Agri Articles
(e-Magazine for Agricultural Articles)
Volume: 05, Issue: 06 (NOV-DEC, 2025)
Available online at http://www.agriarticles.com

Smart Wearable Biomedical Textiles: Monitoring, Diagnostics, and Health Management Systems

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Smart wearable biomedical textiles, also called textile-based bioelectronics or e-textiles, are quickly changing how we keep track of, diagnose, and treat health problems. These systems go beyond what traditional rigid wearables can do by putting sensors, actuators, communication modules, and even power units directly into textiles. This lets them provide continuous, discrete, and personalized healthcare. Recent advancements in conductive fibers, stretchable substrates, nanomaterials, and manufacturing methods like weaving, knitting, embroidery, coating, and printing have made it possible to create textile platforms that can record a wide range of bio signals. These bio signals include electrophysiological signals (ECG, EMG, EEG), mechanical motion, temperature, pressure, and biochemical markers in sweat and other bio fluids. This paper gives an overview of the current state of smart wearable biomedical textile technology, with a focus on its use in monitoring, diagnostics, and health management systems. First, the basic ideas, materials, and textile structures that make e-textile systems work are shown. Next, we talk about the main ways to sense things (mechanical, thermal, electrophysiological, and biochemical), with a focus on how well typical textile-based systems work. The next part talks about system-level parts and how important they are for turning raw sensor data into useful therapeutic data. These parts include signal conditioning, wireless communication, power supply and energy harvesting, data fusion, and AI-enabled analytics. We also look at how these things can help with mental health, sports and fitness, rehabilitation, tracking breathing, monitoring heart health, and caring for the elderly. Finally, we talk about important issues like biocompatibility, longevity, comfort, wash ability, standardization, ethics, and data privacy. We also suggest future research directions aimed at developing intelligent, sustainable, closed-loop textile-based health management ecosystems.

Introduction

Wearable technology that has already gone from being a novelty to being popular includes smartwatches, rings, and fitness bands. But the rigid electronics in these devices are usually strapped to the body in plastic cases, which could make them less comfortable, less likely to stay on for long periods of time, and less able to cover a wide area of physiological information. Textile-based wearables are a new kind of wearable technology that includes sensing, communication, and sometimes power features directly into clothes, bandages, mattresses, or other fabric structures that people use every day. Smart biomedical textiles are made to work with the body's natural interface, which is our skin and clothing, so they can monitor us all the time without getting in the way of our daily lives. Acoustic fibers can "listen" to heart and lung sounds. Sweat-collecting patches can check electrolytes and metabolites. Knitted pressure-sensitive materials can tell if you're standing or breathing. Conductive yarns woven into shirts can work as ECG electrodes.

Several converging trends drive this field:

- New materials like MXenes, conductive polymers, metal-coated fibers, triboelectric layers, and carbon-based nanomaterials like graphene and CNTs.
- Improvements in textile production that make it possible to place conductive elements accurately through knitting, printing, embroidery, and weaving.
- Adding low-power electronics, wireless modules, and flexible interconnects to or onto fabrics.
- AI and data analytics, which turn ongoing physiological streams into information that patients, doctors, and health systems can use.

Materials and Textile Architectures for Biomedical E-Textiles

Materials that are functional and conductible

Smart biomedical textiles are made by combining structural fibers like cotton, polyester, nylon, and elastane with functional elements that provide conductivity, sensing, or actuation. The main groups are:

1. Metal fibers and coatings

Stainless steel fibers and silver-plated yarns are often used because they conduct electricity well and are flexible enough.

- To make circuits and electrodes, thin metal films (Ag, Au, and Cu) can be sputtered or plated onto textiles without using electricity. However, these methods have problems with sticking and breaking under stress.

2. Polymers that carry out

Polymers like PEDOT: PSS, polypyrrole, and polyaniline can be used to coat or print yarns or fabrics. These polymers are very flexible and can change their impedance.

- Blends that include elastomers, like polyurethane and PDMS, make things stretchier, but they might also make them less conductive.

3. Nanomaterials made from carbon

- More and more, graphene, graphene oxide, carbon nanotubes, and carbon black are being used to make percolated conductive networks on fibers.
- These materials may be very sensitive to chemicals, strain, and pressure because they have a lot of surface area and are piezoresistive.

4. Two-dimensional materials and MXenes

- MXenes (like TiC_2T_x) are highly conductive, hydrophilic materials that can be coated onto fibers for high-performance strain, pressure, and bio-sensing. This has made them popular.

5. Triboelectric and piezoelectric materials

- Combinations of materials with different triboelectric polarities (like PTFE and nylon) or piezoelectric polymers like PVDF make it possible for textiles to turn mechanical motion into electrical signals or energy.

Methods of making things and the structure of textiles

The way textiles are made has a big effect on how long they last, how comfortable they are, and how well they work as sensors:

- Woven fabrics can have conductive warp and weft yarns added to them in certain patterns to make electrodes, antennas, or interconnects. These yarns also help the fabric keep its shape.
- Knitted fabrics are great for clothes that stay close to the skin because they are more flexible and fit the body better (like ECG T-shirts and compression sleeves).
- You can put composite sensing layers or thick-film coatings on nonwoven and felt structures.
- You can add conductive yarns to clothes by embroidering or stitching them on. This is especially useful for finding electrodes and leads on clothes that are otherwise normal.
- Coating and printing (screen printing, inkjet, spray coating) let you put functional inks, like sensor patches and stretchy interconnects, in very specific patterns.

Sensing Modalities in Smart Biomedical Textiles

Electrophysiological Sensing (ECG, EMG, EEG, EOG)

The most advanced application of textile sensing is in electrocardiography (ECG). Textile electrodes built into bras, shirts, chest straps, or bed linens can record heart signals without the need for gel or adhesive patches. A lot of research has shown that electrodes that are sewn, knitted, or printed can keep track of an ECG for a long time with a good signal, even when you are doing normal things. Some of the problems that dry textile electrodes need to solve are higher skin–electrode impedance, motion artifacts, and differences between users. Two ways to do this are to increase the surface area of the electrodes and change their location.

- Wearing clothes that are soft and tight to keep the touch steady.
- Using ionic liquid coatings or conductive polymer to lower impedance without making it harder to breathe.

Beyond ECG, textile electrodes and arrays have been investigated for:

- Electromyography (EMG) to monitor muscle contraction during exercise, recuperation, or prosthetic management.
- Textile caps with built-in electrodes for electroencephalography (EEG), but it's still hard to get recordings that are low-noise and high-density.
- Electrooculography (EOG) and other biopotential metrics for human-machine interactions or sleep stage assessment.

Mechanical and Motion Sensing

Textile-based mechanical sensors can sense joint angles and walking patterns when they are under stress, pressure, bending, or vibration.

- The depth and rate of breathing (by expanding the chest and abdomen)
- Levels of activity, balance, and posture

Some of the mechanisms are piezoelectric, capacitive, triboelectric, and piezoresistive effects. Recent studies have focused on the creation of textile-based mechanical sensors, their structural design, and techniques to enhance sensitivity and dynamic range. For example, strain sensors can be knitted or woven with conductive strands that change their resistance when they are stretched.

- Clothing and pressure-sensing mats that help you figure out how likely you are to get bedsores or fix your posture.
- Acoustic fabrics that can pick up speech, background noise, and heart and lung sounds by directing and changing sound waves inside fibers.

Sensing Temperature and Humidity

Textile-based temperature and humidity sensors can be used for a variety of things, such as finding fevers, studying how the body regulates its temperature, and keeping an eye on the skin's microclimate, which is important for wound care and preventing pressure ulcers. Fabrics have been changed to have coatings that are sensitive to moisture, fiber Bragg gratings, and conductive yarn thermistors. Eco-friendly textile humidity sensors have shown good sensitivity and breathability, which meets both comfort and sustainability standards.

Biochemical Sensing of Sweat and Other Fluids

Biochemical sensing is one of the more interesting areas. Smart textiles look at biofluids that are collected without cutting into the skin, like saliva, sweat, or interstitial fluid. Recent systematic reviews have focused on textile-based sweat sensors that keep track of electrolytes (Na^+, K^+, Cl^-), metabolites (glucose, lactate), pH, and other signs of hydration, metabolic state, and illness.

Some of the ways to integrate are:

- Microfluidic channels in textile patches send sweat to places where electrochemical sensors are located.
- Printed on fabric or coated on threads, enzyme-based electrodes that can find specific things.
- Wireless readout modules that send data to clinical systems or cell phones.

System Integration: From Sensors to Health Management

Electronics, Data Acquisition, and Communication

Isolated sensors alone do not create a smart healthcare system. Biomedical textiles must be integrated with:

- **Analog front-ends** for low-noise amplification and filtering of biosignals.
- **Microcontrollers** or system-on-chip platforms for local processing, feature extraction, and data compression.
- **Wireless modules** (Bluetooth Low Energy, Wi-Fi, NFC, or LPWAN) for data transmission to smartphones, gateways, or cloud services.

To maintain wearability, electronics are often packaged in small pods that clip onto garments or are laminated into flexible modules. Detachable designs allow garments to be washed while preserving expensive electronics. Emerging work explores fully textile-based interconnects, antennas, and even simple logic elements to further reduce reliance on rigid boards.

Power Supply and Energy Harvesting

Power remains a major bottleneck for continuous monitoring. Approaches include:

- **Rechargeable batteries** integrated into garment modules or accessories.
- **Energy harvesting** from body motion (triboelectric or piezoelectric textiles), heat (thermoelectric generators), or ambient electromagnetic fields.
- **Ultra-low-power electronics** and duty-cycling strategies to extend battery life.

Self-powered textiles are particularly attractive for long-term health management, as exemplified by triboelectric textile sensors and body-coupled electronic fibers that harvest environmental energy while performing sensing and signalling.

Data Analytics, AI, and Decision Support

Continuous physiological data streams are high-volume, noisy, and context-dependent. AI and machine learning are increasingly used to:

- Detect anomalies (e.g., arrhythmias, abnormal breathing patterns).
- Classify activities and sleep stages.
- Predict risk scores for conditions such as heart failure decompensation or COPD exacerbations.

Applications in Monitoring, Diagnostics, and Health Management

Cardiovascular and Respiratory Monitoring

ECG shirts, bras, and chest bands represent flagship applications of smart biomedical textiles, providing continuous cardiac rhythm monitoring suitable for arrhythmia screening, rehabilitation, and remote cardiac care. Textile ECG systems have been evaluated against Holter monitors and show promising agreement for heart rate and rhythm indices, with ongoing work to address motion artifacts and long-term comfort.

Textile sensors also enable:

- **Respiratory monitoring**, using stretch sensors around the chest and abdomen or airflow-sensitive fabrics in masks and garments.
- **Blood pressure estimation**, using pulse transit time derived from textile ECG and PPG sensors combined with algorithms.
- **Cardiac rehabilitation**, where remote monitoring of ECG, heart rate, and activity supports individualized exercise prescriptions.

Movement, Gait, and Rehabilitation

Textile-based strain and pressure sensors integrated into socks, leggings, or orthoses can characterize gait, detect falls, and assess joint function. These systems are valuable in:

- Post-stroke and orthopedic rehabilitation, providing objective measures of progress.
- Parkinson’s disease management, detecting freezing episodes or tremor patterns.
- Sports performance monitoring and injury prevention through load tracking and movement symmetry analysis.

Chronic Disease Management and Telehealth

Smart textiles are particularly suited for **long-term, at-home monitoring**—a key requirement for chronic disease management. Examples include:

- Diabetes and metabolic disorders: textile sensors that measure glucose and lactate through sweat, along with data on activity and heart rate, may help people make better choices about their medications or lifestyle.
- Heart failure: clothes that keep track of heart rate, breathing rate, thoracic impedance (fluid status), and activity can help find decompensation early.
- Chronic respiratory disease and sleep disorders: textile-based respiratory belts and bed-integrated sensors make it easy to keep an eye on sleep apnea, COPD, and asthma without being intrusive.

These systems interface with telehealth platforms to support remote consultations, automated alerts, and titration of therapies, forming the backbone of **smart health management ecosystems**.

Elderly Care, Mental Health, and Wellbeing

Smart textile systems can monitor mobility, detect falls, and assess loneliness or social isolation in older adults by tracking activity patterns, posture, and social interaction proxies.
Other emerging areas include:

- Mood and stress regulation, where textile sensors keep track of things like heart rate variability, skin temperature, and breathing, and then send calming stimuli or feedback.
- Comfort and sleep quality, thanks to bedding and nightwear that keep track of sleep stages, small movements, and temperature.
- Health and safety at work, using smart clothes to keep an eye on workload, ergonomics, and exposure in tough situations.

Challenges and Future Directions

Biocompatibility, Comfort, and User Acceptance

For long-term health monitoring, garments must feel like normal clothing: soft, breathable, and unobtrusive. Rough, rigid, or heavy sensor modules reduce adherence. Biocompatibility concerns include:

- Skin irritation from metallic coatings or chemical finishes.
- Moisture and heat buildup at sensor–skin interfaces.
- Allergic responses to certain polymers or additives.

Durability, Washability, and Standardization

Textile systems must withstand:

- Repeated stretching, bending, and abrasion during wear.
- Washing, drying, and ironing, including exposure to detergents and mechanical agitation.

Data Quality, Privacy, and Ethics

Smart biomedical textiles generate continuous, high-resolution health data, raising questions about:

- Quality and validation of data: algorithms that are trained on small or biased datasets may not work well with a wide range of people.
- Privacy and security: E-textiles are part of the Internet of Things (IoT) that can be worn, which could put private health information at risk of being hacked.
- Ethical use: Employers, insurers, or other groups could use data to discriminate against or unfairly profile people. Regulatory and ethical frameworks are just starting to catch up.

Integration into Healthcare Systems and Regulation

To move from prototypes to standard care, smart biomedical textiles must:

- Show that it is clinically valid and useful in strict tests.
- Work with electronic health records and clinical workflows.
- Follow the rules for medical devices (when they apply) that include requirements for performance, safety, and quality of manufacturing.

Future Outlook

Looking forward, several trends are likely to shape the next generation of smart biomedical textiles:

- Fully integrated, soft systems in which sensing, processing, and communication are all built into fiber or fabric, which reduces the need for hard modules.
- Closed-loop health management in which textiles not only keep track of but also provide treatments (like thermal therapy, electrical stimulation, and controlled drug delivery) based on what they find.
- Multimodal sensing and data fusion, which takes mechanical, electrical, and biochemical signals and turns them into more useful digital biomarkers.
- Designs that are environmentally friendly and last a long time, using materials that can be recycled, manufacturing that doesn't hurt the environment, and parts that break down in nature.
- Personalized AI models on-device that learn each wearer's baseline and patterns over time, allowing for adaptive analytics that protect privacy.

Conclusion

Smart wearable biomedical textiles are a strong combination of materials science, textile engineering, electronics, and digital health. These systems provide continuous, comfortable, and context-rich health monitoring by embedding sensors and communication capabilities into everyday fabrics. This can help with early diagnosis, personalized treatment, and proactive health management. Textile-based sensors for electrophysiological, mechanical, thermal, and biochemical monitoring have come a long way. These sensors can now be used in wearable systems that work with telehealth ecosystems. Applications now include caring for the heart and lungs, rehabilitation, managing chronic diseases, helping the elderly, and mental health. But it is still hard to get a lot of doctors to use it. We need to talk about long-term durability, washability, biocompatibility, data quality, privacy, and getting approval from the government. Future systems will probably have fully integrated, multimodal, and self-powered textiles, as well as strong AI-driven analytics and ethical governance frameworks.

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