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ADVANCEMENTS IN SMART WEARABLE PATCH SYSTEMS FOR ENHANCED WOUND HEALING

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ABSTRACT
Background: Chronic wounds afflict around 2% of the world's population and cost billions of dollars each year in medical costs. By some estimates, over 13 million people worldwide suffer from chronic wounds yearly. The absence of continuous surveillance in conventional dressings for wounds causes prolongation in the treatment and raises the danger of infection. Timely and practical assessment of wounds is key to reducing infection and healing wounds. This is possible by smart dressings with sensors continuously providing input while monitoring important wound variables involving pH, temperature, and moisture. Considering current and upcoming advancements, this paper examines how intelligent patches could transform healing. **Methodology:** The latest advances in the development, usage of intelligent patches, and their development by different researchers are highlighted in this review. It looks at how sensors are incorporated into these patches and provides an overview of developing intelligent wound dressings by integrating one or more sensors triggered by endogenous and exogenous stimuli. **Results and Discussion:** The fabrication and effectiveness of intelligent dressings have advanced significantly, but there are still issues with sensor precision and resilience, especially regarding the requirement for strict regulations. The discussion also explores the critical need to address legal and technological constraints to enhance the usefulness of such wearable gadgets in medical settings. **Conclusion:** Intelligent patches, a fascinating new development in wound care, enable customized therapy with continuous surveillance. Future studies should address real-world challenges to fully realize their potential to refine wound recovery outcomes in medical care.

INTRODUCTION

Chronic wounds affect about 2% of the global population, resulting in billion-dollar annual medical expenses [1,2]. According to estimates, over 13 million people globally get persistent injuries every year, and as the general population ages, the proportion of individuals with these conditions keeps rising. Indian epidemiological information shows that the prevalence of persistent wounds was 4.5 per 1000 people, while the prevalence of acute wounds was 10.5 per 1000 people [3]. About 6.7 million individuals throughout the US suffer from ulcers caused by diabetes, venous ulcerations, as well as surgical injuries that don't heal, making them an economic strain and adding to the

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system's annual cost of almost $25 billion [4]. The healthcare costs associated with wound management and therapies range from $28.1 billion to $96.8 billion, primarily due to the increasing elderly population and the rising rates of weight gain and diabetes. With a compound annual growth rate (CAGR) of 6.6% through the analysis time frame 2020 2027, the worldwide improved wound management sector is expected to exceed $18.7 billion by 2027 [5]. It is far more difficult to treat persistent wounds compared to ordinary ones. Figure 1 illustrates many sorts of wounds.

The history and tradition of wound treatment go back thousands of years, including prehistoric cultures using natural organic products like honey from bees, animal fats, and herbal remedies to harness their disinfecting and wound-healing abilities [6]. Such natural medications, which were available and inexpensive, were used as the main form of therapy and demonstrated some efficacy in small wound care. Joseph Lister introduced antibacterial procedures in the 19th century, marking a watershed moment in wound care. Noticing the elevated infection rate in post-operative people, Lister developed sterility processes that considerably decreased infection, permitting wounds to recover more easily. His revolutionary work changed the medical procedures by emphasizing the importance of a clean setting in wound treatment. Lister's discoveries lay the groundwork for subsequent wound therapy developments and the beginning of contemporary wound management [7].

In the second half of the 20th century, there was an accelerated advancement in wound care, with the introduction of specialised wound treatments that include foams, alginate, and hydrocolloid dressings. Unlike previous dressings, these sophisticated substances covered the wound and generated a wet healing milieu necessary for cells to function, collagen synthesis, and tissue repair [8]. Traditional dressings enclose wounds, collect drainage, and shield the topmost layer of the lesion against harm and germs [9]. Their simplicity hinders the extensive and ease of use of conventional dressing systems in production, but their lack of real-time wound surveillance hinders infection identification. Medication resistance and new tissue injuries might result from inappropriate medication release during dressing replacement [10]. Yet, in the absence of controlled, sterile circumstances, these old procedures frequently failed against infection and may have resulted in protracted healing, highlighting the limits of prior wound management approaches. Hence, wound patches are developed nowadays, leading to a revolution in wound healing. Despite traditional coverings, these novel patches contain biosensors that can measure various factors at the area of injury, including pH, temperature, moisture, and oxygen levels. These patches go a step further by adding medicine delivery devices that precisely release antibacterial or anti-inflammatory drugs to the lesion, depending on actual time data from sensors. A few intelligent patches additionally offer wireless networking, allowing data to be transferred to medical personnel remotely and facilitating proactive therapy modifications with no regular doctor's appointments [11]. Figure 1 illustrates many sorts of wounds.

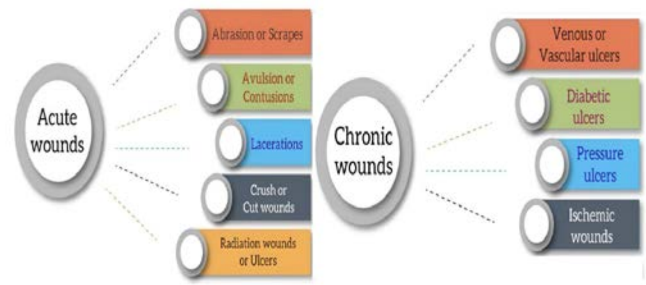

Figure 1: Wound Classification: Acute vs. Chronic

People highly regard wearable patches for their versatility, uninterrupted monitoring, non-invasiveness, sustainability, sensibility, and longevity. Intelligent wearable patches hold considerable promise for managing wounds in future generations as healthcare increasingly depends on massive data and customized therapies. These automated patches allow for constant recovery through continual release of medications, and sensitive sensors identify different wound indicators [12]. Cloud computing, machine learning, and artificial intelligence developments have made it possible to identify errors and transform unstructured data from sensors into therapeutically beneficial data. Figure 2 [13] depicts that one can combine wearable sensors and wireless connections to provide real-time medical diagnosis and services for personalized health care solutions.

Basic concept of smart wearable patch systems

Smart transdermal drug delivery (TDD) platforms provide better use of medications, safeguard against hepatic and intestinal enzyme deterioration, and simplify self-administration compared to oral and intravenous approaches. These also lessen discomfort and complications associated with injections [14-17]. For smooth data transfer and delivery of medicine, smart wearable patch platforms frequently involve backing resources, adhesives, sensors, actuators, generators, and energy-harvesting techniques [18]. One can deliver drugs in a controlled manner by adding medications to substrates or embedding them in water-based gels, microneedles, or nanoparticles. External triggers like electricity, heat, ultraviolet (UV), near-infrared, and environmental factors like pH or enzymes can initiate or enhance medication release. Wireless networks enable specific and widespread absorption through the skin, transmitting sensor information in real-time to gadgets like computers or mobile devices [19].

Figure 2: Smart technology for personalized healthcare solutions

Drug delivery systems (DDSs), coupled to actuators and sensors, respond to stimuli, enabling customized, real-time health care. Malleable polymers, such as polydimethylsiloxane, form the foundation for intelligent wearable patches, while thin-film and miniaturized processes produce essential components like sensors, electrodes, and controllers [20]. Wearable patches that are biocompatible allow for prolonged, periodic use despite irritating the skin or triggering adverse or immunological reactions [21]. Smart wearable patch techniques deliver enhanced advancements compared to marketable healthcare patch mechanisms since they are flawless, thin, breathable, and adaptable. With an emphasis on various stimuli-responsive processes, the research findings shown in Table 1 demonstrate substantial progress in the fabrication of intelligent wound patches. This table presents how Several modern wound healing solutions, like Polymer hydrogels, paper-based patches, bio-electronic systems, transdermal patches, Microneedle dressings, smart bandages, and flexible electronics, have been developed, using different biomarkers such as pH, temperature, redox, electrical, and hydration. Comparing each of their performances in terms of sensitivity, accuracy, cost, and integration with controlled drug administration functions is also included in the table.

Wound healing process

Healing status monitoring

Numerous factors, such as humidity, temperature, pH level, glucose, and infection, influence wound healing. One can monitor the wound healing process by monitoring changes in the pH and glucose levels. Sensor-enabled smart dressings monitor these variables, and stimuli-responsive nanoparticles hold significant potential as cutting-edge wound treatment technologies [34]. These are depicted in Figure 3. Nanoparticles that respond to stimuli derived from bacterial debris have rendered autonomous adaptation of antibacterial techniques with feasible individualized therapy [35].

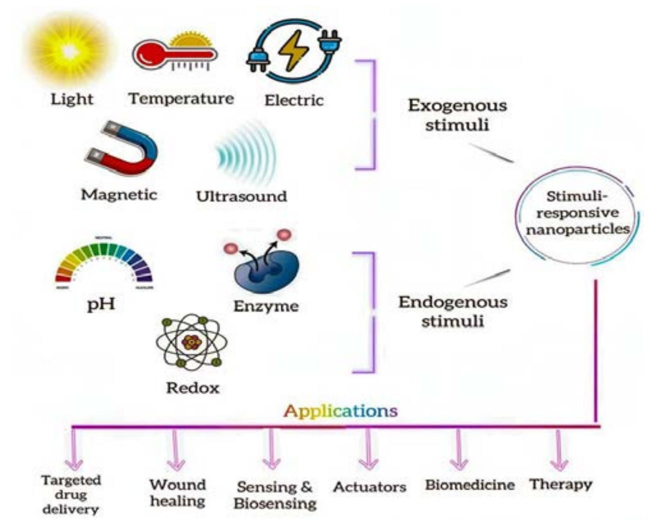

Figure 3: Exogenous and endogenous stimuli used in biosensing and therapeutic applications

On-demand drug delivery

Dynamic mechanisms in smart bandages adapt to modifications in the wound to provide drugs in a regulated manner, either by active or passive delivery. Dynamic drug delivery methods include ionizing radiation, temperature controllers, and pump-based devices. However, advances in wearable electronics and nano-fabrication make monitoring possible while on the go.

Automated wound dressings

Advances in flexible electronics enable multifunctional health gadgets that feature drug release and sensing. These days, automatic wound dressings check pH, look for infections, and release medicine when required. Subsequent bandages should detect accurate biomarkers and administer various medications for increased effectiveness. Zeng et al. [36] studied XKP, a new hydrogel nanocomposite material. The XKP hydrogel, which was made by mixing polydopamine nanoparticles with a food gum matrix, helped wounds heal by reducing swelling and increasing blood vessel renewal in animal tests. This suggests it could be used as a better wound dressing in hospitals.

Wireless connectivity of smart bandage

Smart bandages use wireless connectivity to provide precise information for tracking serious injuries throughout healthcare facilities and everyday life. They also improve the accessibility and efficacy of wound-monitoring patches by helping healthcare providers diagnose wound problems more accurately and manage patients promptly [2].

Smart bandage

A battery-free smart wound dressing consists of an adaptable circuit board, a conducting electrode, barely discernible layers, an analog-to-digital converter, a digital-to-analog converter, a microcontroller, a near-field communication chip & conductive wire. The electrode array collects wound secretions through conductive areas connected to the circuit board. Zeng et al. [37] examined a recently created double-layered wound closure that combines an ionic conducting elastomer (ICE) and a debonding on-demand polymeric adhesive (DDPTA).

ssBy providing temperature-triggered adherence with effortless discharge, the DDPTA prevents haemorrhage and infiltration while adapting to both the skin as well as the lesion to ensure accurate measurements [38] The one-time use patch has a sensor panel that can find markers in lesion discharge, two electrodes that let medication work while also stimulating the skin with electricity, and an electrically charged hydrogel that has anti-allergic and antibacterial peptides in it. We construct it on a thermoplastic elastomer basis, enabling it to expand and bounce after distortion. The bandage firmly adheres to the wound, allowing the animals to roam freely while wirelessly gathering information from sensors through an adaptable electronic circuit board to enable controlled stimulation by electricity and drug delivery [30]. The size and physical attributes of nanomaterials play a crucial role in enhancing wound recovery, as their small size and excellent surface area-to-volume ratio facilitate efficient penetration into wound regions, thereby enabling targeted delivery of medications. Spheres, rods, and fibers are some shapes that can mimic the structure of natural tissues. They can also change how cells attach, move, and line up [39]. Table 1 [22-35] displays multiple intelligent patches developed by different researchers to promote wound healing.

Early Development of Medical Sensors and Wearables

The invention of the Holter monitor by Norman Holter in the 1960s represented one of the first initiatives in the area. The sector of implantable and portable medical equipment has grown significantly in the 1980s and 1990s, partly due to advancements made in pacemaker technology. Further advancements in these years have introduced simplified sensors and ubiquitous healthcare devices, such as glucose monitoring for diabetes management, and the early movement of sensors to evaluate activity levels in hospital settings. Those early gadgets, which mainly gave doctors access to fundamental health data like pH, glucose, and lactate level tracking, set the stage for more sophisticated devices available today. Introduced in the early 2000s, these gadgets allowed for the early identification of arrhythmias in extremely dangerous individuals and remote surveillance of cardiac function [40-43]. In 2000, researchers created portable smart sensors, such as intelligent spirometers, to detect lung function. These sensors allowed for the remote monitoring of individuals with asthma and chronic obstructive pulmonary disease (COPD). Furthermore, intelligent textiles with built-in sensors enabled continuous tracking of respiration rates and temperature levels, significantly aiding in post-surgery healing [44].

Dressings with integrated sensors

Most modern wound dressings primarily aim to protect the injured area from harm. Sensors within the wound milieu can provide significant information that helps expedite the decision-making process for the wound's recovery. It may also reduce the frequency of changing the bandages at the injury site.

Types of sensors in drug delivery system

pH sensors

Researchers have designed various types of pH sensors for use in wound treatment. For instance, researchers have previously constructed numerous electrochemical pH sensors that can continuously track the wound region. Electrochemical pH sensors often use metallic oxide [45], ion-selective electrodes [46], ion-selective field-induced transistors [47], conducting polymeric pH sensors [48,49], and potentiometric evaluation. One can use potentiometric data to construct various wound dressings with integrated sensors, and build these kinds of sensors on extensible and flexible substrates. One type of pH sensor that is useful for creating bandages is the colorimetric sensor, which can determine the pH of the wounds through the analysis of mobile images. Developing a hydrogel patch incorporating pH-responsive pigments to address the issue of illumination and resolution errors is based on picture data analysis using an integrated photodiode that can instantly interface with cellphones to measure pH readings. The problems in incorporating projected systems utilizing computerized images have driven research on using colours with visible alterations to the naked eye. For instance, a coloring substance has been designed to be applied to injury bandages to forecast the pH value of wounds. Once the colorant is exposed to ultraviolet (UV) radiation, it changes to different shades [50].

Temperature sensors

Suitable colorimetric, electrochemical, and temperature sensors are more common in biological areas, like pH sensors [51]. Small, metallic, robust temperature sensors are likely the most common, versatile temperature sensors. A special bandage is created using microfabricated temperature sensor networks that measure the outermost temperature of dermatological lesions [52]. Because power lines are malleable and constructed on a bendable substrate, they can form a cohesive adhesion to the skin layer. The integrated system can illustrate fluctuations in temperature in the wound area [53]. Furthermore, to minimize the cost of production, these sensors are created using conductive inks. Researchers have designed octopus-mimicking coverings as a base to securely fasten sensors to skin, enabling the production of printable carbon-containing sensors [54]. Materials that utilize tiny carbon nanotubes in sensor production have made it feasible to create low-cost, high-sensitivity sensors.

Oxygen sensors

As oxygen sensors stimulate the growth of new cells and the synthesis of collagen, vascular development, and immunological reactions, they are essential for the healing of wounds. Oxygen scarcity, or hypoxia, may slow down these recovery procedures within chronic wounds, causing tissue degradation and protracted repair [55]. Improved wound management techniques are incorporating electrochemical oxygen sensors into malleable, cordless intelligent dressings to address this issue.

Acute hypoxia in persistent wounds may hinder healing and result in unnecessary tissue damage. Therefore, monitoring oxygen levels in tissues provides valuable insights into healing. A study resulted in the invention of an adjustable, cordless bright patch with a unique oxygen sensor constructed from easily accessible electronic elements, enabling real-time tracking of the wound's condition [56]. One can construct the oxygen sensor using an electrochemical galvanic power source on a flexible parylene-C base; it can be electroplated by using both anode and cathode of the framework with zinc and silver electrodes, respectively, and for evaluation, an actual wound examination arrangement is preferred. This approach enables remote monitoring of the oxygen content within the injury area by allowing continuous portable transmission of information to medical devices. Whenever the amount of oxygen falls below critical levels, such developments can offer immediate findings into wound repair, allowing personalized therapy with fast action.

Moisture sensors

Moisture sensors are becoming more vital in injury treatment, particularly regarding patch changing efficiency. A massive trial used moisture sensors to continuously identify the moisture content beneath the coverings. Study results show that over 40 percent of the dressing alterations occurred earlier than expected, indicating redundancy in contemporary healthcare processes. When the humidity levels show differences, these sensors detect moisture by calculating the variations in voltages. This provides real and continuous inputs based on the humidity at the site of damage, enabling the avoidance of unnecessary patch changes that can hinder proper healing. Using advanced technology, healthcare professionals can personalize dressing regimens to match the individual needs of each wound, resulting in improved patient outcomes. Real-time moisture sensors can increase the healing process while reducing patient suffering, transforming wound therapy [57].

Mechanical and electrical sensors

Skin ailments and conditions affect the electrical and mechanical characteristics of skin. Furthermore, investigators observed that activating a wound using mechanical and electrical impulses not only promotes mending but also hinders infection. Mechanical and electrical sensors play a crucial role in treating wounds by recording changes in tissue rigidity with electric resistance, critical indicators of the wounded condition, including water retention. These sensors, which use both mechanical and electrical stimulation, can expedite movements of cells, increase blood flow, and promote tissue development that helps in recovery. Thereby, sensors that measure resistance and stiffness underneath the skin's layer or the injury location might offer valuable information about the tissue's status [58]. pH sensors based on ion-selective electrodes can provide information about the recovery process. However, calibration is required. While biosensors that include uric acid, hydrogen peroxide, and bacteria are considerably more complex and might not be as durable, these are extremely specific for what they detect and provide prompt infection identification and inflammation surveillance. The key information and the trade-offs between ease of use, specificity, and lifespan determine the optimal sensors. Current advancements concentrate on incorporating various sensor functionalities into pliable devices, facilitating thorough evaluations while guaranteeing sturdiness and ease for extended usage [59]. Figure 4 shows how well wearable sensors can find wound biomarkers by considering various substances and sensing methods, such as pH, bacteria, hydrogen peroxide, and uric acid [60-68,20].

Calibration of Integrated Sensors

The calibration of the sensor, which maintains both its efficacy and accuracy, is crucial for identifying changes in wound biomarkers that trigger a regulated release of medication via the nanoparticles. One can employ pH sensors with standard buffer solutions with standardized values, such as 4.0, 7.0, and 10.0, and prepare glucose solutions with different concentrations (0.1–10 mM) to test enzyme-based glucose sensors and determine a trustworthy detection range [25,69].

Testing and Evaluation of smart sensors and patches

In Vitro Testing

Agar diffusion assays, which assess the antibacterial efficacy of these intelligent patches against common wound infections such as *Staphylococcus aureus and Escherichia coli*, are among the *in vitro* models utilized to gauge their effectiveness. Franz diffusion cells are generally used to study the release kinetics of medicinal drugs from the patches, allowing for the measurement of the rate and extent of medication release over time [70,71]. Such in *vitro* studies offer important insights into the functional efficiency of intelligent wound patches, directing future development. For example, the agar diffusion approach is potentially improved by including dynamic conditions that resemble real wound environments, especially the occurrence of wound discharge or mimicked sweat, which may alter antibacterial activity. Furthermore, Franz diffusion experiments are frequently supplemented with mathematical modeling approaches like Higuchi or Korsmeyer-Peppas models to anticipate medication release patterns and enhance the manufacturing settings [72].

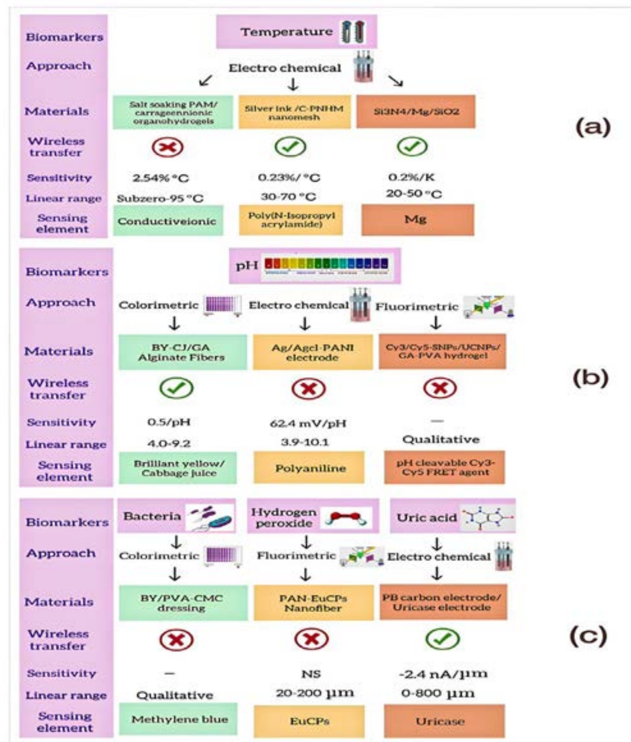

Figure 4: Comparing the performance of wearable sensors for detecting wound biomarkers, considering various materials and sensing methods. (a) Temperature (b) pH (c) Bacteria, Hydrogen peroxide, Uric acid

Gholipour-Kanani et al. conducted an investigation in which they produced entirely novel membranes that were both absorptive and antibacterial and assessed their antibacterial effectiveness against Escherichia coli and Staphylococcus aureus. The agar diffusion method validated the excellent antibacterial activity of the membranes towards various common wound infections [73]. A work published in Polymers described the development and evaluation of polymeric cross-linked hydrogel transdermal patches in depth. Franz diffusion cells were used to examine the drug release kinetics, which shed light on the drug's penetration and release characteristics from the hydrogel patches [74]. New developments have also investigated multifunctional wound patches, in which an exterior barrier maintains moisture retention and an inner bioactive layer assures prolonged drug diffusion, as proven by Franz diffusion studies. Combining these techniques provides excellent bacterial suppression and helps achieve regulated medication release, rendering these patches highly desirable for use in clinical settings [75].

Real-Time Monitoring

Evaluating the effectiveness of the implanted sensors by tracking both the pH and temperature fluctuations in modeled wound settings over time and correlating the results with patches without sensors. Including a network of wireless connections enables instantaneous data transfer to an attached device, giving medical professionals the most recent information on the wound’s condition [76]. Tang et al.'s thorough study covers the latest developments in wearable sensors for ongoing wound temperature and pH monitoring. These sensors provide real-time information on wound conditions and can be incorporated into wound dressings. Numerous sensing mechanisms are highlighted in the paper, and the significance of these technologies in enhancing clinical results is emphasized [77]. A cutting-edge wound dressing with real-time pH monitoring is presented in a paper published in ACS Sensors. A pH sensor built into the dressing gives constant information on the wound environment, essential for gauging the healing rate and spotting possible infections. With real-time data, this technology provides a viable method for remote wound care, enabling medical practitioners to make well-informed judgments [78]. Additionally, the usefulness of continuous surveillance systems is increased by combining cloud-based storage with AI-powered data analytics. These technologies can reduce hospitalizations and enable remote patient monitoring by analyzing user-specific sensor information to detect healing tendencies and recommend tailored treatment plans. A major step toward entirely self-sufficient wound care is represented by this mix of wireless connectivity, sophisticated sensing & AI-driven analytics, which enhances patient quality of life and clinical outcomes [79].

In Vivo Studies

After an effective in vitro trial, it is essential to evaluate the patches in vivo in animal specimens to determine their biological compatibility, remodeling efficiency, and intelligent sensor functionality. This involves combining the assessments of wound contraction and rejuvenation processes with a histological study of wound tissues to evaluate the healing process. An important component of *in vivo* research is how these patches affect the cellular response. The extent to which the patches encourage cellular migration, angiogenesis, and collagen deposition, which are crucial for closing wounds and tissue regeneration, is frequently shown by histological investigation. For example, a study conducted on a mouse model showed that patches containing growth factor-loaded nanoparticles improved tissue remodeling and sped up wound closure, resulting in notable enhancements in collagen and elastin fibers in the dermis [80]. In addition, the patch's effectiveness for therapeutic applications depends on its long-term stability in vivo. When assessing the patches in animal models, consider whether they retain their underlying structure and functionality during healing and the possibility of degradation over time, particularly for biodegradable patches. To ensure the patch doesn't have adverse side effects after extended use, *in vivo* tests also assist in identifying potential problems with skin irritation, allergic reactions, or inflammatory responses [81]. For instance, to speed up the healing process, researchers created a water-powered, electronics-free dressing (WPED) that can electrically stimulate wounds. This inexpensive bandage, which costs about $1 per dressing, presents a viable option for people with chronic wounds, especially those with diabetes [82]. The evaluations of these patches *in vivo* also offer crucial information on their capacity to promote tissue regeneration [83]. Such thorough in vivo investigations are essential for bridging the gap between lab testing and human clinical trials by offering crucial information on the viability and safety of these cutting-edge wound care devices.

Wearable sensor applications in human body systems

Dermatological conditions can damage numerous skin layers, impeding the skin's essential functions. These problems can be divided into inflammatory skin diseases, wound healing issues, and epidermal malignancies. Direct observation is a prejudiced method of evaluating skin diseases and offers inadequate information about the affected skin layers. Therefore, identifying and monitoring wounds and dermatological conditions require precise and quantitative approaches. Figure 5 and Table 2 [84-104] demonstrate the application of wearable sensor devices in human body systems.

Figure 5: Diverse applications of wearable sensors in healthcare monitoring and diagnosis

Challenges and perspectives of wearable sensors

Research on intelligent wound patches has numerous challenges. On the one hand, complex fabrication, a difficult incorporation procedure, and substantial manufacturing costs are among the primary alleged barriers to intelligent wound patches. There is increasing consumer interest in portable sensors that satisfy clinical requirements. Wearable sensors perform better than traditional medical instruments [105]. They can help in immediate diagnosis, patient therapy modifications, and wellness monitoring. In addition, the rising acceptance of the Internet of Things (IoT) and 5G technology allows for quicker data transmission with greater device densities, making it advantageous for wearable applications involving sensors. Wearable sensor incorporation into daily activities and healthcare practices serves as a challenge. Prospective wearable sensors must consider significant improvements in specific areas, such as superior biocompatibility and minimal cost [106]. Biodegradable and versatile materials may enhance biocompatibility while lowering costs for sensor substrates. These have enhanced mechanical qualities and air permeability, which makes them appropriate for extended interaction with the skin. Investigating environmentally friendly substances, like medical-grade silicone or cutting-edge biocompatible polymers, that reduce skin irritation, particularly during long-term use, is one way to avoid skin-related allergies. Other strategies include accurate evaluation or tracking, translating scientific findings into clinical insights by developing intricate algorithms for data understanding, and implementing machine learning strategies to better understand wound healing trends [103].

Comfort and safety of materials

Numerous wearable sensors are designed to adhere strongly to the skin or the outermost tissues for a prolonged duration to collect biological information. Occasionally, sticky materials or sensor devices containing sensitizing substances might cause allergy-induced contact dermatitis. Continuous glucose monitoring triggered reactions have identified acrylate analogues as the primary allergen in several instances of contact dermatitis [104]. Examples of Identified Allergens include Isobornyl Acrylate (IBOA) [107] and 2,2′-Methylenebis(6-tert-butyl-4-methylphenol) Monoacrylate [108]. Acrylate analogs should be used selectively in detectors to maintain user satisfaction and safety when installing sensors. For instance, during the development, IBOA is eliminated within the adhesives of the FreeStyle Libre 2 system, a continuous glucose monitoring device, dramatically reducing user skin irritation [109]. Addressing concerns about material deterioration and hygiene is another way to guarantee that wearable technology stays secure and comfortable even after prolonged usage. Sweat and bacteria buildup can cause illnesses or skin discomfort. Breathable, moisture-wicking, and antibacterial materials are being developed to counteract this. Gadgets are also made with easily cleaned or disposable materials to maintain hygienic standards. [110]. Electronic components that dissipate heat present a safety risk since too much heat might result in burns or pain. Heat output must be controlled to preserve device functionality and avoid adverse skin effects. Researchers are working to reduce heat generation by exploring materials with improved thermal conductivity and creating circuits that function well at lower power levels [111].

Portability and good battery life of the device

Portable sensors are ideal for bedside monitoring. Clinic patients frequently have limited mobility, particularly people who have gotten seriously ill or undergone surgery. Many consumers utilize portable sensors for bedside monitoring since large, stationary healthcare supplies cannot satisfy their immediate screening needs. Individuals experiencing chronic diseases, such as diabetes, may struggle to adhere to their therapeutic schedules and produce too little information to monitor their condition due to huge sensors [112]. For instance, a study on the wearable cardiovascular monitoring system i-CardiAx highlighted the trade-off between battery life and gadget size. A 100 mAh battery needed regular recharging and merely sustained two weeks regardless of power optimization [113]. Thermal problems with high-power wearing EEG headbands forced researchers to use energy-efficient circuits and passive cooling systems [114].

Accuracy and stability of detection

Testing in laboratories and medical examinations is crucial in diagnosing and surveilling diseases. The precision of these data is critical for identifying treatment options and achieving beneficial results for the disease. Nonetheless, problems with biochemical sensors based on biomarkers can occur due to infection or deterioration. For example, food residue can contaminate saliva, evaporated sweat can alter chemical concentrations, and current methods for collecting tear samples can irritate eyes and cause reflex tears, all of which can impact the results of sensor testing [115]. A different study employed context-aware sensor fusion in wearable technology to identify stress. Researchers increased the accuracy and stability of stress monitoring by combining several sensor inputs, lessening the influence of individual variances and environmental fluctuations. This illustrates how integrating different sensor data sources can improve dependability in practical applications [116]. Researchers examined the accuracy of wrist-worn pulse oximeters in peripheral oxygen saturation (SpO_2) monitoring. Their research showed that wrist-based measurements were difficult for current algorithms to retain accuracy, which prompted the creation of better signal processing methods to improve stability. This study highlights the significance of improving detection algorithms for wearable SpO_2 monitors [117].

Identification and analytical performance of data

Cloud computing, deep learning, and AI are examples of information analysis tools that can convert initial data into clinically relevant data and detect aberrant patterns. Modern machine learning and signal processing algorithms need additional modification. Medical professionals need to be engaged in gathering and analyzing data to develop standard protocols for identifying illnesses [118]. For instance, a thorough analysis looked at methods for wearable sensor-based human activity recognition (HAR). The study emphasized how crucial precise data identification and analysis are for personal fitness and healthcare applications. It also tackled issues, including the requirement for uniform assessment standards to guarantee equitable comparisons among various HAR methods [119]. Researchers investigated stress detection by combining information from several sensors on wearable technology. The study underlined how important context-aware sensor fusion is for precisely determining stress levels while considering individual and environmental variances. This method enhanced the analytical performance of stress detection systems [116].

Security of patient health data

Portable sensor devices that lack proper security safeguards could breach the confidentiality of patients, making them subject to hacker tracking and abuse. To ensure complete data security, anonymity is required for content transmission protocols and data storage in wearable sensor systems. Using patient-generated health data should be rigorously limited by implementing effective safety and privacy protocols [120]. In January 2025, the U.S. Food and Drug Administration (FDA) found some patient monitors had security problems. These gadgets display vital patient information from home and medical settings, such as blood pressure, heart rate, and temperature. The FDA warned that defects could grant unauthorized access, enabling abuse or unapproved use of the gadgets, which might give rise to issues. Private patient information may also be hacked and transferred outside the medical environment. Despite the fact that no incidents were ever documented at the time, the FDA recommended that healthcare facilities minimize these risks [121].

Technical Limitations of Sensors in Wound Healing

Many sensor components used in intelligent patches may not withstand prolonged exposure to the humid conditions prevalent in wounds, resulting in degradation and diminished performance. When time evolves, this persistent issue may limit the sensor's ability to generate accurate information, necessitating periodic modifications. Despite numerous discussions of biological functionality, it is critical to contemplate the possibility that different substances will eventually come into contact with bodily fluids and cells, influencing the sensor's efficiency. The preliminary biocompatibility of a material may change in ways that influence its efficacy in managing persistent wounds. Low-power sensor inventions or power production techniques (like leveraging the body's temperature or mobility) are crucial for long-term wearables because many sensors need uninterrupted power, which constitutes an essential hurdle for wearable technology. In medical environments, the brief life span of power sources might render usual restoration or substitution unattainable for ongoing surveillance. Individuals may find ordinary batteries to be heavy and difficult.

Table 1: Fabrication of smart patches by different researchers for wound healing activity

S No	Highlights	Biomarkers	Sensors	Biomarker used	Sensors Incorporated	Sensitivity	Accuracy	Cost	Integration	Ref
1.	Multipurpose theranostics Using Polymer Hydrogel towards the Management of Diabetic Wounds	✓	✓	pH and Redox	Electro-chemical sensor	High	High	Moderate-to-high	Moderately challenging	[22,23]
2.	The development and production of a paper-based, fluidic wound sensor patch.	✗	✓	---	Paper sensor	High	Quite accurate	Low	Easy	[24,25]
3.	The fully operational stretchy wearable bio-electronic system's design	✓	✓	Electrical responsive stimulus	Electrochemical, pH, and temperature sensors.	High, moderate, and high, respectively	High, high, moderate-to-high, respectively	Moderate to high, low to moderate, low, respectively	Moderately challenging, easy, respectively	[23, 26-29]
4.	Smart Patch: Portable, adaptable, and fully printed for pH and moisture sensing in wounds	✗	✓	---	pH and hydration sensors.	Moderate	High, moderate, respectively	Low to moderate, respectively	Easy	[30,27,31,26]
5.	Microneedle dressing created using intelligent silk fibroin	✓	✗	Thermoresponsive stimulus	---	---	---	---	---	[32]
6.	Smart, flexible, electronics-integrated bandages	✗	✓	---	Temperature Sensor	High	Moderate-to-high	Low	Easy	[33,28,29]
7.	A transdermal patch for delivering drugs with pH regulation	✓	✗	pH-responsive stimulus	---	---	---	---	---	[34]
8.	An Electronic Wound Dressing with pH Mediating for Managed Drug Administration	✓	✓	Electrical responsive stimulus	pH Sensor	Moderate	High	Electrical responsive stimulus	Easy	[27]
9.	Intelligent bandages for chronic injury monitoring and care	✓	✓	Thermoresponsive stimulus	pH and temperature sensors	Moderate, high respectively	High, moderate-to- high respectively	Low-to-moderate,	Easy	[28,29]
10.	An Innovative Hydrogel Dressing	✗	✓	---	pH Sensor	Moderate	High	Low-to-moderate	Easy	[27]

For instance, researchers have integrated biopiles into garments to collect sweat energy. These innovative textiles can power devices like smartwatches and heart rate monitors, which makes it easy to keep an eye on activities without having to swap out batteries all the time. This tactic particularly benefits athletes because it offers a convenient and renewable power source during physical activity [122]. Sensor data should help healthcare providers make informed decisions. Sensor calibration difficulties can cause variances in information collected by sensors. Sensor data must be appropriately analyzed and confirmed in healthcare facilities before it can be considered credible and accurate. To preserve accuracy, difficulties may arise in regularly calibrating the sensors. For example, it has been shown that people with darker complexions receive less precise readings from pulse oximeters, which are commonly used to test blood oxygen levels. This disparity results from potential discrepancies in oxygen saturation levels caused by the early calibration procedures, which mostly involved lighter-skinned people [123]. These issues can make it more challenging for clinicians to use the device in clinical settings, as they may not have the necessary time or equipment to perform these calibrations [124].

Table 2: Recently developed wearable sensors for medical applications

Diseases and abnormalities	Location	Sensing type	Sensitivity	Accuracy	Cost	Integration	Medical applications	Ref
Skin diseases and injuries	Dorsal hand	Acousto mechanic	High	High	depends on the materials & fabrication processes.	Easy	Objective quantification of pruritus.	[84,85]
	Surface of the skin	Thermal	High	Moderate-to-high	Low	Easy	Tracking and identifying inflammatory skin conditions	[86,29-30]
	Surface of the skin	Electro-chemical	High	High	Moderate-to-high	Moderately challenging	Screening of melanoma	[23]
	Close to the wounds	Thermal	High	Moderate-to-high	Low	Easy	Clinical and quantitative tracking of cutaneous wound healing	[29,30]
	Wounds	Electro-chemical	High	High	Moderate-to-high	Moderately challenging	Monitoring of wound healing in real time	[91,23]
Cardiovascular diseases	Inner wrists and left dorsal hand	Bioelectric	Crucial	high	Varies significantly	Easy	Recognising cardiac irregularities	[92,93]
	Chest	Textile electronic	---	---	---	---	Ongoing Electrocardiogram observation	[94]

Diseases and abnormalities	**Location**	**Sensing type**	**Sensitivity**	**Accuracy**	**Cost**	**Integration**	**Medical applications**	**Ref**
	Wrist	Textile triboelectric	---	---	---	---	Blood pressure monitoring on an ambulatory basis	[95]
	Hand and foot	Opto-electronic	---	---	---	---	Calculating the pulse oximetry	[96]
	Finger	Opto-electronic	---	---	---	---	Calculating the pulse oximetry	[97]
	Finger, wrist, neck, and nose	Opto-electronic	---	---	---	---	ongoing pulse oximetry observation	
Abnormal human motion	Neck	Tri-boelectric	High	Varies based on humidity, temperature	Low	Easy	monitoring, treating, and controlling the neck	[98,99]
	Shoulder	Physical	High	depends on environmental conditions	Varies based on the type.	Easy	tracking of shoulder motion	[100]
	Wrist	Mechanical	High	Good	Varies	Easy	Motion sensing of five fingers	[101,102]
	Hip and knee	Tri-boelectric	High	Varies based on humidity and temperature	Low	Easy	Sports training and the rehabilitation of lower limbs	[103,99]
Endocrine and metabolic abnormalities	Skin surface	Electro chemical	High	High	Moderate-to-high	Moderately challenging	Management of diabetes	[23]
	Cornea	Electro chemical	High	High	Moderate-to-high	Moderately challenging	Ocular infections, evaluation of oxidative stress, diabetes, uveitis, and keratopathy	[104,23]
	Skin surface	Electro chemical	High	High	Moderate to high	Moderately challenging	Tracking athletic performance and identifying metabolic diseases	[23]
	Finger tip	Electro chemical	High	High	Moderate to high	Moderately challenging	Management of Quantitative Stress	[101,23]

Diseases and abnormalities	Location	Sensing type	Sensitivity	Accuracy	Cost	Integration	Medical applications	Ref
Others	Skin surface	Electro chemical	High	High	Moderate to high	Moderately challenging	Point-of-care medication administration and monitoring	[23]
	Skin surface	Electro chemical	High	High	Moderate to high	Moderately challenging	Levodopa administration and Parkinson's disease management	[102,27]
	Skin surface	Electro chemical	High	High	Moderate to high	Moderately challenging	Alcohol monitoring	[23]

Regulatory Challenges and Ethical Concerns in Wearable Medical Devices

Different regions follow different procedures for classifying and approving wearable medical devices. The Food and Drug Administration (FDA), which oversees products used for illness diagnosis, prevention, or treatment, governs wearables that fall under the category of medical devices in the US. The FDA can clear safe devices through the 510(k) procedure, while devices with elevated risks require a more stringent premarket approval (PMA). In contrast, the European Union adheres to the Medical Device Regulation (MDR) 2017/745, which came into force in 2021. According to the MDR, wearables are subject to an increasingly rigorous framework for regulation, which mandates clinical studies, post-market monitoring, and higher quality standards for every kind of medical device, especially wearables [125,126]. Following approval, post-market surveillance is crucial for wearables. The FDA in the United States has established regulations to control security vulnerabilities in health care equipment at every stage of its life cycle. Makers can incorporate technological safeguards into the design and upgrade procedures to safeguard patient information and preserve system integrity. Wearables generally depend on constant software upgrades, so neglecting to identify and fix security flaws could seriously affect user safety. The MDR in the European Union emphasizes more stringent post-market regulations. These include surveillance systems for monitoring adverse outcomes and ensuring that devices adhere to safety regulations for their lives. Many smart device users struggle with informed consent due to their lack of awareness about using their medical information. Lack of transparency can lead to data transfer without explicit permission from marketers or insurance. Moral hazards are associated with this, including the possibility of prejudice and insurance denials based on current medical data.

CONCLUSION

Intelligent wearable patches offer an unprecedented development and their transformative approach in wound care, providing accurate, continuous tracking, and real-time monitoring of critical wound parameters and personalized therapeutic strategies. They are used to assess the state of the wound while also allowing for instant drug delivery and automated wound management by incorporating several sensors such as pH, temperature, moisture, oxygen, mechanical , and electrical. The latest sensor calibration, testing, and integration developments demonstrate their ability to significantly enhance wound healing outcomes and improve patient quality of life. These patches were developed using unique manufacturing methods to ensure usefulness and ease for patients. Finally, there is a lot of potential for smart bandages, which provide drugs in a regulated manner by dynamic drug delivery methods, including automated wound dressings, wireless connectivity of smart bandages, and smart bandages with integrated sensors, which reduce the frequency of changing the bandages at the injury site. *In vitro* evaluation of these intelligent patches demonstrates their usefulness in improving healing processes and flexibility in various medical applications. The current use of wearable sensors for healthcare diagnosis emphasizes their usefulness in larger medical settings. However, sensor accuracy, material safety, device mobility, privacy concerns, and laws and regulations continue to pose significant challenges. Addressing these issues is crucial for ensuring acceptance and maximizing their impact on patient treatment. In summary, intelligent wearable patches have tremendous potential for enhancing wound treatment and health surveillance. Future research should focus on optimizing these technologies, tackling technical and ethical constraints, and advancing regulatory frameworks to fully harness the capabilities of intelligent patches in revolutionizing wound management.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHORS CONTRIBUTIONS
Sai Ramya Bodagala designed the study to ensure a robust and effective review framework. She played a critical role in writing the manuscript's content. Prasanthi Samathoti drafted and edited it, contributing to its overall coherence and quality. She also served as the corresponding author. Both authors read and approved the final manuscript, confirming their agreement with the content and conclusions presented.

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