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Perspective

The convergence of bioelectronics and engineered living materials

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SUMMARY

Emulating nature's living properties in functional materials is a crucial step toward creating adaptive and self-regulating systems capable of integration with biological tissues. In this perspective, we first investigate the various strategies employed in the field of bioelectronics and engineered living materials to replicate nature's living functionalities. Then, we explore the convergence of bioelectronics and engineered living materials, highlighting an approach called living bioelectronics. We posit that merging these two fields can enable the creation of robust, adaptable devices that replicate the dynamic functionalities of living systems. Living bioelectronics integrate the strength of both disciplines while complementing their weaknesses, heralding opportunities for biosensing, personalized therapies, and applications beyond healthcare.

INTRODUCTION

The field of bioelectronics merges biology, electronics, and materials science to develop devices that sense and stimulate biological tissues, enabling early disease detection and personalized health care. These devices have high sensitivity and specificity in detecting physiological signals and offer therapeutic applications by restoring lost sensory or motor functions and modulating neural activity. Bioelectronics has potential in non-invasive diagnostics, remote monitoring, and personalized therapies.[1,2]

Recent advances in bioelectronics focus on integrating living features like responsiveness, adaptability, memory, and self-healing capabilities. By re-creating adaptive and self-repairing properties of living systems, bioelectronic devices resist environmental stress and device fatigue, prolonging their lifespan.[3] Incorporating tissue-like properties such as softness, programmability, anisotropy, and strain stiffening allows seamless integration with biological tissues and prevents damage due to mechanical mismatch.[4,5] The integration of memristors in bioelectronics enables new functionalities like neuromorphic computing and power-efficient data compression.[6] However, mimicking natural features with purely synthetic materials poses significant challenges.

The field of engineered living materials (ELMs) aims to recreate functional and responsive properties of life by encapsulating live microorganisms within a hydrogel matrix. ELMs can perceive changes in their surroundings and dynamically reconfigure their properties, serving various purposes like biosensing, disease treatment, biofuel production, and environmental remediation. However, the use of live engineered cells in ELMs raises biosafety concerns, limiting their real-life application.[7]

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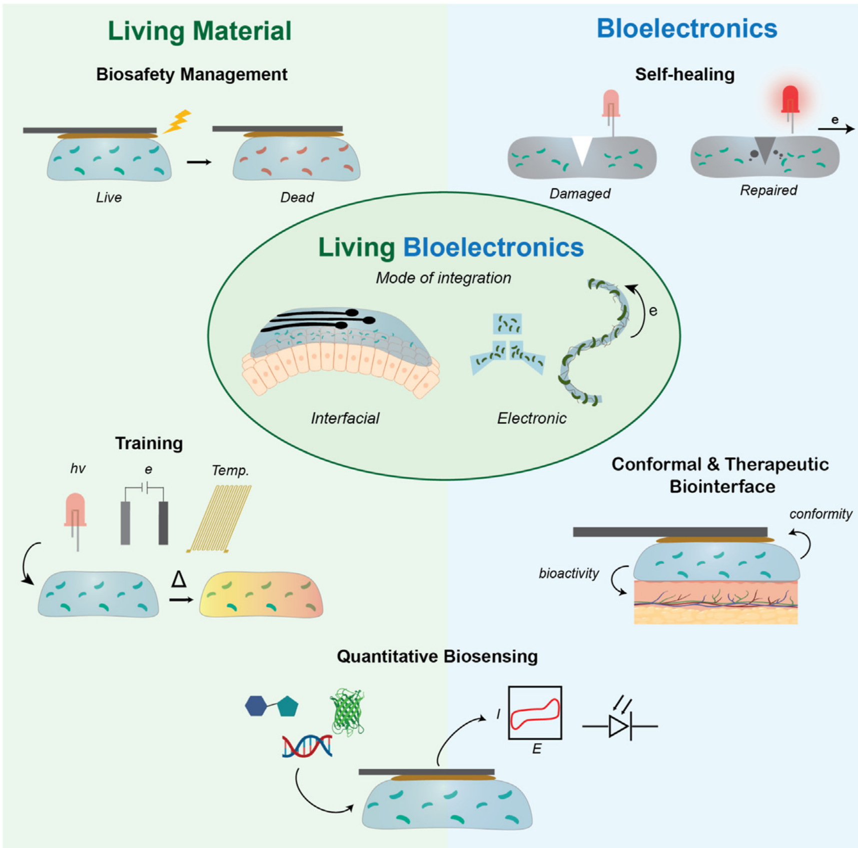

Figure 1. Integration of ELMs and bioelectronics merges the strengths of both disciplines and advances the realization of dynamic living functionalities

ELMs can be integrated into bioelectronics as an interfacial hydrogel or an electronic component. Bioelectronics-triggered disinfection alleviates biosafety concerns in ELMs. The adaptivity of ELMs allows for controlled training of bulk material properties through photonic, electrical, and thermal stimuli supplied by bioelectronics. ELMs provide the self-repairing capacity to resist device fatigue and offer a conformal and therapeutic biointerface to improve disease diagnostics and treatment. ELMs can transduce complex macromolecules into quantifiable signals for improved biosensing.

In this perspective, we analyze the various strategies employed by the field of bioelectronics and ELMs to achieve living properties. We envision that the integration of ELMs and bioelectronics, creating what we call living bioelectronics, amalgamates the strengths of both disciplines and advances the realization of dynamic living functionalities (Figure 1). Among various classes of living materials, we limit our discussion to biological ELMs that incorporate microorganisms as the living component, as discussed in the comprehensive review by Rodrigo-Navarro et al.[8] By leveraging the strength of bioelectronics and ELMs, living bioelectronics has the potential to overcome fundamental challenges in both fields, paving the way for innovative applications in health care and beyond.

STRATEGIES TO IMPART LIVING FEATURES IN BIOELECTRONICS

The rigid inorganic materials used in bioelectronic devices often struggle to interface effectively with soft, dynamic, and responsive living tissues. Additionally, the requirement for power often leads to the use of large, bulky batteries, which in turn reduces their lifespan.[9] To address these challenges, exploring living characteristics within bioelectronics has emerged as a key focus for the next generation of this

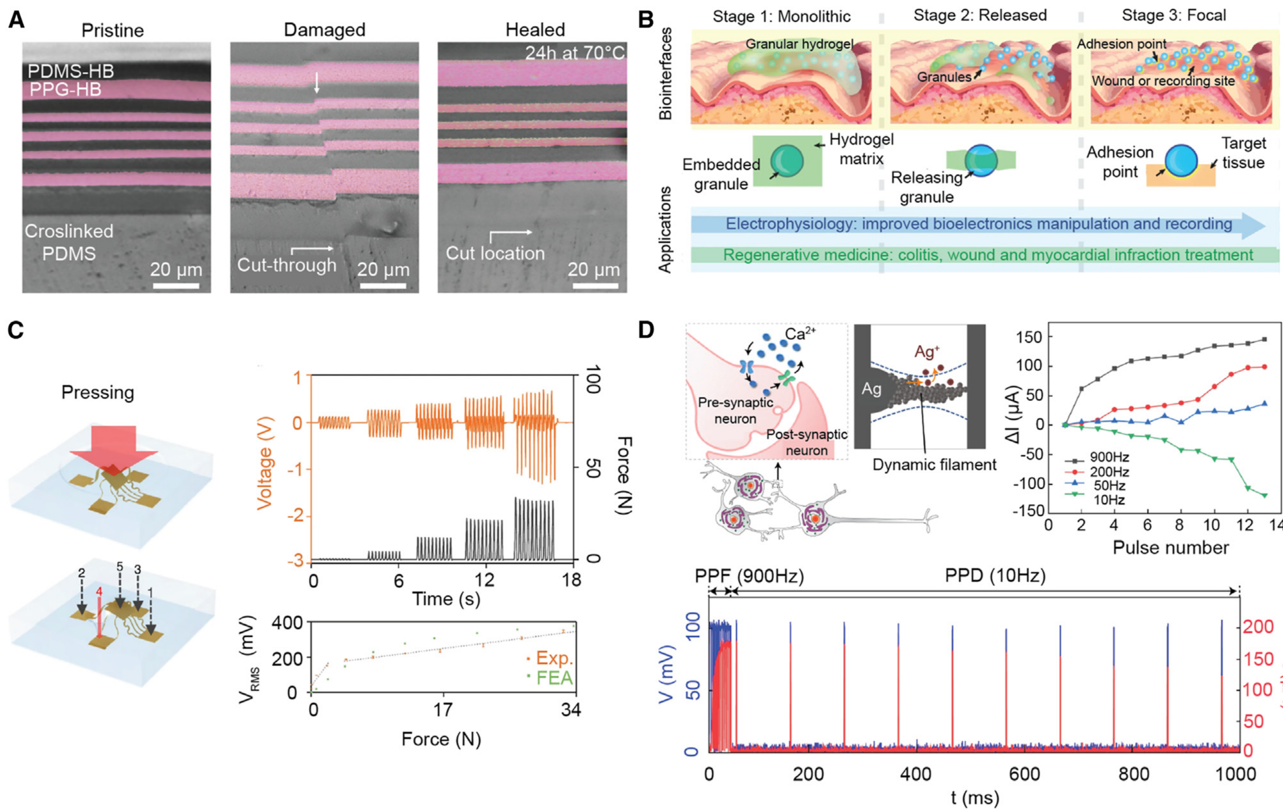

Figure 2. Material design strategies to impart living features in bioelectronics

(A) Differential miscibility drives surface tension-mediated realignment and self-healing of a multilayer material for bioelectronics. Reproduced with permission from Cooper et al., copyright 2023, AAAS.[11]

(B) Granules embedded in a gelatin matrix are released when exposed to body temperature, forming a focal biointerface that facilitates electrophysiology recording. Reproduced with permission from Shi et al., copyright 2024, Springer Nature.[14]

(C) Vibrations from movement allow piezoelectric generators to automatically harvest energy. Reproduced with permission from Han et al., copyright 2019, Springer Nature.[15]

(D) Diffusion of AgNPs creates memory within memristive circuits through repeated electrical stimulation. Reproduced with permission from Fu et al., copyright 2020, Springer Nature.[16]

field. Traditional efforts have largely focused on blending stretchability and tissue-like viscoelasticity to improve biointerfaces.[10] However, integrating additional living attributes such as self-healing, adaptability, and memory shows promise in creating highly resilient, energy-efficient, and intelligent bioelectronic systems. This section introduces selected material engineering approaches aimed at incorporating living features into bioelectronics.

Self-healing and regeneration

The introduction of self-healing features in bioelectronics offers the potential to repair physical damage and restore previous properties and functionalities. One notable example is a self-healing material developed by Cooper et al., which used a polymeric material composed of alternating layers of polydimethylsiloxane and polypropylene glycol, each containing bisurea groups that confer self-healing capacity (Figure 2A).[11] The immiscible backbones of these polymers facilitated surface tension-mediated realignment, while their dynamic bisurea bonds enabled self-healing at higher temperatures. By incorporating insulating $SrTiO_3$ microparticles and conductive carbon nanoparticles (NPs), they created a pressure sensor that maintained sensing capacity despite misalignment, recovering nearly 96% of its capacitance through heat-stimulated realignment. Magnetic NdFeB nanoflakes provided external control over the realignment and healing process using a magnetic field. Other self-healing materials, enabled by reversible hydrogen bonding and metal-coordination bonding,[12,13] have greatly improved fatigue resistance and long-term stability of bioelectronic devices.

Stimuli responsiveness

Bioelectronics mimic the ability of biological systems to respond to stimuli, adapting their function on demand. This capability is particularly useful for improving the conformity of the biointerface, which enhances signal recording efficacy, and for extending device lifespan by responding to changes in tissue conditions. For instance, Shi et al. developed a dynamic hydrogel matrix composed of gelatin that can dissolve and release starch granules in response to temperature and pH changes.[14] When the gelatin matrix dissolves upon exposure to physiological temperature, the released starch granules create a localized, cell-scale biointerface. By chemically altering the granules with therapeutic molecules, the researchers facilitated applications like wound healing and electrocardiogram signal recording (Figure 2B).

Another approach, by Jiao et al., involved developing a device that adjusts its shape and mechanical properties to match the target organ automatically in response to thermal stimuli.[17] Heating the device to body temperature softened the shape memory polymer substrate, allowing implantation through small incisions and improving conformity to the tissue it interfaces with. This enhances the effectiveness of its electrodes for temperature, potential, and pH sensing, crucial for diagnosing conditions like epilepsy or pericardial effusion. The substrate retains sufficient strength to maintain its shape over extended periods, thereby enhancing durability.

Self-powered systems

Bioelectronic devices that generate their own power or harvest energy from their surroundings simplify integration with biological systems by eliminating bulky batteries and external wiring. For example, Han et al. developed self-powered bioelectronic devices using a three-dimensional (3D) piezoelectric generator that captures energy from natural animal movements (Figure 2C).[15] They employed a serpentine-shaped polyvinylidene difluoride generator with sandwiched electrodes, generating voltage from in-plane vibrations and out-of-plane oscillations. When implanted in a rodent's hind leg, this setup enabled energy harvesting from movement, thus enabling autonomous operation. In another study, researchers reported thermoelectric generators consisting of Bi and Sb chalcogenides and Au-Ge electrodes that can generate power through the temperature difference between the body and surrounding air.[18] Photovoltaic generators have also been employed to generate energy through ambient light.[19]

Programmability and memory

The ability to store information for long-term use is a crucial feature in permanent or implantable bioelectronics. This can be achieved through memristors, devices capable of retaining the amount of charge that flows through them. Fu et al. developed diffusive memristors designed to operate at biological voltages of 40–100 mV.[16] When an electrical signal passes through the memristor, it triggers the diffusion of AgNPs, forming a conductive filament (Figure 2D). This process is facilitated by protein nanowire-catalyzed reduction of Ag. Repeated stimulation enhances or depresses current, mimicking synaptic plasticity. These artificial neurons replicate temporal and spatial summation, showing potential for power-efficient bio-computing. In addition to electrical stimulation, repeated mechanical stretching can program the bulk electrical properties of bioelectronic devices. For instance, Lipomi et al. demonstrated reversible alterations in the material's electrical conductivity through strain-induced realignment of carbon nanofibers.[20]

STRATEGIES TO IMPART LIVING FEATURES IN ELMs

In the preceding section, we briefly explored how bioelectronics achieve living properties through material engineering approaches. In contrast, ELMs manifest living properties by incorporating functional microorganisms into synthetic or naturally occurring matrices. Genetic engineering of functional microorganisms and clever design of encapsulating matrix have advanced the application of ELMs in biosensing, environmental cleanup, and regenerative medicine. The following section details strategies for replicating living characteristics within ELMs.

Programmability

ELMs aim to replicate the programmability of natural systems by designing materials that can reconfigure their mechanical and biocatalytic properties. Gilbert et al. created ELMs through a co-culture of genetically programmed *Saccharomyces cerevisiae* and bacteriocellulose-producing *Komagataeibacter rhaeticus*.[21] *S. cerevisiae* secreted enzymes that functionalized the matrix, thereby altering the material's properties. The introduction of catalytic enzymes enabled the oxidation of environmental pollutants, while cellulase secretion reduced the matrix's stiffness. Optogenetic circuits were also integrated into the material, transforming the ELM into a living biosensor capable of detecting blue light and expressing fluorescent reporter proteins.

Biomineralization is a common strategy used to enhance mechanical properties. In one example, *Sporosarcina pasteurii* was encapsulated in gelatin microparticles embedded in a Ca^{2+}-crosslinked alginate hydrogel. When exposed to a mineralizing environment, the encapsulated bacteria hydrolyzed urea, producing carbonate ions that reacted with calcium ions to precipitate $CaCO_3$ minerals (Figure 3A). The hardening of the composite enabled it to withstand pressures of up to 3.5 MPa.[22] Integrating a synthetic polymer matrix can provide additional avenues for reconfiguring material properties. Yu et al. incorporated chloroplasts into a synthetic hydrogel containing a glucose-crosslinkable isocyanate group.[23] The photosynthesized glucose facilitated crosslinking of the hydrogel, enhancing its Young's modulus in response to light.

Compartmentalization

ELMs mimic compartmentalized interactions in nature by organizing microbes with distinct functionalities into modular building blocks. Achieved through 3D printing, separating different engineered cell types in hydrogel matrices can facilitate biocomputing. For example, multicellular logic has been achieved through compartmentalization, where operations such as NOT, AND, OR, and NAND are performed based on the spatial distribution and interactions of genetically engineered *Escherichia coli*.[27] Also, separating bacterial strains with sender and receiver functions into different building blocks simplifies biosensing processes.[28]

The concept of division of labor can facilitate bioprocessing in ELMs. Ou et al. compartmentalized engineered *E. coli* and *Meyerozyma guilliermondii* within microparticles consisting of a carboxymethylcellulose core and a gelatin/gelatin methacryloyl shell, crosslinked to create a heterogeneous scaffold.[24] Enzymatic cascades and interparticle metabolite transfer enabled the conversion of glucose to 2-phenylethanol (2-PE) through cooperative action of the two organisms (Figure 3B). Compartmentalization prevented competitive growth and promoted efficient mass

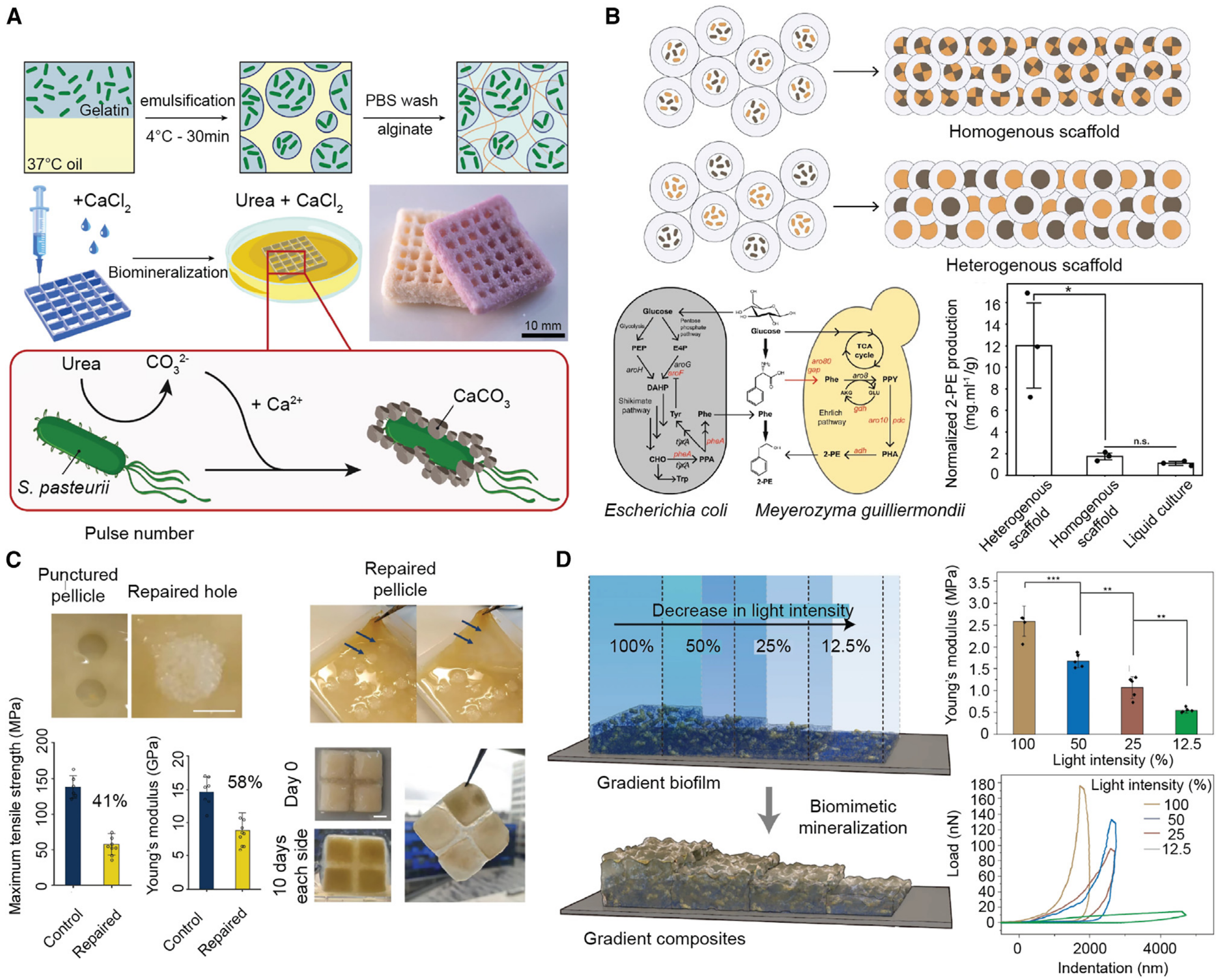

Figure 3. Strategies to imitate living features in ELMs

(A) *S. pasteurii*-driven biomineralization modifies the mechanical properties of a gelatin-alginate matrix in the presence of urea. Reproduced with permission from Hirsch et al., copyright 2023, Elsevier.[22]

(B) Compartmentalization of *E. coli* and *M. guilliermondii* into a heterogeneous core-shell microparticle scaffold enables efficient conversion of glucose into 2-PE through the cooperative action of the two organisms. Reproduced with permission from Ou et al., copyright 2023, Springer Nature.[24]

(C) Bacterial cellulose spheroids used as self-growing building blocks can heal punctured holes and glue fragmented synthetic material, allowing the recovery of tensile strength and Young's modulus. Scale bar, 5mm. Reproduced with permission from Caro-Astorga et al., copyright 2021, Springer Nature.[25]

(D) Light-inducible biofilm growth and biomineralization produce a gradient of biofilm height and Young's modulus at different light intensities. Reproduced with permission from Wang et al., copyright 2020, Springer Nature.[26]

transfer of metabolites, resulting in a 6-fold increase in 2-PE production compared to homogeneous counterparts.

Self-healing and regeneration

ELMs emulate nature's ability for autonomous growth and regeneration by incorporating matrix-forming microorganisms. Bacterial cellulose, known for its high tensile strength, flexibility, biocompatibility, and degradability, is widely used as a self-growing matrix. Caro-Astorga et al. utilized millimeter-scale bacteriocellulose spheroids grown from shaking cultures of *K. rhaeticus* as modular building blocks to create 3D-shaped living materials.[25] These spheroid particles effectively sealed punctures in the bacterial cellulose pellicle, restoring its Young's modulus and even fusing fragmented synthetic materials together within 10 days (Figure 3C). Other than bacteriocellulose, biofilms can be used for self-regenerating material. In one example, Wang et al. developed living patterned and gradient composites by combining light-inducible bacterial biofilm growth with biomimetic hydroxyapatite mineralization.[26] The thickness of the biofilm was precisely controlled using blue light intensity, resulting in a gradient of Young's modulus (Figure 3D).

OUTLOOK ON LIVING BIOELECTRONICS

In summary, we explored how two distinct disciplines—bioelectronics and ELMs—aim to replicate nature's living properties using innovative approaches. Bioelectronics primarily focuses on material engineering, while ELMs emphasize genetic modification and the selection of functional microbes. For instance, bioelectronics achieve self-healing capabilities through dynamic bond-forming materials, whereas ELMs usually attain regenerative properties by engineered organisms that secrete extracellular matrix. Bioelectronics achieve stimuli responsiveness by harnessing chemical and physical properties of synthetic materials, while ELMs accomplish these traits via compartmentalizing microorganisms with genetically encoded logic gates. Despite their differing methodologies, their ultimate goal is harmonious. In this section, we envision the fusion of bioelectronics and ELMs to create living bioelectronics, which synergistically realize nature's dynamic living properties.

How can the integration of ELMs enhance the performance of bioelectronics?

ELMs with high electronic conductivity can replace gold films as self-healing and stretchable interconnects. For example, Chen et al. developed engineered bacteria that self-assembles through nanobody (Nb)-antigen (Ag) pair adhesion (Figures 4A and 4B).[29] This material, known as living assembled material by bacterial adhesion (LAMBA), was conductive and capable of rapid self-healing through cell growth and adhesion. When used as an electromyography sensor, sliced LAMBA maintained conductivity through multiple stretch cycles after healing, effectively addressing the fatigue issue in wearable devices. Additionally, LAMBA's conductivity could be enhanced by programming the expression of a protein that immobilizes AuNPs. This example shows that ELMs with programmable electrical properties, fatigue resistance, and self-regeneration can enable the development of adaptable electronics that respond to environmental changes.

ELMs, when utilized as an interfacial hydrogel, can represent a next-generation biointerface. The soft and viscoelastic properties of living hydrogels can mitigate the mechanical mismatch between tissue and bioelectronics, facilitating the recording of biological signals.[31] Encapsulating commensal microbes enables self-replenishment and sustained secretion of therapeutic biomolecules.[32,33] One notable example is active biointegrated living electronics (ABLE), which seamlessly integrates bioelectronics with interfacial living hydrogel for synergistic inflammation management.[30] Attached to the device, the living hydrogel encapsulates *Staphylococcus epidermidis*, a skin commensal bacteria that provided bioactivity for psoriasis treatment (Figures 4C and 4D). The biomechanical properties of the living hydrogel enhanced the monitoring of psoriasis, by sensing temperature, humidity, impedance, and electromyography signals from the inflamed tissue. ABLE shows that living biointerfaces with bioactivity and tissue-like mechanical properties can facilitate simultaneous treatment and diagnostics of chronic disorders.

How can the integration of bioelectronics enhance the performance of ELMs?

ELMs present multiple risks and caveats that must be addressed. The release of opportunistic pathogens into the environment raises biosafety concerns, which currently

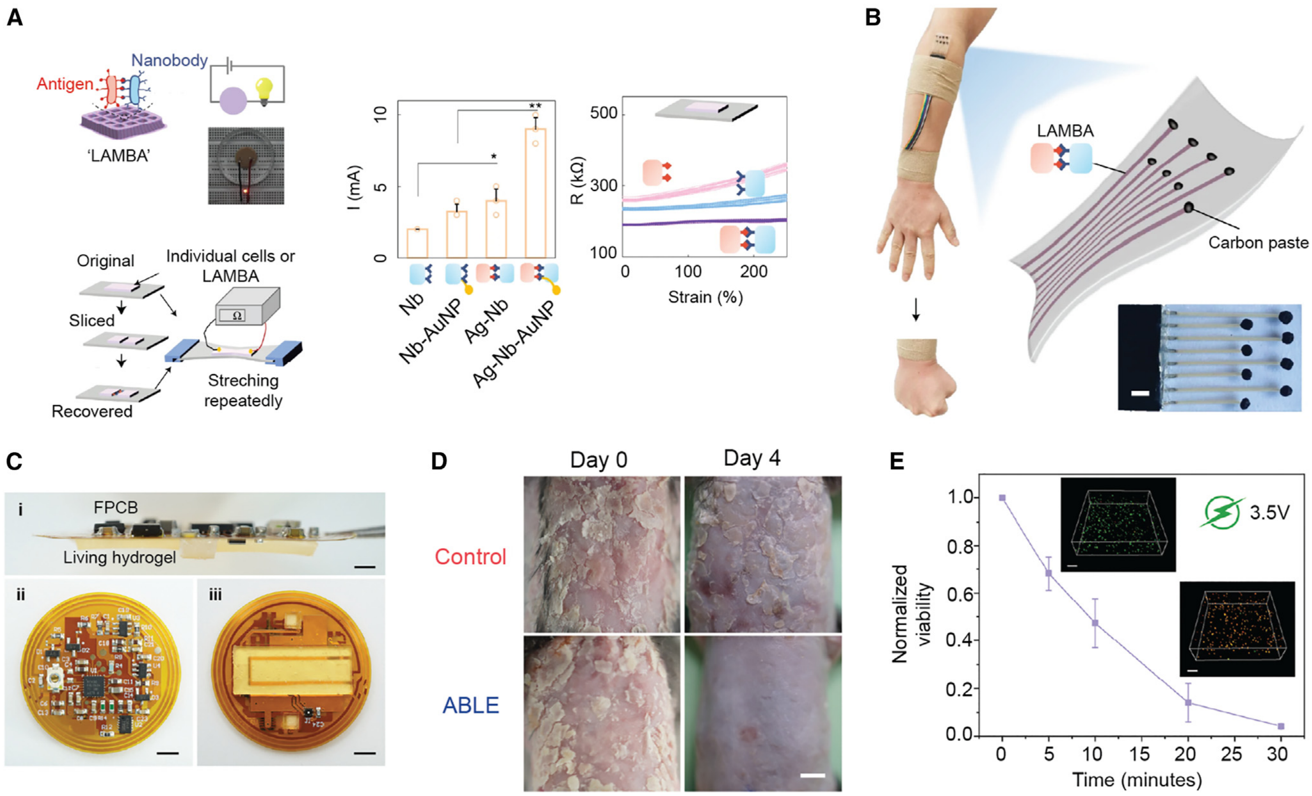

Figure 4. Emerging prospects in living bioelectronics

(A) Conjugating *E. coli* that expresses Ag and Nb pair forms a LAMBA with programmable conductivity and the ability to recover damage induced by slicing and repeated stretching.

(B) LAMBA can be electronically integrated as a self-healing conductor in an electromyography sensor. Scale bar, 2mm. Reproduced with permission from Chen et al., copyright 2021, Springer Nature.[29]

(C) ABLE device interfacially integrates electronics and *S. epidermidis*-embedded living hydrogel for synergistic inflammation treatment. Scale bar, 2mm (top), 4mm (bottom).

(D) ABLE possesses bioactivity to treat psoriasis, a chronic inflammatory disease. Scale bar, 5mm.

(E) Oxidative current effectively disinfects *S. epidermidis*-embedded living hydrogel, reducing biosafety concerns in the ABLE device. Scale bar, 20 μm. Reproduced with permission from Shi et al., copyright 2024, AAAS.[30]

hinders the practical application of ELMs. Uncontrolled use of antibiotics to kill bacteria could contribute to antimicrobial resistance.[34] Moreover, the addition of genetically engineered organisms raises ethical and societal concerns, necessitating stricter regulations for public use.[35] To tackle these challenges, one approach involves coating ELMs with a robust hydrogel shell featuring small pores to prevent bacterial escape.[28] However, when used as an interfacial hydrogel, this tough coating may compromise the desired biomechanical properties needed for tissue integration. Another strategy involves engineering microorganisms to undergo cell death upon reaching a threshold concentration.[36] Nonetheless, this approach requires genetic engineering, which can be challenging for bacteria with limited genetic toolkits.

The integration of bioelectronics provides a drug-free and non-genetic method for addressing biosafety concerns associated with ELMs. For instance, oxidative current can generate reactive oxygen species, which in turn reduces bacterial viability within the hydrogel (Figure 4E).[30,37] Additionally, microfabricated electrodes can create a strong local electric field capable of inducing electroporation in bacteria, compromising their membrane integrity and leading to cell death.[38] By carefully designing electrode geometry and integrating sensing-stimulation feedback loops,[39] localized disinfection may be timed precisely, such as during bacterial outgrowth or contamination events.

We envision that bioelectronics can enable controlled modulation of ELM functionality. This could be achieved by leveraging extracellular electron transfer (EET), which bridges electronics, live-cell metabolism, and material properties. In the presence of redox shuttles, electrodes can consume or deliver charges to bacteria through EET, allowing for electrical control of cell metabolism. While EET is a respiratory process inherent in electroactive organisms like *Shewanella oneidensis*, genes encoding for EET can be introduced into other functional microorganisms, such as *E. coli*.[40,41] Upon introducing EET to organisms, the cell metabolism can be coupled to the material property of ELMs. For example, Graham et al. demonstrated that EET-regulated *S. oneidensis* could activate a Cu catalyst, which in turn crosslinks the hydrogel matrix and adjusts the mechanical properties of ELMs (Figure 5A).[42] By integrating EETs in microbes and developing innovative strategies to link the cell metabolism with the synthetic properties of ELMs, electrical stimuli from bioelectronics can programmatically adjust ELM properties as needed.

Other than harnessing the electroactivity of microbes, bioelectronics can modulate encapsulated bacteria in several ways. The application of oxidation currents could induce oxidative eustress to enhance bacterial metabolism.[46] pH alterations or electrochemical generation of small molecules like H_2 or O_2 can also influence microbial activity within the hydrogel. Integrating microheaters or light-emitting diodes can facilitate temperature- or light-controlled modulation of living components.[47] Localized electric fields from bioelectronics can trigger changes in membrane potential through voltage-gated ion channels, impacting antibiotic resistance, ATP synthesis, and cell division.[48–50] The use of microelectrode arrays could deliver spatiotemporally controlled capacitive stimulation, aiding in the formation of patterned and gradient structures (Figure 5B).[43]

Modulation of ELMs can be combined with sensors to establish a closed feedback loop, enabling precise programming of bulk material properties. For instance, consider a model system involving biomineralizing *S. pasteurii* within an alginate hydrogel. The growth and bioactivity of *S. pasteurii* can be accurately monitored using impedance, pH, or metabolite sensors. Based on sensor inputs, electrodes can apply stimuli to either inhibit or enhance metabolism, thereby achieving the desired bacterial growth and activity levels. This process can result in a biomineralized hydrogel with a highly specific Young's modulus, finely tuned by the feedback loop system. Rapid online analysis and machine learning algorithms can further enhance the precision of living material modulation.[51]

Lastly, bioelectronics can precisely quantify biosensing outputs from ELMs. For instance, Mimee and colleagues developed a hemoglobin-sensitive probiotic biosensor that expresses a luminescence reporter when exposed to gastrointestinal bleeding (Figure 5C).[44] This signal is then quantified by a photodetector, which wirelessly transmits photocurrent data for real-time monitoring *in vivo*. Another study demonstrated that impedance outputs from microelectrodes can accurately quantify population dynamics and outputs from heavy-metal sensors and genetic oscillators.[52] In a recent study, Atkinson et al. electrogenetically engineered *E. coli* to produce an electrical current in response to an endocrine disruptor (Figure 5D).[45] When encapsulated with conductive nanomaterials, the engineered *E. coli* detected the endocrine disruptor in urban water samples within minutes. This example illustrates that the rational design of encapsulation matrices, coupled with electrogenetic

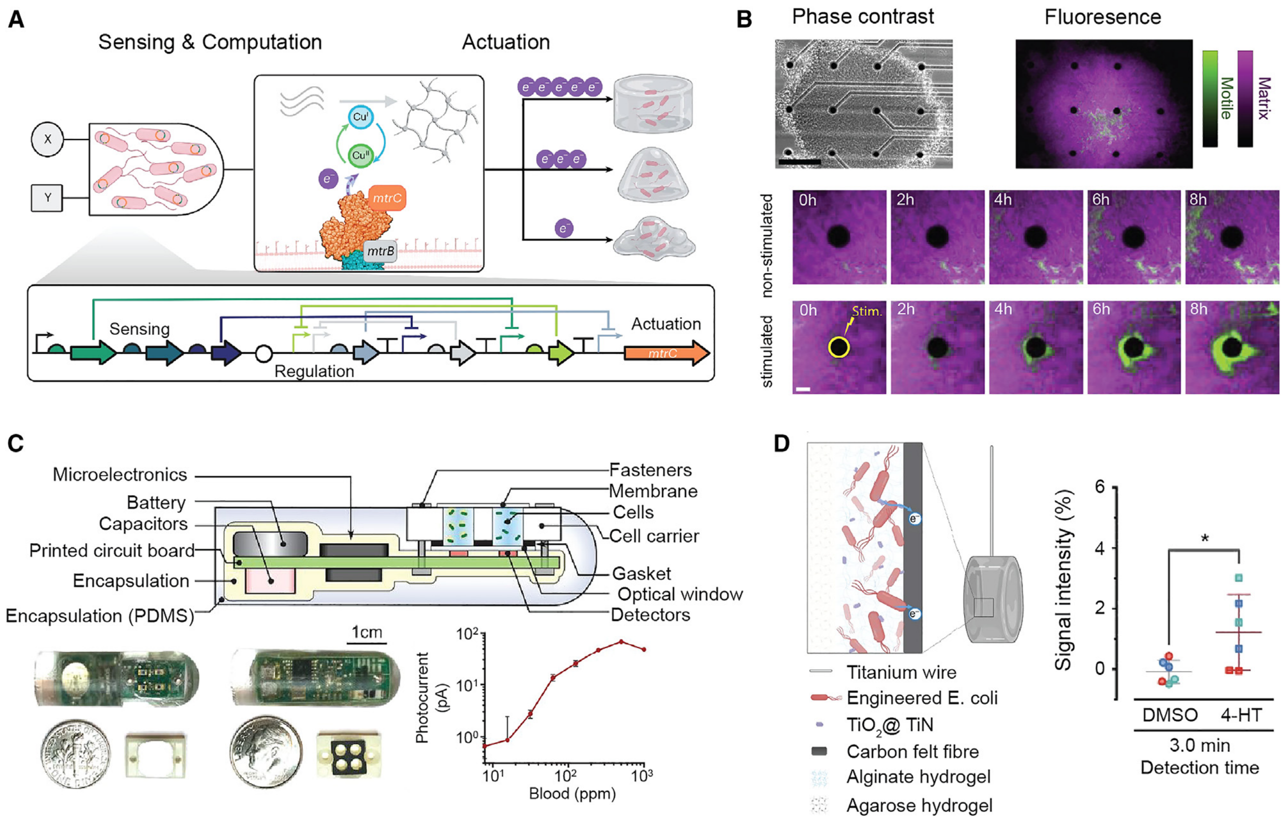

Figure 5. Other emerging prospects in living bioelectronics

(A) The EET-pathway protein MtrC from *S. oneidensis* affects the redox state of a catalytic metal, which crosslinks and modulates the hydrogel's mechanical properties. Electrical control of the EET pathway may allow bioelectronics to train the material's mechanical properties. Reproduced with permission from Graham et al., copyright 2024, Springer Nature.[42]

(B) Applying capacitive stimulation to *Bacillus subtilis* biofilm using a microelectrode array selectively enriches the motile population (green) over the matrix-forming population (pink) near the electrode. Scale bar, 200μm (top), 20μm (bottom). Reproduced with permission from Comerci et al., copyright 2022, Elsevier.[43]

(C) Engineered *E. coli* produces luminescence in response to blood heme. When integrated with an ingestible microelectronic pill, equipped with photodetectors, the luminescence signal can be quantified as photocurrent and wirelessly transmitted for real-time monitoring of porcine gastric bleeding. Reproduced with permission from Mimee et al., copyright 2018, AAAS.[44]

(D) Electrogenetically engineered *E. coli* encapsulated in a conductive hydrogel scaffold enables fast detection of the endocrine disruptor 4-hydroxytamoxifen (4-HT) in urban water samples through EET. Reproduced with permission from Atkinson et al., copyright 2022, Springer Nature.[45]

engineering, can optimize the transmission of electrical signals at the abiotic-biotic interface and enable precise quantification of biosensing outputs.

Design of living bioelectronics

Based on the existing examples of living bioelectronics, two general modes of integrating ELMs and bioelectronics can be proposed: electronic and interfacial (Figure 6). The electronic mode of integration utilizes ELMs as part of an electrical circuit in bioelectronics. Examples include LAMBA (Figure 4A), which utilizes ELMs as self-healing conductors,[29] and a study by Gao et al., which utilizes genetically encoded *S. oneidensis* to build living organic electrochemical transistors.[53] Many ELMs designed for biosensing and bio-computing applications can fall into this category of integration.

In addition, ELMs may be electronically integrated in bioelectronics as a semiconducting module. Photosynthetic organisms such as cyanobacteria and algae can

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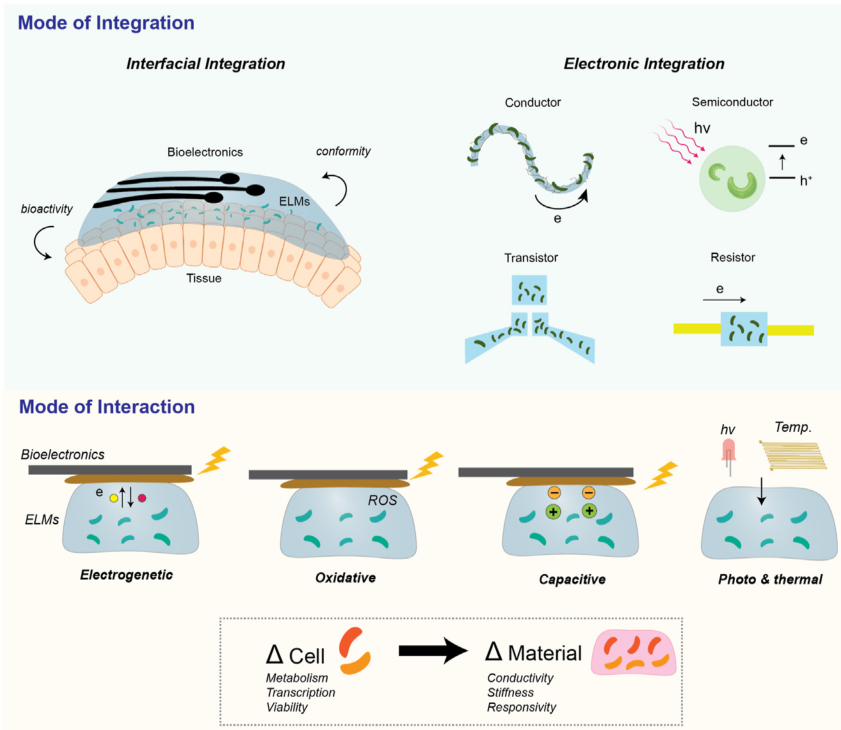

Figure 6. Possible modes of integration and interaction between bioelectronics and ELMs
ELMs can be integrated as an interfacial hydrogel between tissue and bioelectronics, providing a conformal and therapeutic biointerface. Alternatively, ELMs can be electronically integrated as a component of bioelectronics, performing functions such as biocomputing, self-healing, or power generation. Through various modes of interaction, bioelectronics can provide electrical, photonic, and thermal stimuli to train cells in interfacial ELMs, ultimately leading to alterations in material properties.

harvest light and produce electrical signals.[54,55] Through miniaturization and encapsulation in a conductive matrix, living photodiode or photovoltaic cells may be added into bioelectronic circuits. On a more forward-looking note, we envisage that electroactive microbes, when encapsulated in semiconducting hydrogels,[56] could serve as living dopants to regulate bandgap and charge transport properties.

The interfacial mode of integration utilizes ELMs as a signal transducing biointerface between electronics and the tissue. One example is the ABLE device, which integrates *S. epidermidis*-encapsulated hydrogel for inflammation treatment and monitoring (Figure 4B). The next crucial step toward advancing interfacial living bioelectronics will be to exploit diverse modes of interaction between bioelectronics and ELMs. Interfacial ELMs that can adapt their functionality through bioelectronics-supplied stimuli will enable a next-generation biointerface with highly dynamic and reconfigurable properties.

In summary, both the field of bioelectronics and ELMs strive to emulate nature's living properties to create functional and adaptive materials. This perspective envisions the convergence of these two distinct fields into living bioelectronics, combining their strengths while mitigating their weaknesses. The interfacial integration of ELMs will provide a bioactive and conformal biointerface capable of treating and monitoring complex inflammatory disorders. Electronically integrating ELMs will enhance bioelectronics with self-healing capabilities, as well as the ability to compute, sense, and precisely quantify complex biomolecular interactions.

The exciting potential of living bioelectronics lies in the interaction between electrical and biological components. Bioelectronics can modulate cells in ELMs, thereby influencing bulk material properties. Incorporating feedback loops to sense and stimulate integrated ELMs can enable living bioelectronics to dynamically adapt biointerfaces as needed. Despite its promise, ethical considerations in living bioelectronics are critical. Improper disposal of genetically engineered microorganisms and unregulated antimicrobial use could lead to severe consequences. Thus, bioelectronics must integrate proper biosafety measures to disinfect ELMs before disposal. Addressing these societal concerns moves us closer to realizing the functional properties of natural living systems through living bioelectronics.

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AUTHOR CONTRIBUTIONS

S.K. and E.E. wrote the manuscript. B.T. supervised the research. All authors contributed to discussions and finalizing the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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