological systems, offering responsive, adaptive, and precise treatments and interventions tailored specifically to individual physiological conditions.

The development of property biomimetic materials has been marked by focusing on emulating natural mechanical, biogenic, and neuromorphic characteristics to enhance device performances and biocompatibility. A significant trend is the use of hybrid organic-inorganic materials that combine flexibility with mechanical robustness.[49] Key challenges include balancing material softness with durability and ensuring stable performance under dynamic conditions. Emerging directions include the incorporation of nanoscale material properties to improve energy efficiency and the development of self-healing and self-regulating materials for long-term *in vivo* applications.

BEHAVIOR BIOMIMETIC MATERIALS

The intricate and dynamic behavioral characteristics of natural biological systems, including life-formation process, dynamic responses to environmental changes, adaptive functionalities, and regeneration seen in living organisms, offer valuable insights for bioelectronic design (Figure 4A). By mimicking these traits, we can take an innovative approach to the design and application of bioelectronic devices.

Formation biomimetics

The process of life formation offers vital inspiration for materials science, where polymerization and assembly serve as fundamental paradigms. Formation biomimetics is a strategy that focuses on replicating the natural processes involved in the formation and organization of biological structures or substances. By simulating the self-assembly of biological molecules into intricate structures, researchers can develop a variety of chemical synthesis strategies for assembling bioelectronic devices.[50,53,54] Recently, this approach has been applied in gene engineering, where techniques can introduce targeted recognition molecules and chemical precursors into target cells. These molecules then undergo enzyme-triggered polymerization reactions unique to each cell type, enabling the precise chemical assembly of functional materials (Figure 4B).[53] Furthermore, these functional polymers can modify membrane properties and alter neural activity. In addition, researchers have leveraged endogenous metabolites to trigger enzymatic reactions within injectable gels, inducing the polymerization and self-assembly of organic molecules. This method has been successfully demonstrated in zebrafish and leech models, where induced polymerization and gelation occur (Figure 4C).[54] These resulting materials can serve as *in vivo* electrodes, facilitating neural stimulation and opening new avenues for the development of organic bioelectronic devices within the body.

Motility biomimetics

Organisms exhibit complex behavioral characteristics and unique motility, showcasing exceptional adaptability and efficiency across micro to macro scales.[14,55] Motility biomimetics is a biomimicry strategy to replicate the movement and dynamic behaviors of living organisms. This approach draws inspiration from the highly efficient and adaptable motility mechanisms observed in nature, ranging from the molecular scale (e.g., motor proteins like kinesin and myosin) to the macroscopic scale (e.g., the movement of animals or plants). Mimicking these motility traits allows us to deepen our understanding of biological moving mechanisms, fostering innovation in bioelectronic devices.[51] Research on electrochemically driven microelectrodes has demonstrated how electrochemical signals can precisely control the movement of microelectrodes (Figure 4D). This technology enables precise positioning and minimally invasive interfaces for peripheral nerves by actively grasping or wrapping around delicate nerves (Figure 4E).[56] Moreover, it enhances the accuracy of nerve interfaces while minimizing tissue damage compared to traditional electrode implantation methods, such as puncture or suturing. Furthermore, leveraging the disruption and disordered transformation of polymer microcrystalline structures in aqueous environments (Figure 4F), researchers have developed water-responsive supercontractile polymer films as bioelectronic substrates.[57] These films can dynamically conform to the curved morphology of biological tissues, enabling both *in vivo* neural stimulation and electrophysiological signal recording (Figure 4G). This adaptability ensures stable integration and effective signal capture on complex biological tissue surfaces (Figure 4H). After peripheral nerve implant surgery, the electromyography (EMG) signal amplitude, signal-to-noise ratio, and frequency-domain features such as mean and median frequencies reach their peak at the second week post surgery (Figure 4G). This reflects the optimal innervation of the muscle graft by the transected peripheral nerve.

Regeneration biomimetics

In addition to their exceptional motility, organisms possess remarkable regenerative abilities, allowing them to self-heal and repair damaged tissues at various levels—from individual cells to entire organs. By mimicking these regenerative traits, various materials, such as hydrogel and nanocomposite, can be specifically tailored to create more robust bioelectronic devices.[58] A crucial element in this process is the dynamic bonding interactions that endow polymers with self-healing property, such as hydrogen bonds or dynamic covalent bonds.[52,59] Additionally, for complex multilayer bioelectronics, employing structures with interlayer material composition gradients can be advantageous. These structures leverage differences in surface energy between polymers to drive directed chain diffusion, resulting in autonomous interlayer alignment.[60] Furthermore, dynamic bonds between different polymers can significantly enhance interfacial adhesion between layers (Figure 4J). This innovative material design can be applied to sensors, soft robotics, and self-healing circuits (Figure 4K). By incorporating these regenerative principles, bioelectronic devices can achieve advanced durability and functionality, ensuring reliable performance and extended longevity across diverse applications.

Decomposition biomimetics

Another crucial characteristic that can further optimize bioelectronic devices is biological decomposition—a fundamental process for ecosystem cycling and nutrient reutilization, which maintains a balance between consumption and regeneration.[61] By replicating these features, we can develop degradable

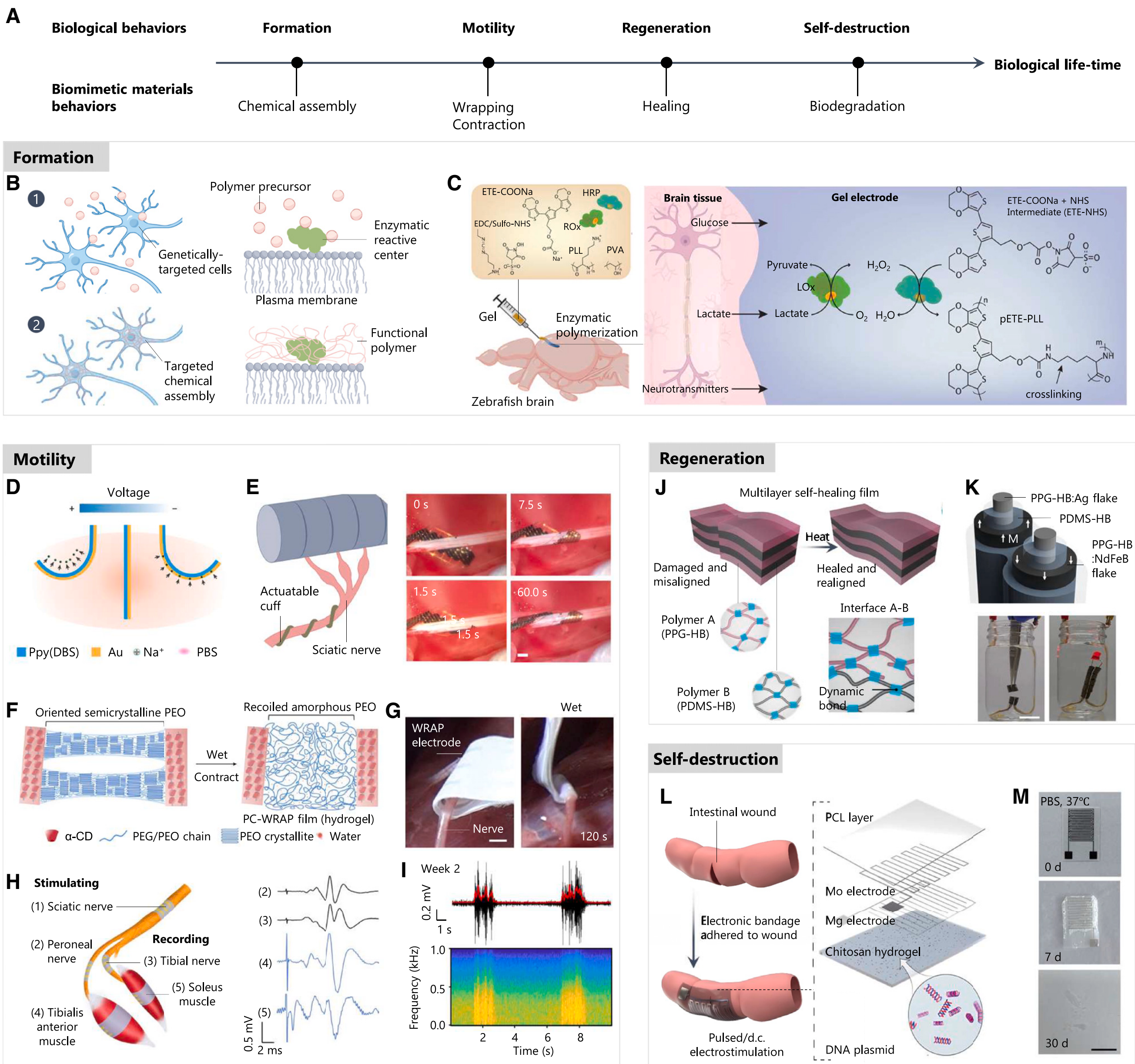

Figure 4. Behavioral biomimetic materials for bioelectronics

(A) Overview of biological behaviors throughout their lifespan and the corresponding behaviors of biomimetic materials.
(B) Introduction of genetically encoded enzymes and polymer precursors followed by chemical assembly on cells.[45]
(C) *In vivo* enzymatic polymerization of conducting polymer gels within the central nervous system.[46]
(D) Reversible bending motion of electrochemical actuators.
(E) Active wrapping of a flexible nerve cuff around the sciatic nerve without sutures.[49]
(F) Transformation of polymer microcrystalline structures in water environments.
(G) Photographs showing a wet-responsive electrode array conformally wrapped around a nerve within 120 s.
(H and I) Functions of a wet-responsive electrode array for neural stimulation and electrophysiological signal recording.[50]
(J) Surface-tension-mediated realignment and healing of fractured multilayer soft electronics.
(K) Demonstration of healing in an electronic fiber with a conductive and magnetic core-shell structure.[51]
(L and M) Performance of electrostimulation electronics in wound healing and their degradation over time.[52]

bioelectronic devices tailored to the needs of both medical and environmental applications.[62,63] Applying this concept, researchers have recently developed a dual electrostimulation soft degradable electronic bandage designed to accelerate healing at intestinal injury sites by promoting cell proliferation and tissue repair through electrical stimulation (Figure 4L).[64] This

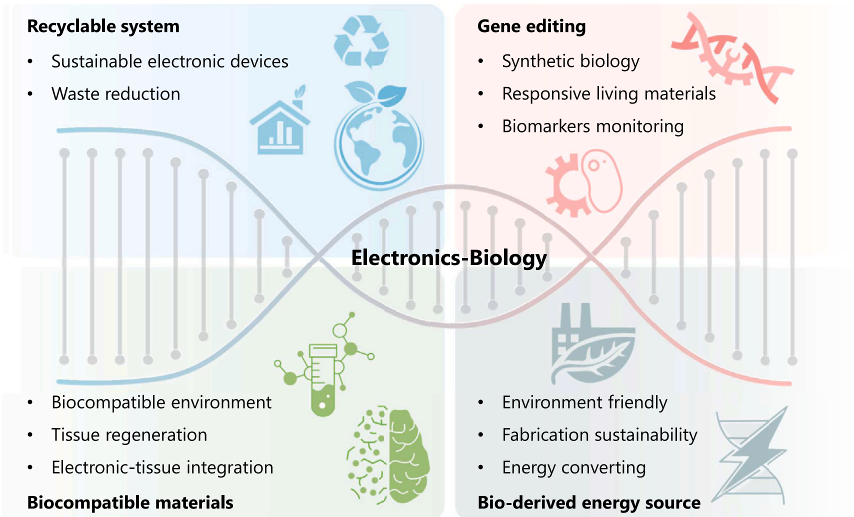

Figure 5. Perspectives on advancing the electronic-biology boundary
The integration of electronics with biology through recyclable systems, gene editing, biocompatible materials, and bio-derived energy sources is driving transformative progress. These advancements significantly impact medical innovation, biological research, sustainable energy solutions, and environmental conservation.

bandage is crafted from degradable polymers that naturally decompose after fulfilling their therapeutic role, thereby eliminating the need for secondary surgical removal (Figure 4M).

The field of behavioral biomimetic materials is advancing toward systems that not only replicate natural behaviors such as self-healing, motility, and decomposition but also incorporate dynamic adaptability. Current trends include the development of biodegradable electronic devices and materials capable of autonomous self-assembly in response to environmental stimuli.[65] Key challenges include controlling the precision of these processes and ensuring environmental safety in the case of decomposition. Future directions include creating fully programmable biomimetic materials that evolve their functions in response to biological cues, opening new possibilities for regenerative medicine and sustainable technologies.

CONCLUSIONS AND PERSPECTIVES

Biomimetic materials, combined with their unique properties and intricate behavioral characteristics, offered rich inspiration and practical guidance for the advanced bioelectronics. This perspective explores the latest advancements in biomimetic materials for bioelectronics, emphasizing three key approaches: structural biomimetic materials, property biomimetic materials, and behavior biomimetic materials. These innovations have paved the way for embedding sophisticated functionalities into bioelectronic devices, significantly advanced their potential in medical and technological applications. While these advancements provided exciting opportunities, several challenges must be addressed to maximize their impact. Critical challenges for biomimetic materials in bioelectronics include achieving stable integration between electronic and biological components, enhancing long-term stability, biocompatibility, and advancing scalable manufacturing processes. Constructing stable and seamless electronic-tissue interfaces is essential, requiring a delicate optimization of mechanical and electrical properties within the materials. For example, bioelectronic devices need to maintain continuous conformability and adhesion with dynamic tissues to ensure a stable and low contact impedance for high-quality electrical or chemical signals recording.[41] Meanwhile, long-term stability of devices also poses a critical challenge in biomimetic bioelectronics. Implantable bioelectronic devices, for instance, are often exposed to ionic body fluids, leading to material degradation and performance deterioration over time. This significantly impacts the reliability and functionality of these devices during long-term operations.[66]

Additionally, the issue of long-term biocompatibility has not been adequately addressed. Once implanted, devices frequently trigger foreign body responses, leading to complex immune reactions and fibrotic encapsulation, which severely compromise their performance and operational stability. To overcome these issues, the development of immunocompatible materials has become a key research focus. By introducing immunomodulatory functional groups, these materials aim to enhance biocompatibility, reduce immune responses, and extend the device lifespans.[67] Such advancements impose higher demands on biomimetic bioelectronics but also point to promising new directions. Nature-inspired strategies—such as mimicking natural structures, dynamic adaptability, or signal transmission mechanisms—offer potential solutions to the grand challenges such as material degradation, biocompatibility, and signal stability, paving new pathways for widening the applicability of bioelectronic devices.

Drawing inspiration from nature's design while addressing these critical challenges paves new directions for the development of bioelectronic devices. By mimicking the structural designs and functional characteristics of biological systems, future bioelectronics aim to become smarter, more efficient, multifunctional, biocompatible, and environmentally friendly. These advancements will provide innovative solutions for healthcare, environmental monitoring, and sustainable technological applications.

First, in terms of intelligence, biomimetic materials have transformative potential in robotics, where soft actuators mimic biological muscle functions to enable adaptive motion.[68] In prosthetics, neuromorphic materials facilitate seamless neural integration, improving motor control and sensory feedback.

Furthermore, in terms of biocompatibility, the use of bio-derived polymers such as collagen, chitosan, alginate, dextran, and silk offers better biocompatibility, making them ideal for manufacturing bioelectronic devices and soft robots. These materials integrate seamlessly with biological tissues, actively promoting tissue regeneration and repair (Figure 5).[69,70]

Additionally, regarding versatility, gene editing presents a novel approach to material design, allowing synthetic biology techniques to develop highly responsive and adaptive living materials and devices.[71] These advancements hold significant promise for detecting and monitoring biomarkers, exemplified by small capsule devices designed for *in vivo* detection of volatile inflammation markers.[72]

In terms of eco-friendliness, one promising approach involves creating recyclable and reusable systems, such as employing recyclable vitrimer-based printed circuit boards, which help reduce electronic waste and environmental burdens.[73] Moreover, the potential of bio-derived energy sources should not be underestimated. Synthetic biology is opening a new avenue for bioelectronics by designing and constructing active synthetic electronic systems. This approach is environmentally friendly and can significantly boost the autonomy and sustainability of electronic devices.[74]

In conclusion, exploring biomimetic materials provides valuable inspiration and practical guidance for advancing the future of bioelectronics. By consistently applying nature's design principles, we can enhance the synergy between technology and the natural world, unlocking vast potential in personalized healthcare, regenerative medicine, and sustainable technologies.

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AUTHOR CONTRIBUTIONS

J.C. supervised the project. J.Y. and J.C. developed the framework and organized the figures. J.Y. organized and designed the figures. J.Y., S.W., and X.X. wrote the initial manuscript under J.C.'s guidance. K.S. and F.M. provided scientific editing of the manuscript. All authors have provided feedback and contributed to writing the manuscript. J.C. submitted the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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