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Smart Medical Textile Technologies: Principles, Materials, and Applications

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تقنيات النسيج الطبي الذكي: المبادئ والمواد والتطبيقات

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Abstract:
Smart medical textiles are an emerging class of materials that bring together textile engineering, materials science, and biomedical innovation. Designed to work in harmony with the human body, these fabrics sense physiological and biochemical changes and translate them into meaningful data. Using conductive fibres, nanocoatings, hydrogels, and Janus textile structures, they can monitor temperature, strain, respiration, pH, and ion concentration while remaining soft, breathable, and comfortable to wear. Recent advances in electrochemical biosensing have allowed fabrics to measure sweat and other body fluids with impressive sensitivity, while textile-based strain and thermal sensors now provide continuous monitoring of movement and skin temperature. Improvements in coating technology and flexible connectors have made these sensors more durable, washable, and biocompatible. At the same time, hybrid hydrogels and Janus fabrics enhance skin contact and guide body fluids toward sensing areas—an innovation that has greatly improved wound-care dressings. These "smart" bandages can detect infection risk early by monitoring pH and moisture, yet still allow the skin to breathe. Despite rapid progress, key challenges remain. Devices must be calibrated to handle variation in body fluids and movement, and global standards for washability, durability, and safety are still developing. Achieving energy independence through small triboelectric and thermoelectric generators is another essential step toward fully self-powered systems. Looking ahead, integrating artificial intelligence and multimodal sensing will enable more reliable interpretation of complex biological data. By combining comfort, intelligence, and sustainability, smart medical textiles are moving from experimental prototypes to practical healthcare tools capable of transforming personal health monitoring and wound management.

Keywords: Smart medical textiles, wearable biosensors, hydrogels, Janus textiles and wound care.

الملخص
تُعد الأقمشة الطبية الذكية فئة جديدة من المواد تجمع بين هندسة النسيج وعلوم المواد والابتكار في المجال الطبي الحيوي. صُممت هذه الأقمشة لتعمل بتناغم مع جسم الإنسان، إذ تستشعر التغيرات الفسيولوجية والكيميائية الحيوية وتحوّلها إلى بيانات ذات معنى. من خلال استخدام الألياف الموصلة، والطلاءات النانوية، والمواد الهلامية المائية (الهيدروجيل)، وهياكل الأقمشة الثنائية السطح (Janus)، يمكن لهذه المواد مراقبة درجة الحرارة، والشد، والتنفس، ودرجة الحموضة، وتركيز الأيونات، مع الحفاظ في الوقت نفسه على النعومة وقابلية التهوية وراحة الارتداء. لقد سمحت التطورات الحديثة في أجهزة الاستشعار الكهروكيميائية بقياس العرق وسوائل الجسم بدقة عالية، في حين أصبحت أجهزة الاستشعار النسيجية للشد والحرارة توفر مراقبة مستمرة للحركة ودرجة حرارة الجلد. كما أدت التحسينات في تقنيات الطلاء والتوصيلات المرنة إلى زيادة متانة هذه الأجهزة وقابليتها للغسيل وتوافقها الحيوي. وفي الوقت نفسه، عززت الهياكل الهلامية المائية والأقمشة الثنائية السطح من جودة التلامس مع الجلد وتوجيه السوائل نحو مناطق الاستشعار، مما أدى إلى تحسين كبير في ضمادات الجروح الذكية التي يمكنها كشف خطر العدوى مبكرًا عبر مراقبة درجة الحموضة والرطوبة، مع الحفاظ على قدرة الجلد على التنفس. رغم هذا التقدم السريع، ما زالت هناك تحديات أساسية، منها الحاجة إلى معايرة دقيقة للأجهزة لتتعامل مع اختلاف سوائل الجسم

والحركة، وغياب المعايير العالمية الخاصة بالثبات بعد الغسيل والسلامة الحيوية. كما تمثل الاستقلالية الطاقية تحديًا آخر يتطلب تطوير مولدات كهروضغطية وحرارية دقيقة لتشغيل الأجهزة ذاتيًا. في المستقبل، يُتوقع أن يؤدي دمج الذكاء الاصطناعي مع تقنيات الاستشعار المتعددة إلى تحسين موثوقية تحليل البيانات الحيوية. إن الجمع بين الراحة والذكاء والاستدامة يجعل الأقمشة الطبية الذكية تنتقل من مرحلة النماذج البحثية إلى أدوات عملية قادرة على إحداث ثورة في مجال الرعاية الصحية الشخصية وإدارة الجروح.

الكلمات المفتاحية: الأقمشة الطبية الذكية؛ أجهزة الاستشعار الحيوية القابلة للارتداء؛ المواد الهلامية المائية (الهيدروجيل)؛ الأقمشة المزدوجة السطح (يانوس)؛ العناية بالجروح.

1. Introduction

Smart medical textiles are advanced textile systems precisely designed to interact with the human body. They detect physiological or biochemical signals and convert them into usable information, while maintaining the comfort, breathability, and adaptability unique to textiles (Xu et al., 2025; Younes et al., 2023). Meanwhile, wearable, rigid devices enable textiles to sense across large areas, conform to the body's detailed geometry, and support continuous, non-invasive monitoring during daily activities. Recent innovations include textile-based electrochemical platforms for analyzing sweat and biofluids; and sensors embedded in fabrics to measure temperature, resistance, and stress, facilitating cardiac and respiratory monitoring; In addition, other textiles have the ability to assess pH, moisture levels, and secretions while maintaining optimal microclimate conditions (Li, S. et al., 2023; Akter et al., 2024; Huang et al., 2024; Raju et al., 2022; Moradifar et al., 2024; Kumar et al., 2025). From a materials science perspective, progress has been fueled by the development of conductive fibers and yarns, polymeric and nanocoatings, and soft hydrogel systems that ensure precise contact with the skin without interface obstructions. Structures designed with differential wettability, such as Janus textiles, provide directional fluid transport that separates sampling from skin contact and can also direct biofluids toward transducers without causing them to soak (Li, Z. et al., 2024). At the platform level, strategies for integrating electronics with textiles now include woven and woven structures, printed conductive tracks, embedded electrodes, and coated joints designed to withstand repeated washing, bending, and stretching (Blecha et al., 2024; Fu et al., 2024). Concurrent developments include the application of biocompatible and antimicrobial finishes, primarily to reduce the risk of infection and enhance durability for long-term use (Orasugh et al., 2025). Physiological monitoring is an early demonstration area that has proven its importance and has led to more application-focused research. In this context, textile electrodes and strain sensors facilitate the capture of electrocardiogram/electromyography (ECG) signals, as well as monitoring respiratory effort and, ideally, skin temperature mapping. Increasing emphasis is placed on signal quality during movement, sweating, and washing cycles (Xu et al., 2025; Huang et al., 2024; Neelakandan et al., 2024). In conjunction with the above, textile-based electrochemical sensors are used to measure electrolytes, metabolites, and hydration status in sweat. This is achieved using enzymes or redox-mediated conversion, taking into account the significant impact of design decisions on detection limits, dynamic range, and selectivity (Li, S., et al., 2023; Akter et al., 2024; Li, S., et al., 2024; Fakhr et al., 2024). Wound care has also been a major focus of smart medical textile research. Studies are currently underway on fabric-mimicking electronic dressings that continuously monitor moisture and pH, helping to identify infection risks earlier than traditional visual inspection. These could also play a role in modifying therapeutic interventions through fabric heating or drug-enriched coatings (Raju et al., 2022; Moradifar et al., 2024; Kumar et al., 2025; Prakashan et al., 2024). However, challenges related to durability, washability, and safety pose significant obstacles to the successful translation of data into information. Conductive paths must be resilient to mechanical fatigue, delamination, exposure to detergents, and abrasion, and the soft coating must maintain low skin resistance while ensuring breathability. When calculating biocompatibility assessments, cumulative exposure, leachable substances, and prolonged skin contact must be taken into account (Li, S. et al., 2023; Fu et al., 2024; Fakhr et al., 2024). Sustainability and energy independence are currently critical and emerging issues: triboelectric, piezoelectric, or thermoelectric mechanisms, along with energy-efficient electronics, can be powered by self-sensing, reducing battery consumption and enhancing wearability, even if providing a stable power supply with movement and perspiration is a real challenge.

Regional studies highlight the importance of educational and industrial pathways for integrating medical and technical textiles into local markets, highlighting the potential for technology transfer and standardized testing (Sherif, 2017; Ajeeb, 2019; Hussein, 2023; Abu Hashish, 2024). These studies reinforce the fundamental principles and materials upon which smart medical textiles are built, detailing the differences in sensing methods and their applications in physiological monitoring and wound care, and focusing on considerations related to durability and safety. These studies emphasize intensive work to explore existing challenges, including signal drift, calibration issues, washout effects, and range shift between users. Regional studies also summarize a brief perspective on potential factors such as multimodal fusion and data-driven validation pipelines, with a brief overview of the role of artificial intelligence in the future work section based on demand.

2. Textile Materials and Structures for Biosensing

1.2 Conductive Fibers, Yarns, and Textile Core Structures

Conductive pathways within textiles are created using self-conducting fibers, metal-coated or carbon-loaded yarns, and conductors printed or coated on conventional substrates such as polyester, nylon, and cotton. The structural configurations of knitted and woven textiles facilitate tuning of pressure and strain sensitivity by controlling yarn tension and loop geometry, while nonwovens offer ample surface area for the application of functional coatings (Blesha et al., 2024; Fu et al., 2024). Substrate selection is critical, facilitating the interaction between comfort, flexibility, and moisture transport, while ensuring the mechanical stability necessary to maintain low-noise contact during movement (Li, S. et al., 2023).

2.2 Functional Coatings and Surface Modification

Metallic, polymeric, or carbon-based thin coatings facilitate the development of advanced sensing substrates from conventional textiles. Methodologies used include dip coating, spraying, screen printing (inkjet), and in situ polymerization. Parameters such as lamination strength, flexural tolerance, and wash durability influence the coating's morphological properties and adhesion. Flexible coatings and protective topcoats mitigate cracking and oxidation while maintaining essential breathability (Fu et al., 2024; Fakhr et al., 2024). Biochemical sensing is also an important field. Enzyme layers and selective membranes enable molecular recognition while simultaneously addressing the problem of contamination in sweat secretions or wounds (Li, S. et al., 2023; Li, S. et al., 2024).

3.2 Hydrogels and Soft Interfaces

Hydrogels (e.g., polyethylene glycol (PEG), polyvinyl alcohol (PVA), and conductive ionogels) are able to conform to the microscopic features at the skin-fabric interface, preventing contact obstruction for impedance measurements or electrocardiogram (ECG). Water pathways also facilitate ion transport in electrochemical sensing applications.

The mechanical compatibility of hydrogels mitigates motion distortions, and user comfort is significantly affected by water activity and permeability coefficients during prolonged use (Li, S. et al., 2023; Kumar et al., 2025). The functional integration of hydrogel and hybrid textile structures is particularly evident in wound dressings, where they simultaneously manage the moisture and pH levels of the sensing layer (Moradifar et al., 2024).

4.2 Janus Textiles and Directional Transport

Janus structures combine hydrophilic and hydrophobic surfaces to form a fluid-binding valve. This structure facilitates the transport of body fluids to sample collection areas away from the skin, making them more reliable for sampling. Technologies such as surface energy control and micro surface patterning help manage the direction and pressure of fluid flow. This enables rapid sample collection without damaging wet tissue, making them suitable for capturing sweat across large areas and handling wound fluids.

5.2 Connections, Packaging, and Washability

Electrical robustness relies on flexible connections and structural properties that accommodate stretching, bending, and twisting. Protective layers provide an encapsulation that protects conductors and enzymes from detergents and mechanical stresses, while maintaining air permeability to avoid skin irritation. Standardized washing protocols and post-wash performance measurements—such as signal-to-noise ratio and baseline deviation—are now being reported to support development and validation (Li, S., et al., 2023; Fu et al., 2024; Fakhr et al., 2024). Antimicrobial coatings can also be added to reduce bacterial burden during long-term use, provided their safety is documented (Urasough et al., 2025).

3. Principles of Textile-Based Biosensing

Smart medical textiles translate physical or chemical changes at the skin and fabric interface into measured electrical output, while maintaining wearable properties such as comfort, fit, and air permeability. This section provides a summary of the working mechanisms and performance parameters of common sensor classes, focusing on body fluids (most notably sweat), electrophysiological measurements, respiration/biomotors, and thermal monitoring.

3.1 Sensing Sweat and Body Fluids via Electrochemistry and Electrical Impedance

In sensitive textiles, potentiometry is used to track ions, amperometry/voltammetry to sense enzyme targets and redox reactions, and affine measurement to monitor non-faradic phenomena. Cell geometry is defined by conductive threads or printed electrodes that embody WE/RE/CE, while permeable membranes and hydrogels provide selectivity and reduce skin-interface resistance (Li, S., et al., 2023; Li, C., et al., 2024; Kumar et al., 2025). The porosity and wettability of the fabric control sample flow and evaporation rate. Janus textiles direct sweat/secretions toward the sensing layers, reducing soaking (Li, Z., et al., 2024). Hydrogel-textile hybrids also stabilize the fluid interface and improve the signal-to-noise ratio during motion (Li, S., et al., 2023; Kumar et al., 2025). Key performance indicators include limit of detection (LOD), linear range, selectivity, response time, hysteresis, and baseline drift. Calibration strategies—such as proportional designs and internal standards—help address variability in sweat rates and compositions. Packaging chemistry and anti-fouling techniques also support long-term performance stability (Akter et al., 2024; Li, C. et al., 2024; Fakhr et al., 2024; Fu et al., 2024).

3.2 Physiological Monitoring via Strain/Strain, Electrical Measurements, and Thermal Sensing

Textile strain sensors rely on conductive networks embedded within knitted or woven structures, where the geometry determines the measurement factor and operating range (Fu et al., 2024). Textile electrodes used in ECG/EMG benefit from moisture-controlled hydrogel interfaces and a flexible fit that reduces motion artifacts and increases signal-to-noise ratio (Li, S. et al., 2023; Xu et al., 2025; Huang et al., 2024). Thermal sensing using printed thermistors/thermal resistance elements enables mapping of the skin microclimate, provided the coating remains breathable to maintain measurement accuracy and wear comfort (Huang et al., 2024; Moradifar et al., 2024).

3.3 Data Reliability, Quality, and Validation

Sources of interference arise from impedance changes due to movement, conductivity changes due to sweating, cross-sensitivities, and enzymatic degradation. Mitigation measures include hydrogels, directional-drawn Janus fabrics, mechanical isolation/separation of measuring areas, and anti-accumulation finishes (Li, S. et al., 2023; Li, Z. et al., 2024; Oraso et al., 2025). Validation should preferably include Bland–Altman analysis against clinical/laboratory references, with movement challenge tests and systematic environmental surveys to detect cross-sensitivities (Akter et al., 2024; Li et al., 2024; Xu et al., 2025; Huang et al., 2024).

4 Healthcare Use Cases

4.1 Physiological Monitoring (ECG/EMG), Respiration, Temperature, and Sweat Analysis

Textile electrodes and flexible structures enable 24-hour ECG/EMG and respiration tracking while maintaining stable contact pressure, while distributed temperature pixels and sweat patches extend spatial coverage. Measurement quality in practice depends on reliable sampling, breathable packaging, and clear calibration procedures (Li, S. et al., 2023; Xu et al., 2025; Huang et al., 2024; Akter et al., 2024; Li, S. et al., 2024).

4.2 Wound Care Interfaces (Moisture/pH/Exudate and Infection Risk)

Smart dressings integrate absorbent and breathable layers with electrochemical moisture and pH sensors for early infection warning and targeted moisture management. Designs focus on gentle adhesion, conformational compatibility, and mechanical shear release. Wireless readout should also be designed with a low power budget (Raju et al., 2022; Moradifar et al., 2024; Kumar et al., 2025; Prakashan et al., 2024).

5. Durability, Washability, and Safety

Continued conductivity and sensor stability after washing and mechanical cycles are critical factors. Recommended methods include mechanically compliant connectors, vapor-permeable multilayer coatings, textile-adapted printing/curing processes, and standardized pre/post-wash reporting (Fakhr et al., 2024; Fu et al., 2024; Li, S. et al., 2023). Balancing safety and antimicrobial properties also requires selecting materials that minimize toxicity and irritation while maintaining sensor performance (Urasough et al., 2025; Raju et al., 2022).

6. Sustainability and Autonomy

Light or battery-free operation is sought through fabric-integrated triboelectric/thermoelectric/piezoelectric harvesters, supported by low-consumption sensor platforms and periodic readings. This requires balancing mechanical compliance, vapor permeability, and wash durability with shipping and storage outputs (Nilkandan et al., 2024; Li, C. et al., 2024).

7. Regional/Arab Context

Arab sources indicate priorities for industrial adoption, antimicrobial finishes using available nanoparticles, and educational and skill-building pathways to support the localization of future biomedical textile manufacturing (Sherif, 2017; Ajeeb, 2019; Hussein, 2023; Abu Hashish, 2024).

8. Challenges and Research Gaps

Key gaps include: calibration under body fluid variation, mitigating motion artifacts, standardized reporting of washability, breathable and protective packaging, system-wide mechanical separation, and clinical validation under realistic conditions (Akter et al., 2024; Li, C., 2024; Fakhr et al., 2024; Fu et al., 2024; Xu et al., 2025; Raju et al., 2022).

9. Future Work

Multimodal integration, curated datasets, and joint optimization of materials and architecture could accelerate the transition to application. Smart bandages that combine moisture/pH mapping with gentle adhesion and remote monitoring are a promising direction (Li, S., 2023; Li, S., 2024; Li, Z., 2024; Fu, 2024; Moradifar, 2024; Kumar, 2025; Prakashan, 2024).

10. Conclusion

Smart medical textiles integrate materials, structures, and sensing technologies into wearable, spatially distributed measurement systems. Despite advances in electrochemical/accurate body fluid sensing, strain/temperature monitoring, and Janus/hydrogel interfaces, robustness, calibration, and clinical validation remain key challenges. Common design and standard reporting will be essential for reliable practical applications.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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