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Research Article

DESIGN OF CONDUCTIVE SELF-HEALING MATERIALS FOR BIO-INTERFACE RECORDING APPLICATION

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Abstract

The development of self-healing materials for bio-interface recording applications represents a translational approach to addressing the challenges of durability, biocompatibility, and performance stability in biomedical devices. This study presents the design, fabrication, and evaluation of self-healing materials tailored for bio-interface recording systems. By integrating dynamic chemical bonding and supramolecular interactions, the proposed materials exhibit autonomous healing capabilities under physiological conditions, ensuring prolonged operational lifespan and reliability. The mechanical properties of these materials are optimized to mimic biological tissue, promoting seamless integration with soft, dynamic biological environments. Additionally, the electrical and electrochemical properties are fine-tuned to maintain signal fidelity for high-resolution recording. In this work, we will review the soft materials and their mechanisms for self-healing phenomenon, which are essential parts of materials design. Then, we will discuss about potential design of self-healing conductive materials. Based on this, we review the materials' ability to recover from mechanical damage without compromising functionality, providing a robust platform for long-term electrophysiological monitoring. These advancements pave the way for next-generation bioelectronic devices that are resilient, adaptive, and compatible with the complexities of living systems.

Keywords: Design, Bio-Interface.

INTRODUCTION

The rapid advancements in bioelectronics have opened up possibilities in healthcare, diagnostics, and therapeutics (1-3). Bio-interface recording devices, which capture physiological signals such as neural, cardiac, and muscular activities, play an important role in bridging the gap between biological systems and electronic platforms (4, 5). These devices enable precise monitoring and control of biological functions, fostering innovations in prosthetics, brain-computer interfaces, and wearable health monitors. However, achieving long-term stability and functionality in these systems is a persistent challenge due to their inherent exposure to dynamic biological environments and mechanical stresses. The development of self-healing materials offers a groundbreaking solution to these challenges by enabling devices that can autonomously repair themselves, ensuring durability and reliability over extended periods of use.Bio-interface recording applications present unique material design challenges. Devices in these systems must conform to the soft, irregular surfaces of biological tissues while maintaining biocompatibility, electrical conductivity, and mechanical resilience (6, 7) (Figure1).

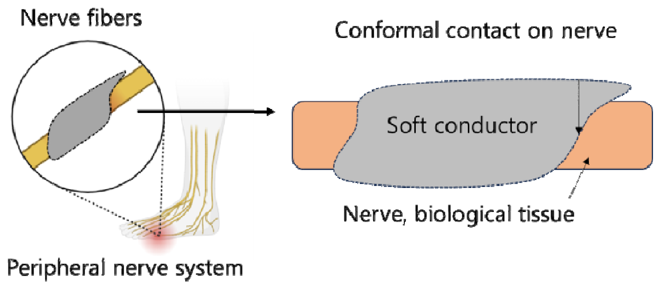

Figure 1. Conformal contact of soft electrodes on biological nerve

Traditional materials, despite their high performance in controlled environments, often fail to meet these stringent requirements when deployed in vivo. Mechanical mismatches between rigid electronic components and soft biological tissues can lead to delamination, signal degradation, and even adverse tissue reactions (8). Environmental factors, such as temperature fluctuations, hydration, and exposure to biofluids, further exacerbate these issues. To address these limitations, researchers are increasingly turning to self-healing materials as a means to enhance the robustness and adaptability of bioelectronic devices. Self-healing materials are engineered to autonomously restore their structural and functional integrity after damage. This capability is achieved through dynamic molecular mechanisms, such as reversible dynamic bonds, hydrogen bonding, ionic interactions, and supramolecular assembly (Figure 2). In recent years, polymeric materials with self-healing properties have gained significant attention for their potential to address the wear and tear experienced by bio-interface recording devices. These materials can recover from microcracks, scratches, and even more substantial structural damages, thereby extending device life spans and maintaining their functionality in demanding operational environments. One of the critical design considerations for self-healing materials in bioelectronics is their compatibility with physiological conditions. Materials used in these applications must be able to heal at body temperature and under moist conditions, often without the need for external stimuli. Hydrogels, elastomers, and conductive polymers have emerged as promising candidates due to their intrinsic flexibility, biocompatibility, and ability to form dynamic bonds. We will review the fundamental requirements of soft materials to design self-healing properties and their underlying mechanisms from the next section. We then highlighted potential modifications to these materials for use in soft, conductive, self-healing systems. Building on this, we reviewed their ability to recover from mechanical damage without

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compromising functionality, establishing a robust platform for long-term electrophysiological neural monitoring.

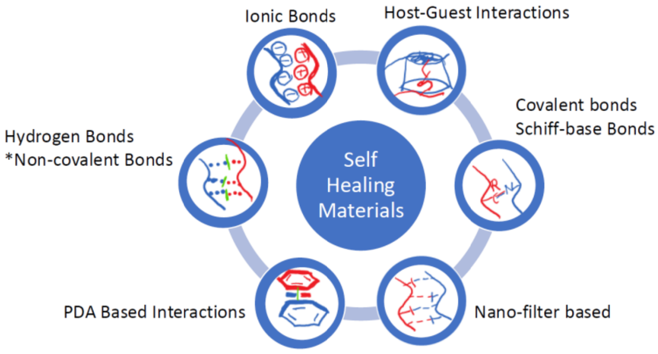

Figure 2. Diverse types of chemical bonding for self-healing materials

Self-healing mechanism based on soft materials

Welding is a common repair technique; however, the repaired site often remains the weakest point in the material. This issue is further compounded when the damage occurs in locations inaccessible for repair. These limitations have motivated efforts to design materials capable of self-healing, guided by a deeper understanding of material chemistry and target applications. The ultimate goal is to develop materials that can self-repair at microscopic or even nanoscopic levels, halting crack propagation and restoring the material's original physical/mechanical properties. There are various strategies for creating self-healing materials. Broadly, these materials achieve healing through either intrinsic mechanism, relying on reversible bond formation, or extrinsic methods, involving the triggered release of a pre-embedded healing agent. Additionally, certain systems are designed to respond to predetermined external triggers beyond mechanical damage, such as optical, thermal, electrical, ballistic, or chemical stimuli. In all these approaches, microcracks are repaired before they propagate further, effectively preventing catastrophic failure. Some commercially available materials can also be classified as healable. For example, materials with low glass transition temperatures (T_g) can flow and fill microcracks when heated above their T_g. Materials that heal autonomously whether through intrinsic or extrinsic methods do so in response to mechanical damage. By contrast, externally triggered systems rely on stimuli unrelated to direct damage. The development of self-healing mechanisms in soft materials represents a significant milestone in material science, offering innovative solutions to challenges in various fields such as electronics, biomedical devices, robotics, and sustainable engineering. Soft materials, characterized by their elasticity, deformability, and molecular flexibility, mimic biological tissues and provide an ideal platform for self-healing technologies. These materials aim to restore functionality and structural integrity after experiencing mechanical damage, such as cuts, tears, or fractures, making them highly desirable for applications where reliability and durability are critical. Self-healing mechanisms in soft materials can be broadly classified into intrinsic and extrinsic systems. Intrinsic self-healing relies on reversible interactions or dynamic covalent bonds within the material’s molecular framework. These bonds include hydrogen bonding, ionic interactions, metal-ligand coordination, and reversible covalent linkages, such as disulfide bonds or Diels-Alder reactions (9). Upon damage, these dynamic bonds can reform under appropriate conditions, such as exposure to heat, light, or specific chemical triggers, enabling the material to repair itself autonomously. For instance, hydrogen-bonded networks in polymers have demonstrated remarkable self-healing capabilities under ambient conditions, offering practical solutions for applications in wearable electronics and soft robotics (10). Extrinsic self-healing, on the other hand, involves the incorporation of external healing agents, such as microcapsules, embedded nanoparticles, within the material matrix (11). When the material is damaged, these agents are released to fill the damaged area and restore the material’s properties. Microcapsule-based systems, for example, have been extensively explored for their ability to deliver liquid healing agents to the damaged site. While extrinsic mechanisms often exhibit impressive healing performance, their reliance on finite reservoirs of healing agents can limit long-term durability. Advancements in self-healing soft materials have focused on enhancing their mechanical properties, healing efficiency, and environmental adaptability.

Self-healing conductive materials

One of advanced type of design based on self-healing mechanismis conductive self-healing materials, merging the ability to autonomously repair mechanical damage with the restoration or preservation of electrical conductivity (Figure 3). These materials address the critical challenges of reliability, durability, and performance in modern technologies such as flexible electronics, wearable devices, soft robotics, energy storage systems, and bioelectronics (12-14). To achieve conductivity, these materials are often integrated with conductive fillers like carbon nanotubes, graphene, metallic nanoparticles, or conductive polymers. These fillers not only enhance the material's electrical performance but also play a role in bridging gaps formed during damage, facilitating the restoration of electrical pathways. For example, graphene-based self-healing materials have shown exceptional potential for use in flexible and stretchable devices due to their high electrical conductivity, mechanical strength, and adaptability (15). Similarly, hydrogels infused with conductive fillers have been developed for applications in wearable sensors and health monitoring systems, where the seamless restoration of conductivity after damage is essential for accurate diagnostics (16). Beyond these specific mechanisms, the design of self-healing conductive materials often draws inspiration from biological systems, mimicking the self-repairing abilities of human skin or plant tissues. These bio-inspired strategies result in materials that not only self-heal but also adapt to their environments, making them highly versatile and resilient. One of the most significant advantages of self-healing conductive materials is their ability to operate under a variety of environmental conditions, including ambient temperatures and humidity levels. This eliminates the need for specialized repair environments, increasing their practicality for real-world applications. Additionally, their integration into devices reduces maintenance costs and enhances product lifespans, contributing to sustainability. For instance, in energy storage systems such as batteries or super capacitors, self-healing conductive materials can repair electrode damage caused by repeated charge-discharge cycles, thereby improving the device's longevity and safety. In the realm of soft robotics, these materials enable actuators and sensors to recover from mechanical damage, ensuring consistent performance in dynamic applications. Despite these advancements, challenges remain in the development of self-healing conductive materials. Achieving a balance between mechanical robustness and healing efficiency is a persistent issue, as enhancing one property often compromises the other. Furthermore, scaling up the production of these materials while maintaining cost-effectiveness and environmental sustainability is essential for their widespread adoption. Researchers are addressing these challenges by exploring bio-based and recyclable materials to create sustainable self-healing systems that minimize environmental impact. Future developments in this field are expected to focus on multifunctionality, integrating properties such as thermal stability, transparency, and environmental adaptability alongside self-healing and conductivity.By leveraging advanced intrinsic and extrinsic mechanisms, as well as integrating innovative conductive components, these materials offer a promising solution to the limitations of conventional systems. As research progresses, the adoption of self-healing conductive materials will pave the way for a new era of resilient, sustainable, and high-performing technologies that can adapt to and thrive in the demands of modern life.

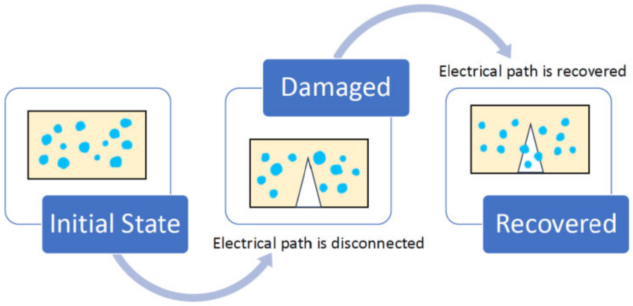

Figure 3. Design and principle of self-healing soft conductor

Neural recording using self-healing electrodes

Neural recording using self-healing electrodes represents a groundbreaking advancement in bioelectronics, offering unprecedented durability and functionality in interfacing with neural tissues. Traditional neural electrodes are prone to mechanical damage and degradation over time due to repeated use, implantation stress, and physiological movements, which compromise signal quality and device longevity. Moreover, modulus mismatch induced the large stress to nerve while movements of body. Self-healing electrodes designed with soft materials overcome these challenges by integrating materials capable of autonomously repairing damage while maintaining electrical conductivity. For instance, self-healing hydrogels doped with conductive fillers like graphene or metallic nanoparticles have been used to create electrodes that repair microcracks caused by mechanical stress (17). These hydrogels not only recover their structural integrity but also restore their ability to transmit high-fidelity neural signals. An example of such technology is the development of stretchable self-healing electrodes for chronic neural recording in dynamic environments. These electrodes, made from polymeric networks with reversible hydrogen bonds or ionic interactions, can withstand deformation during body movements without losing signal continuity (18). In one study, researchers demonstrated self-healing polymer-based electrodes capable of recovering their electrical performance within minutes of being cut or punctured (19). These electrodes were successfully used to record neural signals from rat brains, showcasing their potential for long-term applications in neuroscience research. Another notable application is the use of self-healing conductive materials in flexible implantable devices for spinal cord injury monitoring (20). These electrodes, embedded with microcapsules containing liquid conductive agents, can autonomously repair damage caused by the compressive forces of the spinal column, ensuring consistent signal acquisition. Additionally, bio-inspired self-healing materials have been engineered to mimic the soft, elastic properties of neural tissues, reducing immune response and improving the biocompatibility of implants. By integrating self-healing capabilities into neural recording electrodes, researchers have developed devices that not only enhance the reliability of neural interfaces but also extend their lifespan, enabling more robust and sustainable monitoring of nerve activity for applications such as neural-machine interfaces, epilepsy detection, and neuroprosthetics. These innovations represent a significant step forward in creating resilient, high-performance bioelectronic systems that adapt to the challenges of long-term use in dynamic biological environments.

Conclusion

In conclusion, the design of self-healing materials for bio-interface recording applications improves the robustness of sensor system, enabling long-term recording of bio-signals. These materials address critical challenges associated with the long-term stability, durability, and biocompatibility of devices used for interfacing with biological systems. By incorporating intrinsic mechanisms such as dynamic covalent bonds, hydrogen bonding, and ionic interactions, or extrinsic methods like microcapsules and vascular networks, self-healing materials enable the autonomous repair of mechanical damage. Combining the self-healing materials with conductive fillers, self-healing conductive materials have been achieved, which is essential part of neural recording. The integration of these materials into bio-interface recording systems, such as neural electrodes and implantable sensors, ensures consistent signal fidelity, reduced immune response, and extended device lifespan, paving the way for advanced applications in neural-machine interfaces, chronic neural monitoring, and personalized healthcare. Furthermore, bio-inspired approaches that mimic the adaptability and resilience of natural tissues have opened new possibilities for creating materials that seamlessly interact with dynamic biological environments. As the field progresses, future efforts must focus on enhancing the scalability, affordability, and sustainability of self-healing materials while improving their performance in real-world biomedical applications. By overcoming these challenges, self-healing materials will not only revolutionize bio-interface recording technologies but also contribute to the development of resilient, adaptable, and sustainable medical devices that improve the quality of life for individuals worldwide.

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