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REVIEW ARTICLE

Bioelectronic Tools for Surgeons in the Advancement of Precision Operative Care

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Abstract

The convergence of engineering biology and surgery has led to the development of bioelectronic medicine. This field uses electrical signals to diagnose monitor and treat physiological dysfunction. Bioelectronic medicine now plays an important role across the perioperative continuum. This narrative review examines how bioelectronic technologies are transforming modern surgical practice. It outlines the fundamental principles of bioelectronic surgical devices. Special emphasis is given to intraoperative neuromonitoring for neural protection. The review also discusses tissue identification using electrical stimulation. Haptic feedback systems are highlighted as solutions to the loss of tactile sensation in robotic surgery. The integration of bioelectronic tools into robotic platforms enhances surgical precision. Bioelectronic assisted interfaces such as augmented reality and wearable sensors provide improved control and situational awareness for surgeons. These technologies support safer and more efficient intraoperative decision making. The review further explores the expanding role of bioelectronics in minimally invasive surgery. Neuromodulation techniques for postoperative pain management are discussed. Continuous physiological monitoring of organ function is also reviewed. A major focus is placed on the transition toward advanced postoperative care. Patient specific physiological profiling is becoming increasingly important. Adaptive closed loop systems capable of autonomous drug delivery and electrical stimulation are emerging as new standards. Finally, the review discusses the future of precision surgery. Emphasis is placed on implantable wireless devices. AI enhanced decision support systems are highlighted. Biohybrid regenerative interfaces are also explored. This review provides clinicians and researchers with a comprehensive overview of how bioelectronic technologies are reshaping surgical outcomes and improving patient recovery.

1. Introduction

Traditional medicine is undergoing rapid transformation due to technological advancements. Digital health technologies robotics and artificial intelligence are accelerating this change at an unprecedented pace (Trinidad Borras & Benavent, 2025). Within this evolving landscape bioelectronic medicine has emerged as a distinct therapeutic approach. It utilizes the electrical properties of the nervous system to treat diseases and injuries. Bioelectronic medicine differs from conventional systemic pharmacology. It delivers targeted electrical stimulation to specific neural circuits and physiological pathways (Gonzalez-González et al., 2024). This approach reduces off target effects and improves therapeutic precision. The impact of this paradigm shift is particularly evident in surgical practice. The integration of bioelectronics is redefining surgical accuracy and postoperative recovery outcomes (Lerman et al., 2025).

Surgical techniques have evolved from open procedures to laparoscopic and robot assisted surgery. These advancements demand sophisticated instruments that maintain effective interaction between the surgeon and patient tissues. Robot assisted surgery improves visualization and dexterity. However it also leads to loss of tactile perception and haptic feedback (Abiri et al., 2019; Okamura, 2009). This sensory limitation creates a disconnect between the surgeon and the operative field. Bioelectronic technologies are addressing this limitation through real time sensory digitization. These systems restore feedback by converting physical tissue responses into interpretable electrical signals. At the same time the rise of personalized medicine has increased demand for wearable and implantable bio microelectromechanical systems. These BioMEMS enable continuous and minimally invasive monitoring of biochemical and electrophysiological parameters (Abhinav et al., 2025). The role of bioelectronics now extends beyond the operating room. Closed loop systems that integrate sensing and therapy are increasingly used in postoperative care. Examples include smart wound dressings and implantable neurostimulators for pain management (Baniya et al., 2024; Zhang et al., 2023). These technologies may reduce the burden of chronic disease and decrease reliance on opioid based analgesics (Finneran Iv & Ilfeld, 2025; Venna et al., 2025). Modern healthcare is progressively adopting data driven models. Understanding the convergence of artificial intelligence robotics and bioelectronics is therefore essential for clinicians and medical educators. This review provides a comprehensive overview of these developments. It traces their progression from fundamental biophysical principles to clinical implementation in microsurgical applications.

2. Core Principles of Bioelectronic Surgical Tools

2.1. Neural Monitoring and Functional Mapping

The primary objective of intraoperative neurophysiological monitoring is the preservation of neural integrity during surgical procedures that place the nervous system at risk. Intraoperative nerve monitoring (IONM) has progressed from basic signal observation to comprehensive and multimodal assessment of the brain brainstem spinal cord and peripheral nerves (Ghatol & Widrich, 2025). Commonly used techniques include somatosensory evoked potentials motor evoked potentials and electromyography. These modalities enable real time detection of neural compromise and allow immediate corrective surgical actions. In supratentorial brain tumor surgery the balance between maximal tumor resection and preservation of eloquent brain function is critical. Recent meta-analysis demonstrate that the combined use of preoperative mapping and intraoperative neurophysiological monitoring improves surgical outcomes. Higher rates of gross total resection and lower rates of permanent focal neurological deficits have been reported. These benefits are most evident in tumors located within highly eloquent brain regions (Baig Mirza et al., 2025).

Functional mapping is essential in glioma surgery. Awake craniotomy allows direct electrical stimulation of cortical and subcortical regions. This approach facilitates identification of speech motor and sensory pathways. It reduces the risk of unexpected postoperative deficits (Saito et al., 2015). Advanced mapping techniques such as navigated transcranial magnetic stimulation have further enhanced surgical planning. nTMS demonstrates accuracy comparable to direct cortical stimulation. It has been shown to influence surgical strategy in a significant proportion of cases (Umana et al., 2021). Large clinical cohort studies confirm the value of IONM in cortical and subcortical mapping. These studies demonstrate that extensive tumor resection can be achieved without permanent neurological deficits. This outcome is highly dependent on the systematic use of bioelectronic monitoring tools during surgery (Staub-Bartelt et al., 2023).

2.2. Electrostimulation-Guided Tissue Identification

Beyond brain functional mapping bioelectronic principles are applied to tissue identification in peripheral surgical procedures. Thyroid surgery carries a significant risk of injury to the recurrent laryngeal nerve. Damage to this nerve can result in vocal fold paralysis and long term voice impairment. Intraoperative neurophysiological monitoring has changed the approach to nerve preservation during thyroid surgery. It enables both anatomical identification and functional assessment of the recurrent laryngeal nerve (Schneider et al., 2020). Techniques such as neurostimulation of laryngeal palpation and intermittent IONM have demonstrated reliable prediction of postoperative nerve function.

Neurostimulation of laryngeal palpation shows high negative predictive value. This makes it a useful alternative when advanced monitoring systems are not available. It provides a safe and practical option for nerve assessment in resource limited settings (Al-Hakami, 2025). Accurate tissue identification is also critical in spinal surgery. The prevention of iatrogenic injury to the spinal cord and nerve roots is a major surgical priority. Bioelectrical impedance analysis has emerged as a promising method for tissue differentiation. This technique distinguishes cortical bone cancellous bone spinal cord and muscle based on electrical properties. Recent studies demonstrate high classification accuracy using machine learning approaches such as support vector machines. These models analyze impedance data in real time and provide immediate feedback at the instrument tip (Chen et al., 2023). This electrostimulation assisted tissue identification improves the safety of pedicle screw placement and decompression procedures. Such bioelectronic guidance reduces reliance on subjective tactile feedback. It enhances surgical precision and consistency across operators. These advances support safer and more standardized spinal surgical workflows.

2.3 Bioelectronic Feedback for Surgical Precision

The transition from conventional surgery to robotic assisted surgery has resulted in the loss of natural tactile sensation. This absence of haptic feedback limits the surgeon's perception of tissue properties during manipulation. Restoring this sensory input has therefore become a critical objective in robotic surgical system design. Haptic feedback systems have been developed to address this limitation. These systems use integrated sensors and actuators to reproduce the sensation of touch (Abiri et al., 2019). Haptic feedback can be classified into kinesthetic feedback which conveys force information and cutaneous feedback which conveys surface texture and pressure. Most commercially available robotic platforms currently lack these capabilities. Experimental studies demonstrate that reintroduction of haptic feedback improves surgical performance. Reduced applied force shorter task completion time and decreased tissue trauma have been consistently reported (Bergholz et al., 2023; Okamura, 2009). These findings highlight the functional importance of tactile information in robotic procedures. Bio inspired control algorithms further enhance haptic perception. Cutaneous afferent population models simulate the firing patterns of human mechanoreceptors. These models improve performance during artificial palpation tasks. Surgeons are able to localize subsurface structures such as tumors and vessels with greater accuracy and reduced force compared to reliance on visual feedback alone (Ouyang et al., 2021). Multimodal feedback systems provide additional advantages. The combination of vibrotactile and pneumatic force feedback enables discrimination of tissue stiffness and consistency. These properties are essential for identifying pathological changes during surgery (Abiri et al., 2019). Together these advances demonstrate the potential of bioelectronic haptic feedback to bridge the sensory gap in robotic surgery. Such systems are expected to enhance surgical precision reduce tissue injury and improve overall procedural safety.

3. Intraoperative Applications of Bioelectronics

3.1. Integration with Robotic Surgical Platforms

The integration of bioelectronics with robotic surgical platforms represents a major step toward autonomous and intelligent surgery. Robotic systems have already transformed minimally invasive surgery. Platforms such as the da Vinci Surgical System provide enhanced dexterity three dimensional visualization and tremor filtration (Pushpan & S P, 2024). Despite these advances current robotic systems remain largely surgeon controlled. The future direction of surgical robotics lies in increasing levels of autonomy. Artificial intelligence and machine learning enable robotic systems to perform specific surgical tasks with graded autonomy. These tasks range from basic functions such as suturing to complex procedures such as soft tissue anastomosis (Rivero-Moreno et al., 2024). Surgical autonomy can be described across defined levels. Teleoperated systems operate without autonomy. Fully autonomous systems perform tasks without direct human control. Most clinical systems currently function at low autonomy levels. They primarily assist surgeons through motion scaling navigation guidance and tremor suppression. Experimental platforms demonstrate higher degrees of autonomy. The Smart Tissue Autonomous Robot has shown effective performance in supervised autonomous surgical tasks (Rivero-Moreno et al., 2024). These systems integrate bioelectronic sensing with artificial intelligence. They can perceive the surgical environment plan procedural steps and execute movements with high precision. In specific tasks autonomous robotic systems have demonstrated accuracy comparable to or exceeding human performance (Schmidgall et al., 2025). Continued development of intelligent surgical robots may reduce variability in surgical outcomes. This approach has the potential to standardize care and reduce dependence on individual surgeon expertise.

3.2. Bioelectronic-Assisted Surgeon Control Interfaces

The interface between the surgeon and the surgical system is evolving due to advances in bioelectronic technologies. Surgical navigation is increasingly supported by augmented reality and mixed reality systems. These technologies overlay digital anatomical information onto the real surgical field. Extended reality improves spatial orientation during surgery. It supports intraoperative decision making. Critical structures such as tumors and vascular networks can be visualized even when they are not directly visible (Murphy & Cahill, 2025). Real time imaging further enhances visual guidance. Fluorescence guided surgery using indocyanine green allows visualization of tissue perfusion and vascular anatomy during procedures. This approach provides dynamic feedback and improves surgical accuracy (Murphy & Cahill, 2025). Bioelectronic interfaces also enhance motor control. Wearable bioelectronic sensors are used to monitor surgeon movement and physiological status. Examples include smart garments and electromyography based monitoring systems. These devices can assess posture workload and fatigue. The collected data can be used to improve ergonomics and reduce operator strain (Libanori, 2022). Brain computer interfaces represent an emerging area of surgeon system interaction. These systems explore direct control of robotic or prosthetic devices using neural signals. BCIs offer a future pathway for intuitive and responsive surgical control (Gao et al., 2025). Together these bioelectronic interfaces promote a cooperative interaction between the surgeon and the surgical platform. This symbiotic relationship combines human expertise with machine precision. It has the potential to significantly enhance surgical performance and safety.

4. Bioelectronics in Minimally Invasive and Robotic Surgery

4.1. Neuromodulation for Pain and Functional Recovery

Minimally invasive and robotic surgeries reduce tissue trauma when compared with open procedures. However postoperative pain and delayed functional recovery remain significant clinical challenges. Bioelectronic neuromodulation offers a non-pharmacological approach for pain management. It serves as a potential alternative to opioid based therapies. Percutaneous auricular nerve stimulation is an emerging neuromodulation technique. This method delivers electrical stimulation to nerves of the external ear. It modulates central pain pathways involved in nociceptive processing (Finneran Iv & Ilfeld, 2025). Clinical studies report reduced postoperative pain scores and decreased opioid consumption. These effects have been observed in procedures such as cesarean section and orthopedic surgery (Finneran Iv & Ilfeld, 2025). Other neuromodulation strategies are also under investigation. Transcutaneous electrical nerve stimulation is widely studied for postoperative pain control. Systematic reviews indicate a significant reduction in opioid requirements following spinal surgery. Transcranial direct current stimulation has shown potential analgesic benefits in selected clinical contexts (Venna et al., 2025). These neuromodulation techniques are non invasive. They exploit mechanisms such as neuroplasticity and the gate control theory of pain. This results in effective analgesia with fewer systemic side effects than conventional medications. Implantable neurostimulation systems are also advancing. Spinal cord stimulators are increasingly designed as closed loop systems. These devices adjust stimulation parameters in real time based on physiological feedback. Such adaptive neuromodulation improves pain control and enhances postoperative recovery outcomes (Lerman et al., 2025).

4.2. Continuous Physiological Monitoring After Surgery

The ability to constantly record physiological parameters after surgery is one of the major benefits of bioelectronic systems. For an example of urology is the implementation of implantable sensors to monitor the bladder activity in real time and capture information about the pressure and volume that can be used to manage neurogenic bladder dysfunction (Kim et al., 2024). These wireless, battery-free systems can have a long duration of operation allowing a peep through the dynamics of physiological changes that are taking place in the process of recovery. Wireless bioelectronic devices have been installed in wound healing context to monitor the wound environment and provide therapeutics. Such products are capable of tracing inflammatory biomarkers, pH, and temperature, and they give early indications of an infection or stagnant recovery (Baniya et al., 2024) (Figure 1 & Table 1). In addition, they are able to proactively intervene because they can administer drugs or electrical shock to stimulate tissue regeneration. As an example, a wearable system that can be stretched and is wireless has been demonstrated to speed the process of healing a chronic wound by multiplexing monitoring with electro-responsive delivery of drugs and electrical stimulation (Shirzaei Sani et al., 2023). These technologies represent the change in passive dressings to the active, bioelectronic wound care solutions.

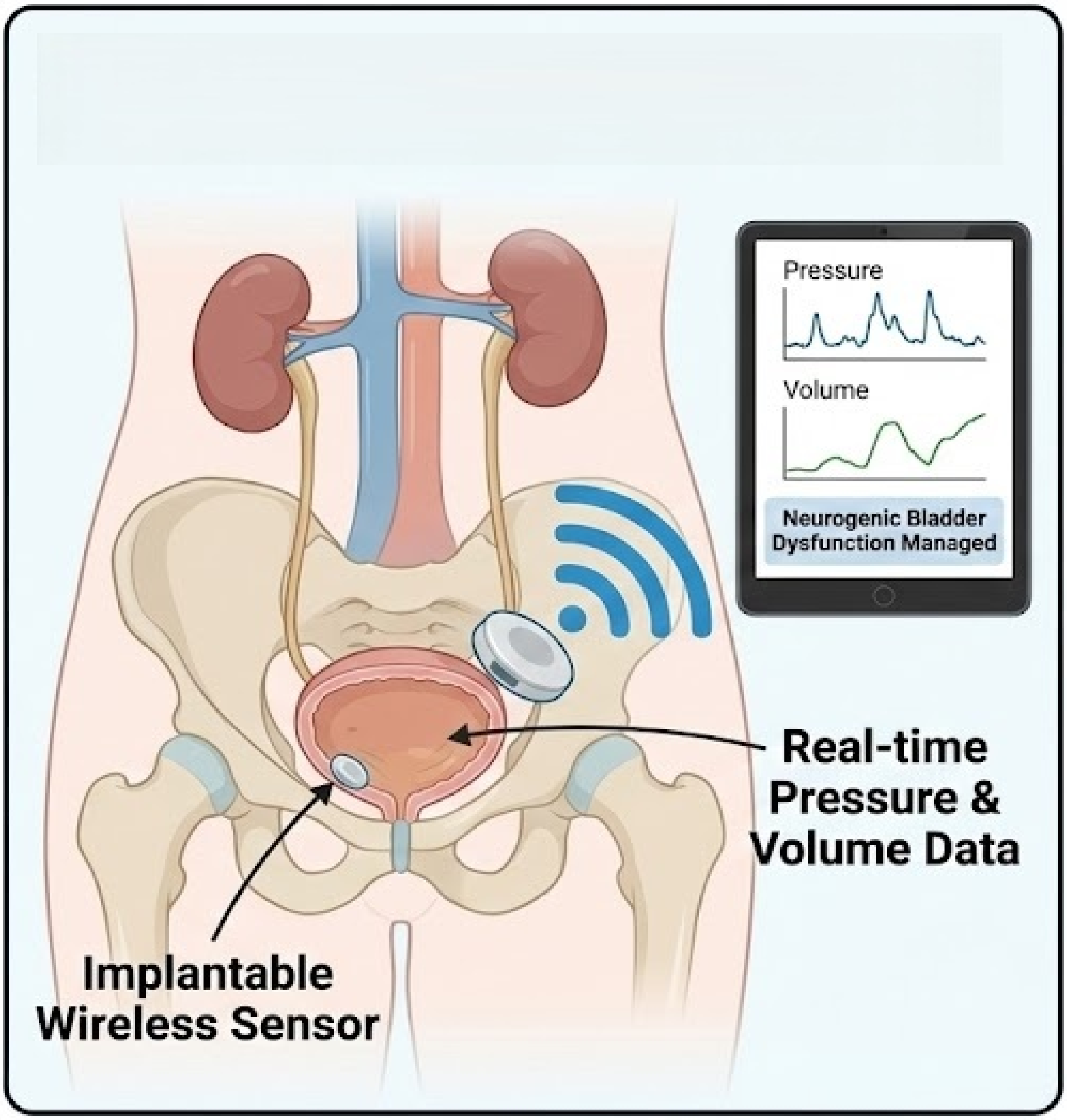

Figure 1: Wireless implantable bioelectronic sensor for continuous urodynamic monitoring and data transmission

Table 1: Comparative Overview of Bioelectronic Surgical Tools

Surgical Application	Bioelectronic Device	Key Function	Impact on Care
Intraoperative Neural Monitoring	Multimodal IONM (MEP, SSEP, EMG) & nTMS	Real-time assessment of neural integrity and preoperative mapping of eloquent motor/language areas	Maximizes tumor resection rates while significantly reducing the risk of permanent neurological deficits (Baig Mirza et al., 2025; Staub-Bartelt et al., 2023).
Robotic Surgery Feedback	Vibrotactile & Pneumatic Actuators	Restores lost haptic sensation by digitizing force and tactile information for the surgeon	Enhances surgical precision, reduces applied force on tissues, and minimizes iatrogenic tissue trauma (Abiri et al., 2019; Ouyang et al., 2021).
Spinal Tissue Identification	Bioelectrical Impedance Probes	Differentiates tissue types like cortical bone, cancellous bone, spinal cord via electrical impedance classification	Improves safety during pedicle screw placement by preventing accidental breach into the spinal cord (Chen et al., 2023).

Postoperative Pain Control	Percutaneous Auricular Nerve Stimulation (PANS)	Modulates central pain pathways via electrical stimulation of auricular cranial nerves	Significantly reduces postoperative opioid consumption and pain scores, mitigating opioid-related side effects (Finneran Iv & Ilfeld, 2025).
Wound Management	Wireless Closed-Loop Smart Bandages	Monitors biomarkers like pH, temperature and autonomously delivers therapeutics or electrical stimulation	Accelerates chronic wound healing, detects infection early, and enables personalized tissue regeneration (Baniya et al., 2024; Shirzaei Sani et al., 2023).
Internal Organ Monitoring	Implantable Soft Bioelectronic Sensors	Continuous, real-time monitoring of organ mechanics like bladder pressure and volume	Provides continuous physiological data to guide management of dysfunction like neurogenic bladder without catheters (Kim et al., 2024).

5. Postoperative Roles of Bioelectronic Technologies

5.1. Patient-Specific Physiological Profiling

Wearable and implantable bioelectronics are allowing the gradual shift of postoperative care to individualized physiological profiling. All these gadgets will gather extremely abundant data on vital signs, biochemical level, and physical activity, which can generate a digital twin of the patient (Trinidad Borràs & Benavent, 2025). BioMEMS sensors have the capability of the detection of certain metabolites, electrolytes, and other biomarkers in sweat, interstitial fluid, or blood, which provides an example of the molecular health picture of the patient (Abhinav et al., 2025) (Figure 2). Such high-resolution data allows surgeons to identify minor variations to the baseline level in the patient, allowing them to intervene in the complication like sepsis or organ failure in its early stages. As an example, real-time heart rate variability (HRV) and other autonomic parameters could be used to determine the emergence of infection or inflammatory processes even before clinical symptoms are manifested to the patient (Lerman et al., 2025). With the help of this data combined with electronic health records (EHRs) and AI analytics, surgeons/physicians will be able to suggest postoperative management strategies based on the specific physiological characteristics of a patient (Huang et al., 2025).

5.2. Adaptive and Closed-Loop Bioelectronic Systems

The highest use of bioelectronic medicine in after surgery care is the closed-loop system, and it is autonomous to detect physiological status and provide therapeutic intervention. These systems involve a combination of sensors, control algorithms and actuators to preserve homeostasis (Zhang et al., 2023). As an example, bio energy based closed-loop systems have the potential to extract power using the body to energize sensors and drug delivery units, and creating self-sustainable medical machines (Zhang et al., 2023). Closed-loop devices can also be used in wound care to track wound conditions and either release antibiotics or growth factors on demand, which optimizes the healing environment (Baniya et al., 2024; Shirzaei Sani et al., 2023). On the same note, in metabolic conditions, closed-loop controls can manage glucose through an automatic increase or decrease in insulin delivery in response to the continuous monitoring of glucose levels (Marquez et al., 2024). These systems work accurately and robustly even in the presence of biological variability through the development of advanced control algorithms, like sliding mode control, machine learning-based controllers, etc. (Marquez et al., 2024). These adaptive regimes are a significant improvement of open-loop treatments, and have the possibility of providing set-and-forget control of complex postoperative diseases.

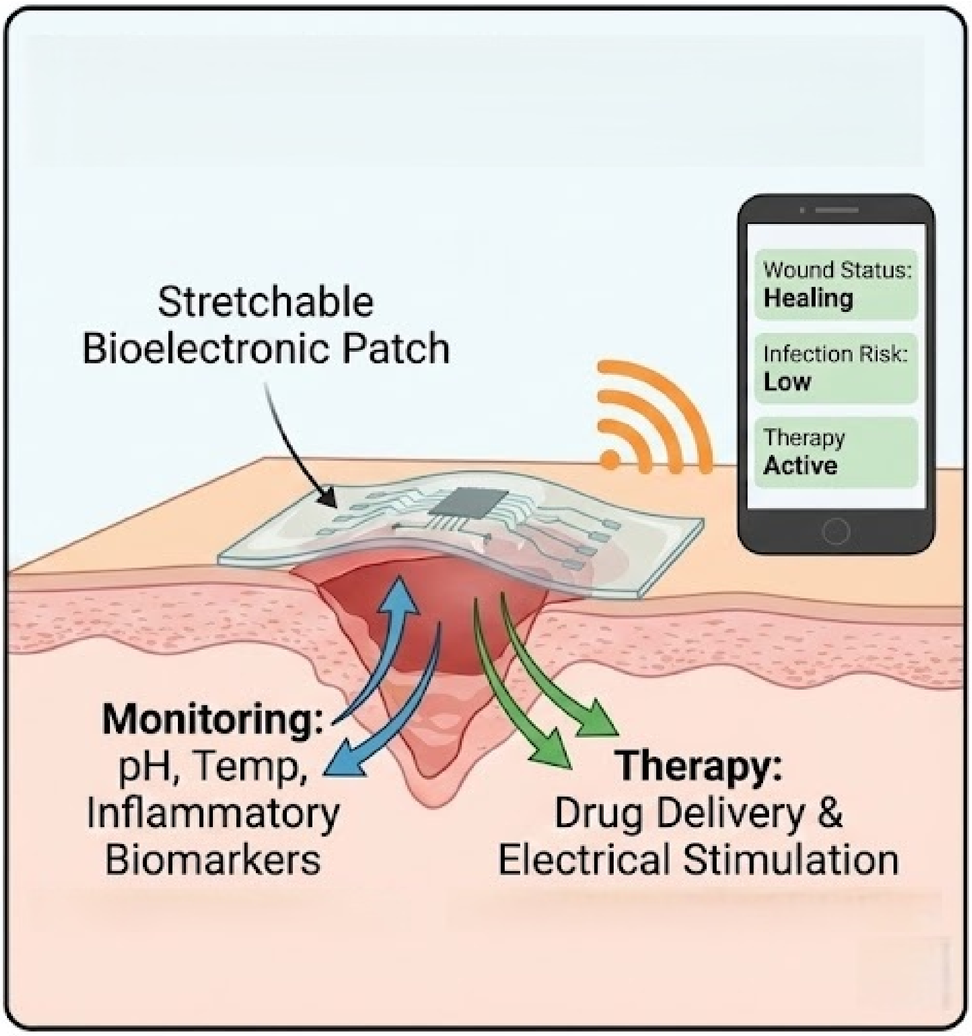

Figure 2: Stretchable wearable bioelectronic patch enabling closed-loop monitoring and therapy for postoperative wound management

6. Bioelectronics in Precision and Personalized Surgery

6.1. Implantable and Wireless Bioelectronic Devices

Precision surgery Advanced implantable bioelectronics provides the capability to interact with the body on a granular frequency, which is required to perform precision surgery. Innovation has recently seen the creation of soft, pliable, and biological neural interfaces which reduce the foreign body response and allow functionality to last (Gao et al., 2025). These implants have the potential to record neural activity at the high-spatial and temporal resolution and provide focused stimulation to either restore or regulate disease conditions (Song & Serdijn, 2025). The wireless power and information transfer is essential to the clinical feasibility of these implants. Deep-tissue implants can be realized through technologies like ultrasonic power transfer and near-field communication, which makes them work without transcutaneous wires and avoids the risk of infection and enhances patient comfort (Libanori, 2022; Zhang et al., 2023). Moreover, bioresorbable electronics mean the devices which can be dissolved in the body once used out of their purpose, is an invention that eliminates the necessity in surgical removal, making it perfect to be used temporarily in monitoring or therapy during the postoperative period (Wang et al., 2024). These are temporary devices that are able to offer essential information at the vulnerable recovery stage before disappear to minimise long term complications.

6.2. AI-Enhanced Bioelectronic Surgical Systems

The capabilities of bioelectronic surgical systems are engineered by artificial intelligence. The bioelectronic sensors create a large amount of high-dimensional data that is processed by AI algorithms to extract actionable insights to the surgeon (Huang et al., 2025). In robotic surgery, AI promotes autonomy by allowing the machine to identify the anatomic structures, plan the route to the surgery, and adjust to the deformations of the tissues during operation (Schmidgall et al., 2025). Moreover, AI is part of the role of closed-loop neuromodulation systems. Neural signals can be decoded by machine learning models to determine pathological conditions, including seizures or flares of chronic pain and activate stimulation to prevent them (Lerman et al., 2025; Levi et al., 2018). Within the precision medicine framework, AI allows combining multimodal patient data, such as genomics, imaging, bioelectronic recording, and phenotyping patients and forecasting their reaction to particular interventions (Ho et al., 2020). This has been bringing AI and bioelectronics together that is creating a future where surgery can no longer be considered a procedural intervention, but a data-driven, precision therapy that is optimized per person.

7. Emerging and Future Bioelectronic Innovations

The future of bioelectronic surgery is in the creation of biohybrid systems, which would simply be a combination of biological elements together with electronic devices. Biohybrid regenerative bioelectronics involve the integration of living cells or tissues and synthetic sensors and actuators to form implants that are able to connect to the host tissue and function again (Carnicer-Lombarte et al., 2025). These machines make use of the regenerative potential of biology and the accuracy of electronics to cure diseases including spinal cord injuries and muscle defects (Hong et al., 2025). Material science is also contributing to advances in innovation. It is possible to make bioelectronics with soft, stretchable, and conductive materials, including hydrogels and liquid metals, which match the mechanical properties of human tissue (Hong et al., 2025). Additionally, wearable and implantable system powering can be sustained using self-powered systems which draw energy through biomechanical motions like triboelectric nanogenerators (Libanori, 2022). With the maturation of these technologies, we will witness a new generation of bioelectronic surgical instruments that will be bio-integrated, autonomous and will have the ability to induce actual tissue regeneration.

8. Conclusion

Bioelectronic surgical and regenerative systems represent a major shift in modern healthcare practice. Care is no longer limited to reactive and episodic intervention. It is becoming proactive continuous and individualized. Neural monitoring electrostimulation and haptic feedback have improved surgical precision and intraoperative safety. Robotic platforms combined with artificial intelligence have expanded the scope of operable procedures. These technologies enable more controlled and accurate surgical execution. Bioelectronic devices are also transforming postoperative care. Continuous physiological monitoring allows early detection of complications. Closed loop therapeutic systems support adaptive recovery and long-term disease management. Advances in materials science wireless communication and artificial intelligence are driving the integration of these technologies. Together they form a unified bioelectronic care ecosystem. Emerging systems include bioresorbable biohybrid and autonomous devices. These technologies enable treatments tailored to individual patient physiology. Translation from laboratory research to clinical practice is rapidly advancing. For nursing professionals and surgical teams this transformation is highly relevant. Understanding and adopting bioelectronic approaches is essential to deliver high quality patient care in contemporary healthcare systems.

Declarations

Ethics approval statement

Not applicable

Consent to participate

Not applicable

Consent to publish

Not applicable

Data Availability Statement

The data are available from the corresponding author upon reasonable request

Competing Interests

The authors declare that they have no conflict of interest

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