Smart Biomaterials in Bioelectronic Sutures: A Review of Conductive Polymers and Sensing Materials

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Abstract:

The advancement of smart biomedical technologies has revolutionized wound care by introducing interactive, data-driven solutions. This review focuses on the development and potential of pH-sensitive bioelectronic sutures, which surpass traditional sutures by offering real-time, drug-free monitoring of wound healing. While conventional sutures provide only mechanical support, these next-generation devices integrate electrochemical pH sensors to assess the wound microenvironment continuously. The review begins with an overview of wound healing and the pivotal role of pH as a biomarker in distinguishing between acute and chronic wounds. Real-time pH tracking enables early infection detection, supports precise treatment decisions, and minimizes reliance on empirical therapies. The review also addresses key challenges, such as ensuring biocompatibility, stability under moist and inflamed conditions, and accurate calibration of sensors. Ethical and regulatory considerations are also examined.

Advancements in materials science-particularly the use of carbon nanomaterials, metal oxides, and conductive polymers-enhance sensor performance. Additionally, techniques in microfabrication and fiber integration allow for the miniaturization of sensors into flexible suture threads. The emergence of battery-free, energy-harvesting systems and wireless communication with mobile health platforms is transforming remote wound monitoring. Artificial intelligence (AI) applications further augment predictive capabilities, especially for high-risk wounds such as diabetic ulcers and surgical sites. pH-sensitive bioelectronic sutures represent a breakthrough in personalized and preventative wound care. Their integration into clinical settings promises to improve healing outcomes by making wound management more intelligent, responsive, and minimally invasive, thereby redefining future standards in healthcare.

Keywords:

Smart biomaterials, Bioelectronic sutures, Conductive polymers, Sensing materials, Biomedical applications

1. Introduction

1.1 Overview of the Wound Healing Process

Wound healing is a highly complex, dynamic biological process that restores the integrity of the skin and underlying tissues after injury. It is a fundamental response of the body to tissue damage, involving a series of well-orchestrated cellular and molecular events. The efficiency of this process is critical to survival and functional recovery. In the pharmaceutical and biomedical context, understanding the wound healing process provides the groundwork for developing innovative therapeutic strategies, including novel interventions such as smart sutures and bio-responsive wound monitoring systems. [1]

1.2 Definition and Types of Wounds

A wound can be defined as a physical injury that results in the disruption of the normal structure and function of the skin. Wounds are broadly categorized into acute and chronic. Acute wounds follow a predictable healing pattern and resolve in a timely manner, whereas chronic wounds fail to proceed through an orderly healing process, often getting stalled in the inflammatory phase. Chronic wounds, including diabetic ulcers, pressure sores, and venous ulcers, are a major health concern globally due to their high prevalence, prolonged treatment time, and economic burden. [2]

1.3 Overview of Wound Healing and the Role of Smart Sutures

1.3.1 Phases of Wound Healing

Wound healing is a dynamic and highly coordinated biological process comprising four overlapping but distinct phases: **hemostasis, inflammation, proliferation, and remodelling**. Each phase is regulated by cytokines, growth factors, immune cells, and extracellular matrix components. Any disruption in this progression can result in delayed or chronic wounds [4].

1.3.1.1 Hemostasis Phase

Immediately after injury, the body initiates hemostasis to prevent blood loss. Platelet activation leads to fibrin clot formation and the release of growth factors such as PDGF and TGF-β, which trigger inflammation and recruit immune cells. Advanced hemostatic materials, including bioactive sutures, now aim to combine wound closure and monitoring functionalities [4].

1.3.1.2 Inflammatory Phase

This phase lasts approximately 2–5 days and is essential for pathogen clearance and wound debridement. Neutrophils and macrophages dominate, releasing cytokines like IL-8, VEGF, and EGF to support healing. Importantly, the wound becomes acidic (pH 5.5–6.5), making pH a valuable biomarker for inflammation and infection detection, and a target for bioelectronic sutures [5].

1.3.1.3 Proliferative Phase

Tissue regeneration occurs via angiogenesis, fibroblast proliferation, and reepithelialization. Fibroblasts lay down collagen and ECM components, while keratinocytes close the wound surface. VEGF plays a key role in capillary formation. Wound pH begins to normalize (approaching 7.4), which can be tracked in real-time by smart sutures [6][7].

1.3.1.4 Remodelling Phase

The final phase, lasting weeks to months, involves collagen type III being replaced by type I and tissue strength restoration. Vascular regression reduces metabolic demand. In chronic wounds or patients with diabetes, this phase may be significantly impaired [8].

1.3.2. Factors Influencing Wound Healing

Multiple intrinsic and extrinsic factors affect wound healing:

- **Patient-related**: Age, nutrition, comorbidities (e.g., diabetes), smoking.
- **Wound-related**: Size, depth, infection, ischemia.
- **Treatment-related**: Dressings, surgical techniques, antiseptics, antibiotics.

A critical but underappreciated factor is **pH**, which affects enzymatic function, bacterial activity, and oxygen release. pH-sensitive smart sutures enable clinicians to assess wound health and intervene early [9].

1.4. Conventional vs. Modern Wound Management

Traditional wound care practices focus on reactive measures such as cleaning, antiseptics, and dressings. While effective, they rely on external observation and lack real-time feedback [10].

Modern strategies incorporate continuous monitoring, personalized care, and smart biomaterials. Innovations such as bioelectronic sutures with integrated pH sensors transform sutures from passive tools to diagnostic devices. These align with the shift toward drug-free, data-guided therapies [11].

1.5. Role of Sutures in Wound Closure

1.5.1 Primary Function of Sutures

Sutures are vital in bringing wound edges together, promoting hemostasis, minimizing infection risk, and facilitating tissue regeneration. They support collagen deposition, epithelial migration, and angiogenesis during healing [12][13].

1.5.2 Types of Sutures

Sutures vary by:

- **Absorbability** (e.g., catgut vs. nylon),
- **Material** (natural vs. synthetic),
- **Structure** (monofilament vs. multifilament),
- **Coating** (antimicrobial or smooth polymers).

These parameters are chosen based on wound type and patient needs [14].

1.5.3 Limitations of Traditional Sutures

Conventional sutures provide no feedback on healing and depend on manual inspection. They are insufficient for:

- Chronic wounds
- Early infection detection
- Remote post-operative care [15]

1.6. The Need for Drug-Free, Bioresponsive Technologies

Chronic and surgical wounds often require prolonged pharmaceutical interventions. However, overuse of antibiotics and antiseptics contributes to **antimicrobial resistance (AMR)**, allergic reactions, and disrupted microbiota [16].

Emerging bioresponsive, drug-free technologies—such as pH-sensitive smart sutures—enable targeted healing support, reduce dependence on drugs, and lower treatment costs. These innovations represent a sustainable solution to global wound care challenges [17].

2. Basics of Bioelectronic Sutures

The integration of electronics into biological materials marks a significant advancement in medical technology. One such innovation is bioelectronic sutures, which combine traditional suture materials with miniaturized electronic components. These sutures are not merely mechanical supports for wound closure—they function as diagnostic tools, offering real-time data on the wound environment, including parameters such as pH, temperature, and moisture. As wound care shifts towards a more data-driven and non-invasive approach, bioelectronic sutures have emerged as a revolutionary concept in both surgical and pharmaceutical practice. [19]

Bioelectronic sutures are advanced medical threads that combine traditional wound-closing functionality with integrated electronic components for real-time wound monitoring. While they physically support tissue approximation like conventional sutures, they also contain embedded biosensors and conductive materials that provide continuous feedback on the wound environment. These sutures are fabricated from biocompatible, flexible polymers such as polylactic acid (PLA), silk fibroin, or polyurethane, into which nanoscale or microscale electronics are integrated. Components may include pH or temperature sensors, signal transmission lines, and energy-harvesting units, often enabling battery-free operation [20].

The core technology relies on electrochemical biosensors, such as ion-sensitive field-effect transistors (ISFETs) or carbon-based electrodes coated with pH-responsive polymers. These sensors detect changes in local pH—a key indicator of wound status—and convert them into electrical signals. These signals are transmitted via conductive threads to external devices like wearable patches for further analysis. Some designs incorporate wireless communication modules, allowing data to be sent directly to smartphones or cloud systems. This feature makes bioelectronic sutures ideal for telemedicine applications, enabling remote wound monitoring and early intervention in cases of infection or delayed healing.

2.1 Advantages over Conventional Sutures

Traditional sutures serve only a mechanical role and provide no insight into the biological conditions at the wound site. Bioelectronic sutures, in contrast, enable: [21]

- Continuous, real-time wound monitoring
- Early detection of infection or abnormal healing
- Reduction in hospital visits through remote tracking
- Drug-free, non-invasive diagnostics

2.3 Evolution from traditional sutures to smart sutures

The art and science of wound closure have evolved significantly over centuries, with sutures playing a central role in surgical and clinical care. From rudimentary threads used in ancient times to today's high-performance smart sutures, the journey reflects the advancement of materials science, biomedical engineering, and clinical innovation. This evolution marks a significant shift not only in wound closure techniques but also in the broader approach to wound healing and post-operative monitoring. [22]

3. Role of pH in Wound Healing

The pH of a wound microenvironment plays a pivotal role in regulating the biological processes involved in tissue repair. It directly influences enzymatic activity, oxygen availability, bacterial colonization, and overall cellular behaviour. As a result, pH serves as a reliable biomarker for assessing the status of wound healing and detecting early signs of infection, making it a key parameter in modern, data-driven wound management. [23]

3.1 Understanding Wound pH Dynamics

Healthy, intact skin typically maintains a slightly acidic pH (around 4.5 to 6.5), often referred to as the "acid mantle." This acidic environment helps inhibit the growth of pathogenic bacteria and supports the skin's barrier function. However, when the skin is injured, the pH of the wound bed changes significantly. In acute wounds, the pH initially rises due to tissue damage and blood exposure but gradually returns to normal as healing progresses. A return to acidic pH is generally associated with favorable healing conditions, as it enhances fibroblast activity, promotes angiogenesis, and supports re-epithelialization. [24]

3.2 pH as a Diagnostic Indicator

Monitoring the pH of the wound bed provides critical insights into:

Infection status: Elevated pH (>7.5) often correlates with bacterial proliferation and the onset of infection.

Healing phase: A shift from alkaline to acidic pH can indicate the transition from the inflammatory phase to the proliferative phase.

Wound chronicity: Persistent alkalinity may indicate stagnation in the healing process and signal the need for intervention.

The ability to detect these pH shifts in real-time enables early diagnosis, improves clinical decision-making, and helps prevent complications before they become severe. [25]

3.3 Importance of pH monitoring in diabetic, chronic, and surgical wounds

The monitoring of wound pH has emerged as a crucial diagnostic tool in the management of various types of wounds, especially diabetic, chronic, and post-surgical wounds. Each of these wound categories presents unique challenges, often involving delayed healing, increased risk of infection, and difficulty in clinical assessment. By tracking pH levels in the wound bed, clinicians can gain real-time insights into the wound's healing trajectory, allowing for more informed, personalized, and timely interventions. [26]

3.3.1 Diabetic Wounds

Diabetic foot ulcers are one of the most common and serious complications of uncontrolled diabetes mellitus, characterized by poor vascularization, neuropathy, and increased susceptibility to infection. These ulcers often become chronic due to impaired immune response and reduced oxygenation. In diabetic wounds, the wound pH tends to remain alkaline, which supports the growth of pathogenic bacteria such as Pseudomonas aeruginosa and Staphylococcus aureus. Elevated pH also enhances the activity of proteases like matrix metalloproteinases (MMPs) that degrade extracellular matrix components, delaying the healing process. Monitoring pH in such wounds allows for early detection of infection, enabling clinicians to intervene before complications such as tissue necrosis or amputation arise. With continuous pH sensing technologies, such as bioelectronic sutures, diabetic wounds can be monitored even outside clinical settings, enhancing patient outcomes and reducing hospitalization. [27]

3.3.2 Chronic Wounds

Chronic wounds—including venous leg ulcers, pressure ulcers, and ischemic wounds—fail to progress through the normal stages of healing and often remain in a prolonged inflammatory state. This stagnation is frequently associated with a persistent alkaline pH (>7.5). Such conditions hinder fibroblast migration, collagen synthesis, and angiogenesis—all vital for tissue regeneration. Additionally, chronic wounds are more prone to biofilm formation, where bacterial communities thrive in an alkaline microenvironment, resist antibiotics, and evade immune surveillance. By integrating pH monitoring into wound care—via sensors embedded in dressings, sutures, or wearable patches—clinicians can detect deviations from the normal healing environment and adjust treatment plans accordingly. This supports a more proactive and less invasive approach, minimizing the need for empirical drug use or surgical intervention. [28]

3.3.3 Surgical Wounds

While surgical wounds are usually acute and heal predictably, post-operative infections or complications can significantly alter their healing path. A sudden increase in wound pH may indicate bacterial colonization, localized inflammation, or the onset of surgical site infection (SSI). Currently, SSI detection relies on visual cues or lab tests that are often delayed. With real-time pH monitoring integrated into sutures or dressings, clinicians can detect and act upon these biochemical changes much earlier. This can be particularly useful in outpatient or home care settings where continuous professional observation isn't feasible. [35]

3.4 Electrochemical pH Sensors: Fundamentals

3.4.1 Principle of Electrochemical Sensing in the Context of Bioelectronic Sutures

In the evolving landscape of wound care, electrochemical pH sensors have become a cornerstone of bioresponsive healing technologies. These sensors are particularly vital in the development of bioelectronic sutures, which aim to monitor the wound microenvironment continuously and in real-time. The fundamental operating principle of these sensors is based on detecting the electrochemical changes associated with variations in hydrogen ion concentration (H^+) at the wound site. Among the various electrochemical sensing techniques, potentiometric and amperometric methods are the most commonly applied for pH sensing in biomedical contexts. [36]

A. Potentiometric Sensors

Potentiometric sensors work on the principle of measuring the electrical potential (voltage) between two electrodes in an electrochemical cell, without drawing any current. The potential difference is directly related to the activity of hydrogen ions (H^+) in the surrounding environment, as described by the Nernst equation. In pH sensing, a reference electrode (e.g., silver/silver chloride) and an ion-sensitive electrode (often coated with pH-sensitive materials like iridium oxide or polyaniline) are used. The hydrogen ions in the wound interact with the sensing electrode, leading to a measurable voltage change that correlates with the local pH level. This method is especially suitable for continuous, low-power applications, making it ideal for implantable or wearable pH-monitoring systems, such as bioelectronic sutures. These sensors are also miniaturizable and biocompatible, aligning with the design requirements for integration into thin suture threads or wound dressings. [37]

B. Amperometric Sensors

Amperometric pH sensors measure the current generated by redox reactions involving hydrogen ions at the electrode surface. In these sensors, a constant voltage is applied, and the resulting current—proportional to the concentration of the target analyte (in this case, H^+ ions)—is measured. While amperometric methods are more commonly used for detecting specific molecules like glucose, lactate, or oxygen, they can also be adapted for pH sensing by using redox-active materials sensitive to pH changes. These sensors generally offer higher sensitivity and can be more suitable for multi-analyte systems, where pH monitoring is just one function among several. However, they tend to be more complex and require higher power, which may limit their integration into passive or battery-free suture systems. [38]

Advantages in Wound Monitoring

- Both potentiometric and amperometric sensors offer several advantages when used in wound monitoring applications:
- Real-time monitoring of healing progress
- Early detection of infections via pH shifts
- Non-invasive and continuous data acquisition
- Compatibility with flexible, biocompatible materials

In the context of bioelectronic sutures, potentiometric sensors are generally preferred due to their low power consumption, simplicity, and ease of integration into flexible suture fibers. These sensors can be embedded directly into the suture thread or coated along its length, allowing for seamless interaction with the wound environment. [39]

3.4.2 Materials used in pH sensors: carbon-based, metal oxides, conductive polymers

The effectiveness of pH sensors—especially in bioelectronic sutures designed for real-time wound monitoring—depends significantly on the choice of sensing materials. These materials must not only be sensitive to changes in hydrogen ion concentration but also be biocompatible, stable, flexible, and integrable with textile-like structures such as sutures or wound dressings. Among the various classes of materials, carbon-based materials, metal oxides, and conductive polymers have shown the most promise for electrochemical pH sensing in biomedical applications. [40]

3.5 Fabrication of pH-Sensitive Bioelectronic Sutures

3.5.1 Suture materials: biodegradable vs. non-biodegradable

The successful fabrication of pH-sensitive bioelectronic sutures depends not only on the integration of sensing technology but also on the selection of suture materials that are biocompatible, durable, and responsive to biological environments. Sutures act as both structural and sensing platforms in smart wound monitoring systems. The choice between biodegradable and non-biodegradable materials plays a crucial role in determining the application, duration, and mode of operation of the bioelectronic suture. [41]

3.5.1.1 Biodegradable Suture Materials

Biodegradable sutures are designed to break down naturally in the body over time through hydrolysis or enzymatic action, eliminating the need for removal. These sutures are commonly used in internal tissues, deep wounds, or surgical sites where long-term monitoring is unnecessary or removal is impractical.

Common Biodegradable Polymers:

- Polyglycolic acid (PGA)
- Polylactic acid (PLA)
- Polydioxanone (PDO)
- Polycaprolactone (PCL)

These materials are known for their biocompatibility, controlled degradation rates, and mechanical strength. For pH-sensitive applications, these polymers can be:

- Coated with a pH-sensitive conductive layer (e.g., polyaniline or iridium oxide)
- Blended with conductive fillers (e.g., carbon nanotubes) to create electroactive suture threads
- Electrospun into microfibers that allow for embedding sensing components within the matrix
- Biodegradable sutures are ideal for temporary monitoring, such as in acute wounds or post-operative healing, where pH feedback is needed for only a short duration.

Advantages:

- Naturally absorbed by the body
- Lower risk of chronic inflammation
- No need for removal procedures
- Compatible with internal organs and tissues

Challenges:

- Limited lifespan for long-term monitoring
- Potential degradation of sensing layers over time
- Integration of electronics must not interfere with degradation
- Non-Biodegradable Suture Materials

Non-biodegradable sutures are permanent unless removed surgically. They are preferred in external wounds, skin closures, or areas requiring extended mechanical support, and are often used when long-term wound monitoring is essential.

Common Non-Biodegradable Materials:

- Nylon (polyamide)
- Polypropylene
- Polyethylene terephthalate (PET)
- Silk (natural fiber, coated for reduced reactivity)

These materials offer excellent mechanical strength, knot security, and dimensional stability, making them suitable carriers for long-duration sensing electronics. They can be:

- Directly functionalized with sensing layers
- Braided with conductive filaments
- Used as substrates for flexible printed sensors

Advantages:

- Stable over long durations
- More suitable for multi-analyte sensor integration
- **Durable in external, moist, or infected environments**

Challenges:

- Risk of chronic inflammation or foreign body response
- Must be manually removed if not needed permanently
- May pose issues with tissue compatibility over time

3.6 Techniques: microfabrication, weaving electronics into fibers

The transformation of conventional sutures into bioelectronic platforms capable of sensing pH or other wound biomarkers requires advanced fabrication techniques that enable the seamless integration of electronics into flexible, thread-like materials. Two of the most prominent techniques used for this purpose are microfabrication and weaving electronics into fibers.

These methods allow for the creation of miniaturized, stretchable, and biocompatible smart sutures that retain their mechanical properties while gaining intelligent functionality. [42]

3.6.1 Microfabrication

Microfabrication involves processes borrowed from the semiconductor and flexible electronics industries to produce microscale sensors and circuits. In the context of smart sutures, these techniques are used to create ultra-thin, flexible, and sensitive electrochemical sensors, which can be embedded onto or within the suture material. [43]

Photolithography: Used to etch microscale patterns onto a substrate, allowing precise design of sensor electrodes.

Sputtering and Vapor Deposition: Thin films of conductive materials like gold, platinum, or iridium oxide can be deposited onto flexible substrates to serve as pH-sensitive elements.

Inkjet Printing and Screen Printing: Printable inks containing carbon nanomaterials or conductive polymers can be patterned directly onto sutures or thin flexible strips that are later integrated into sutures.

Soft Lithography and Microcontact Printing: Used for patterning soft, stretchable materials such as PDMS (polydimethylsiloxane) with embedded conductive networks.

Microfabrication techniques enable the development of ultra-miniaturized sensors that can be combined with flexible, biocompatible polymers, making them highly suitable for implantable or wound-contacting applications like bioelectronic sutures.

5.2.2 Weaving Electronics into Fibers

Another promising method for fabricating bioelectronic sutures is the weaving or embedding of electronics directly into the fiber structure of the suture itself. This approach is inspired by the field of smart textiles and allows for the construction of sutures that are both structurally strong and electronically functional. [44]

Twisting or Braiding Conductive Filaments: Ultra-fine wires or conductive polymer threads (e.g., silver nanowires, graphene fibers) are braided or twisted with traditional suture materials like nylon or polyglycolic acid. This ensures flexibility and durability while embedding the sensing elements within the suture body.

Coaxial Fiber Design: A central core (typically a conductive material) is surrounded by insulating and protective layers, forming a multilayer fiber that behaves like a smart suture.

Electrospinning: This technique produces nanofiber mats or threads embedded with conductive nanoparticles or sensing molecules, which can be spun into suture threads with both mechanical and electrical properties.

6. Applications in Wound Monitoring

6.1 Real-time pH tracking in acute vs. chronic wounds

In the evolving landscape of wound care, real-time pH tracking through smart, bioelectronic sutures is emerging as a transformative approach to non-invasive and personalized monitoring. The ability to detect subtle biochemical changes—particularly pH shifts—within the wound microenvironment offers clinicians a powerful diagnostic tool to evaluate healing progress, detect early signs of infection, and tailor interventions. The significance of pH tracking becomes even more apparent when comparing the physiological behaviour of acute versus chronic wounds, both of which follow distinct healing trajectories but benefit greatly from continuous monitoring. [45]

Acute wounds, such as those resulting from surgical incisions, minor injuries, or trauma, typically follow a predictable healing process characterized by rapid progression through the inflammatory, proliferative, and remodelling phases. In these wounds, pH levels initially rise due to exposure to blood and inflammatory mediators, often reaching slightly alkaline or neutral values in the early phase. However, as healing advances, the wound environment gradually becomes more acidic, typically stabilizing between pH 5.5 to 6.5, which is ideal for cell proliferation, angiogenesis, and collagen synthesis. Real-time pH monitoring in acute wounds can serve as a confirmation that healing is proceeding normally. Any sustained deviation from this pattern—such as persistent alkalinity or sudden pH spikes—can signal complications like infection or delayed healing, prompting timely medical attention. In the context of post-operative care, especially for patients recovering at home, bioelectronic sutures with pH sensing capabilities allow for continuous monitoring without the need for repeated clinical visits, reducing healthcare burden while enhancing patient safety. [46]

7. Recent Developments and Future Perspectives

The evolution of wound care is undergoing a revolutionary transformation with the advent of pH-sensitive bioelectronic sutures, which offer not only physical wound closure but also dynamic monitoring capabilities. These advanced systems mark a significant leap from passive dressings and traditional sutures to interactive, diagnostic tools capable of real-time monitoring and early warning of complications such as infection or delayed healing. Recent progress in microfabrication, flexible electronics, and biosensor integration has enabled the creation of sutures that are responsive to biochemical signals like pH, a key indicator of wound status. [47]

Among the most promising developments is the seamless integration of bioelectronic sutures with mobile health (mHealth) systems. These technologies allow wound data—such as pH fluctuations or temperature changes—to be transmitted wirelessly to smartphones or clinical dashboards. Such integration empowers both clinicians and patients to monitor wound status remotely, reducing hospital visits and enabling faster response to infection or inflammation. Mobile health connectivity also allows data to be stored, tracked, and visualized over time, supporting longitudinal assessment and personalized healing pathways. [48]

In parallel, the use of artificial intelligence (AI) is emerging as a transformative tool in wound care. By analyzing large datasets generated from sensor readings, AI algorithms can predict wound healing outcomes, detect anomalies, and recommend interventions. Machine learning models trained on patterns of pH variation and wound profiles are particularly effective in forecasting infection risk or identifying stalled healing, especially in patients with chronic wounds such as diabetic ulcers. This predictive capacity opens the door to proactive care, enabling early decisions that may prevent severe complications.

8. Conclusion

The advancement of wound care technologies has reached a pivotal point, transitioning from passive healing aids to active, intelligent systems that support real-time diagnostics and personalized intervention. This review comprehensively explored the evolving landscape of pH-sensitive bioelectronic sutures, emphasizing their significance as both structural and sensing platforms in modern wound management.

The foundation of this innovation lies in a deep understanding of the wound healing process, where pH plays a crucial role as a biochemical marker. By continuously monitoring pH fluctuations, bioelectronic sutures offer a unique, non-invasive method to track healing progression, detect infections early, and inform treatment decisions—without relying on pharmacological agents. This capability is particularly vital in managing complex wound types such as diabetic foot ulcers, chronic non-healing wounds, and post-surgical incisions, where timely detection of abnormalities can prevent complications and improve clinical outcomes.

Key elements in the development of such systems include the selection of appropriate suture materials (biodegradable vs. non-biodegradable), miniaturization of electrochemical sensors, and their seamless integration into flexible threads. The review outlined various sensing principles—especially potentiometric mechanisms—and the use of advanced materials like carbon nanomaterials, metal oxides, and conductive polymers that contribute to the sensors' responsiveness and stability.

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