

Innovative Applications of Wearable Electronic Textiles in Health Monitoring: From Smart Socks to Scoliosis Corrective Garments: A Practical Exploration

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ABSTRACT

Wearable electronic textiles, the result of a deep integration of flexible electronics and traditional textile processes, are profoundly transforming the field of health monitoring. This article focuses on innovative practices, systematically examining the technical pathways and application value of wearable electronic textiles, from foot health to spinal management. Taking smart socks as an example, their core lies in the direct weaving of fabric pressure, temperature, and humidity sensors into the sock body. This integration enables continuous monitoring of plantar pressure distribution and local microenvironmental changes, providing dynamic assessment and early warning of diabetic foot ulcer risk, significantly enhancing patients' self-management capabilities. In the field of scoliosis management, smart orthotic garments are breaking through the limitations of traditional braces. By embedding a network of fabric strain sensors within key garment structures, they capture three-dimensional torso posture changes and pressure distribution in real time. Combined with analysis by a built-in microprocessor, the system provides instant biofeedback and dynamically optimizes correction force, establishing a closed-loop management system of "real-time monitoring - immediate feedback - precise intervention," effectively improving treatment compliance and clinical outcomes. The article further explores the potential and key challenges of this technology in scenarios such as long-term chronic disease monitoring, postoperative functional recovery tracking, and sports biomechanical analysis. Core challenges include ensuring the long-term stability of sensor signals in complex environments, ensuring the comfort and durability required for extended daily wear, safeguarding user privacy and security associated with collecting physiological data, and overcoming the bottlenecks of large-scale, low-cost manufacturing processes necessary for market adoption. Existing practices demonstrate that wearable electronic textiles, with their "burdenless" integration and continuous monitoring and intervention capabilities, are quietly reshaping health management models and driving the shift toward personalized, preventative healthcare. Future breakthroughs will rely heavily on the deep integration and collaborative innovation of multiple disciplines, including materials science, microelectronics, intelligent algorithms, and clinical medicine.

KEYWORDS

Wearable Electronic Textiles; Health Monitoring; Smart Socks; Scoliosis Correction Garments; Flexible Sensors; Biofeedback; Chronic Disease Management; Telemedicine.

1. INTRODUCTION

The core use case for health monitoring is rapidly shifting from hospitals to individual, daily routines and preventative measures. While traditional medical devices can provide accurate data, their bulk, discomfort, and difficulty supporting continuous monitoring over extended periods of time limit their widespread adoption in daily health management and early warning settings. These challenges have

given rise to the key technology direction of wearable electronic textiles. Through textile technology, they ingeniously weave conductive materials, microsensors, data processing units, and even actuators into clothing or fabric substrates, creating a new generation of comfortable, multifunctional, and aesthetically pleasing smart health products.

Compared to traditional rigid devices, electronic textiles' core advantages lie in their exceptional softness, breathability, and natural conformity to the body's large surface area. They seamlessly adapt to the complex curves of the human body, achieving comfortable, non-invasive contact with the skin. This characteristic makes them particularly valuable in applications requiring long-term, continuous monitoring of specific physiological or biomechanical parameters—for example, real-time tracking of plantar pressure distribution, monitoring changes in trunk posture, and capturing the activity of specific muscle groups. This "non-invasive" monitoring capability has transformative potential for chronic disease management, rehabilitation training, and posture correction.

This article focuses on two typical applications of wearable electronic textiles in the field of health monitoring: smart socks for foot health and smart orthotic garments for scoliosis management. These two areas were chosen because they address critical health issues, from peripheral circulation to the human core skeleton, and therefore have broad demand. Furthermore, they showcase the technical capabilities and implementation challenges of electronic textiles in integrating sensing, providing biofeedback, and even enabling active intervention. By analyzing practical examples ranging from smart socks to orthotic garments, this article aims to clarify current technological progress, assess their application value and commercialization challenges, and explore future breakthroughs, providing insights for related research and development and application.

2. TECHNICAL FOUNDATIONS AND CORE ADVANTAGES OF WEARABLE ELECTRONIC TEXTILES

The key to achieving health monitoring capabilities in wearable electronic textiles lies in seamlessly integrating electronic components into clothing. This relies on the synergy of several core materials and processes.

Functional fiber materials, particularly conductive fibers, are the foundation. These fibers must undergo traditional textile processes such as spinning and twisting to transform them into functional yarns.

Integrated manufacturing processes transform these materials into practical circuits and sensors. Common methods include: using conductive inks to print circuits and electrodes onto fabric; using computer-controlled flat or circular knitting machines to weave conductive yarn directly into fabric, similar to knitting a regular sweater, to form pre-defined sensor networks and wires; and even employing intricate embroidery techniques to "embroider" desired circuit patterns onto fabric surfaces using conductive yarns.

Flexible interconnect technology is also essential. It must ensure reliable and stable electrical conductivity between sensors, microchips, and small power sources while maintaining sufficient flexibility and bendability. This is typically achieved through conductive adhesives, heat-compression welds, or specialized, flexible connectors with a fabric-like texture [1].

The core advantage of this technology lies primarily in its comfort, ensuring long-term wear. Equipped with the look of everyday clothing, e-textiles are lightweight, breathable, and feel natural, conforming to the body's curves. It completely eliminates the problems of traditional rigid devices, such as irritation, tightness, and skin irritation. Naturally, people are more willing to wear it daily, which is a prerequisite for continuously obtaining high-quality body data. Secondly, it can monitor multiple parts of the body simultaneously. By sewing multiple sensor nodes in different parts of the clothing, multi-dimensional information from a large area of the body can be simultaneously collected,

providing a more comprehensive and precisely located physiological and motion data map. Furthermore, it can achieve truly non-interrupting monitoring. Users can do what they need to do, and the device works silently in a natural state of activity, and the data captured more accurately reflects their health status in daily life. Finally, as a piece of clothing, it is naturally easy to make look good, which makes users more willing to accept it. Moreover, the support properties of the clothing itself can also be used, for example, to provide unique assistance in applications requiring physical correction.

3. PRACTICAL EXPLORATION OF SMART SOCKS IN FOOT HEALTH MONITORING

Foot health is crucial for people with diabetes, peripheral artery disease, and the elderly. Traditional clinic checkups are often delayed, making it difficult to detect subtle changes in risk factors during daily activities. Smart socks, a key application area for electronic textiles, are attempting to address this challenge. Their core lies in a network of flexible sensors woven into the socks, which continuously and in real time track biomechanical and physiological signals related to foot health.

The most common configuration involves densely packed arrays of piezoresistive or capacitive flexible pressure sensors in strategic areas of the sock sole, like nerve endings. These sensors meticulously map the pressure distribution across the sole of the foot during standing and walking. Abnormally high pressure in specific areas or overall pressure imbalances are often warning signs of impending plantar ulcers. Temperature sensors, placed close to the skin in vulnerable areas of the foot, monitor temperature changes. Unexplained localized warming is often an early warning sign of inflammation or deeper tissue damage. Some more advanced smart socks also incorporate moisture sensors to monitor perspiration and are even experimenting with integrating simple bioimpedance sensors to detect subtle changes in localized tissue swelling.

Currently, the most pressing application of smart socks is early warning of diabetic foot ulcers. The socks continuously collect data such as pressure and temperature, which is analyzed by a microprocessor inside the socks or wirelessly transmitted to a mobile phone or the cloud for analysis, gradually building a personalized risk model. The system can identify warning signs, such as persistently exceeding pressure limits in a specific area, a significant temperature difference between the two feet, or a sudden temperature spike in a specific "hotspot." If an abnormality is detected, it immediately alerts the patient or healthcare provider, prompting a detailed examination or adjustment of activity. For example, Sensoria Fitness's smart socks focus on analyzing gait and foot strike patterns, while Siren Care's diabetic socks focus on non-invasive, continuous temperature monitoring and cloud-based early warning services. User feedback indicates that these devices significantly enhance awareness of subtle foot problems in high-risk individuals, making daily self-monitoring much more convenient. Preliminary studies also suggest they can help reduce the incidence of ulcers [2].

However, the popularization of smart socks still faces many challenges: the size differences and knit tightness of different socks will affect the consistency of sensor readings; whether the sensor itself can withstand the test of repeated wearing and washing, its long-term stability and service life remain to be verified; ensuring the accuracy of data analysis algorithms and achieving true personalized customization are technical difficulties; finally, how to make users truly willing to wear them for a long time and seamlessly integrate them into their daily habits is also a key issue in product design.

4. APPLICATION OF E-TEXTILES IN SCOLIOSIS MANAGEMENT: SMART ORTHOTIC

Scoliosis, especially the adolescent idiopathic type, requires long-term management, focusing on posture monitoring and physical correction. Traditional treatments rely on regular X-rays and rigid braces, which present numerous challenges: X-rays emit radiation, and long intervals between examinations lead to delayed feedback; rigid braces are uncomfortable and affect appearance, leading many children to be reluctant to continue wearing them.

Smart orthotic garments offer a new approach. They utilize e-textile technology to weave flexible strain sensors, like a neural network, into key locations on the garment—such as the sides of the spine, around the shoulder blades, and around the waist. These sensitive "antennae" continuously capture subtle changes in the body's surface, deriving real-time information about the spinal curvature and muscle condition. Flexible pressure sensors can also be incorporated into the garment to monitor the appropriate and even pressure distribution of the brace or garment itself, preventing pressure sores and discomfort.

This smart garment transcends the passive support model of traditional braces, achieving a dynamic closed-loop system of "sensing + alerting + intervention." The posture data collected by the sensors is rapidly analyzed by a small chip embedded in the garment. If the system detects a child's posture is incorrect or their spinal curvature exceeds the safe range, it will immediately alert them through subtle vibrations on the garment or a mobile app, prompting them to make adjustments. For growing adolescents, the instant feedback provided by smart orthotic garments is crucial, helping them quickly find the right posture and enhance their body awareness. More advanced designs are even experimenting with making the corrective force "smarter," for example by leveraging the inherent physical properties of certain fabrics or incorporating externally adjustable components. When the system detects a trend toward worsening scoliosis, it can fine-tune the pressure at specific locations, either automatically or remotely, allowing the doctor to adjust it remotely [3]. Smart modular systems like SpineCor, which combine dynamic bracing with sensor feedback, have proven effective in practice, making children more comfortable wearing them and potentially improving treatment outcomes.

The benefits of smart orthotic garments are substantial: most directly, they reduce psychological stress for children, eliminating the need for conspicuous "armor." More importantly, the real-world posture data they continuously record provides unprecedented, reliable support for doctors to remotely monitor the patient's progress and adjust treatment plans accordingly.

5. EXPANDING APPLICATION SCENARIOS AND COMPREHENSIVE BENEFIT ANALYSIS

The application of e-textiles in health monitoring is no longer limited to the feet and spine and is expanding to more scenarios. For example, in cardiopulmonary monitoring, electrodes made of conductive fabric sewn into underwear or chest straps can continuously capture electrocardiogram signals, helping to detect irregular heartbeats. If respiratory wave monitoring technology (RIP) is added, it can also track the speed and depth of breathing, which is particularly useful for managing asthma, chronic obstructive pulmonary disease, and screening for sleep apnea. Looking at neuromuscular rehabilitation, equipping smart tights or protective gear with electromyography (EMG) sensors can provide real-time visualization of the force and coordination of specific muscles, providing quantitative feedback to guide rehabilitation training after stroke or sports injuries. For Parkinson's tremor management, highly sensitive textile accelerometers can record tremor frequency, amplitude, and triggering conditions throughout the day, optimizing treatment parameters for medication or deep brain stimulation. Innovative applications, such as a prototype "electronic nose"

scarf with integrated gas sensors, are exploring the monitoring of environmental pollutants or exhaled biomarkers. Furthermore, leveraging the large surface area of e-textiles that adhere to the skin, combined with bioimpedance technology, smart clothing can be developed for long-term, continuous monitoring of core body temperature, localized edema, or changes in body composition.

The promotion of these applications holds significant potential for comprehensive benefits. At the clinical level, electronic fabrics enable long-term, continuous, and contextual monitoring that traditional devices cannot support, greatly improving the ability to detect health risks and the exacerbation of chronic diseases at an early stage. The rich and objective data they provide strongly support accurate diagnosis, the development of personalized treatment plans, and dynamic efficacy evaluation. In terms of patient experience, they significantly improve the convenience and autonomy of health management. Comfortable wear, instant feedback, and early warning functions enhance patients' self-efficacy and sense of security [4]. Telemedicine data transmission facilitates communication between doctors and patients, and is particularly helpful for those with limited mobility or living in remote areas, reducing the burden of frequent trips to the hospital. From an economic perspective, while the initial investment may be relatively large, it can help detect problems earlier, prevent serious complications, reduce unnecessary emergency room visits and hospitalizations, and streamline the recovery process, potentially saving overall medical expenses in the long run. Furthermore, the large amount of real-world clinical data collected through this method provides a valuable new resource for medical research.

6. CURRENT CHALLENGES AND FUTURE DEVELOPMENT DIRECTIONS

Wearable electronic textiles have broad prospects for use in health monitoring. However, large-scale popularization still requires overcoming multiple obstacles such as biocompatibility, signal stability and cost control.

6.1. Technical Bottlenecks Need to Be Overcome

Poor signal stability: Sensors are susceptible to interference from temperature and humidity fluctuations, fabric deformation, human activity artifacts, and sweat, leading to data drift or high noise, which can affect diagnosis. This requires developing more tolerant materials, improving sensor structure, and employing more effective anti-interference signal processing algorithms.

Short battery life: Flexible batteries have limited capacity, and frequent charging impacts performance. This requires a combination of ambient energy harvesting technology and system-level low-power design.

Low durability and difficulty in maintenance: Devices are easily damaged by daily wear, bending, friction, and washing. The key lies in improving the reliability of flexible packaging, the robustness of interface connections, and the overall manufacturing process.

High difficulty in mass production: Translating laboratory research requires overcoming challenges such as material costs, complex process compatibility, equipment adaptability, and quality control to achieve large-scale, low-cost, and high-yield production.

6.2. Real-World Tests in Application Implementation

Data Security and Privacy Concerns: Continuously collected physiological data is highly sensitive, and users are extremely concerned about this. A robust end-to-end data encryption system must be established, ensuring secure storage and transmission channels, and clear and transparent mechanisms for managing user data ownership, access rights, and usage policies must be established.

Clinical Validation and Regulatory Thresholds: Products must undergo rigorous clinical trials to demonstrate real-world monitoring effectiveness, long-term safety, and clear clinical value. At the same time, they must meet increasingly stringent and complex medical device regulatory requirements, a necessary step for market launch.

User Acceptance Determines Success: Will users be willing to wear the device long-term? This involves multiple factors, including physiological comfort, device usability, aesthetic design, product price, and perceived data value, requiring in-depth, interdisciplinary design optimization [5].

6.3. Future Breakthroughs

Future development requires a multi-pronged approach: developing a new generation of intelligent fibers and materials with higher performance and stability; improving system integration and intelligence, leveraging edge computing for localized real-time data processing and preliminary decision-making, reducing the burden on the cloud and improving response speed; exploring the integration of multiple monitoring functions into a single fabric platform; establishing unified, scientific performance testing and evaluation standards and industry norms. Of particular importance is strengthening substantive cross-disciplinary collaboration between medicine and engineering, promoting large-scale, prospective clinical studies, and conclusively demonstrating their effectiveness in improving health outcomes. At the same time, we will improve business operations, reduce various expenses, make product prices more affordable, and benefit a wider range of people.

7. CONCLUSION

Wearable electronic textiles are revolutionizing health monitoring by integrating flexible electronic functionality into everyday clothing. Their core value lies in their comfortable, seamless, and long-term collection of critical physiological and biomechanical data, addressing the shortcomings of traditional devices. This opens new avenues for early warning, precise intervention, personalized rehabilitation, and remote management. Practical applications have already demonstrated success, such as smart socks that warn of diabetic foot disease and smart clothing that dynamically monitors and corrects scoliosis, demonstrating their ability to address specific clinical challenges. This technology is rapidly expanding into key medical fields such as cardiovascular, respiratory, and neurological rehabilitation, with the potential to assist in precise diagnosis and treatment, empower patients, and optimize resources.

However, large-scale clinical implementation of electronic textiles still faces numerous challenges: technical improvements in signal stability, battery life, product durability, and mass production capabilities are required; applications must undergo rigorous clinical validation, address key issues such as data security and privacy, establish a regulatory framework, and enhance physician-patient acceptance.

Future breakthroughs will rely heavily on deep collaboration and cross-disciplinary efforts across fields such as materials science, micro-nanoelectronics, intelligent algorithms, clinical medicine, and textile engineering. Only through the close integration and innovation of medicine and engineering can their full potential be unleashed. With the emergence of more advanced intelligent materials, enhanced edge computing capabilities, improved system integration, and the accumulation of solid clinical evidence, wearable electronic textiles are poised to evolve from laboratory concepts into reliable medical-grade tools. This represents a shift toward more comfortable, continuous, intelligent, and preventative health monitoring, ultimately providing strong support for building a personalized, patient-centered, and preventative healthcare system.

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