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Recent Developments in Smart Functional Clothing Technology

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Abstract

Smart functional clothing represents a transformative evolution in the textile and apparel industry, integrating advanced materials, embedded electronics, and intelligent systems into garments that go far beyond traditional functions of protection and aesthetics. Recent developments have accelerated the transition of smart clothing from experimental prototypes to commercially viable products used in healthcare, sports, defense and everyday life. Innovations in electronic textiles, flexible sensors, energy harvesting, artificial intelligence, and sustainable materials are reshaping how clothing interacts with the human body and surrounding environment. This article examines the latest advancements in smart functional clothing technology, explores its multidisciplinary applications, discusses current challenges and highlights future directions that may redefine the role of clothing in modern society.

Keywords: Smart textiles, Wearables, Sensors, Functional clothing

Introduction

Clothing has long been regarded as a passive element of daily life designed to protect the body, ensure comfort, and express personal or cultural identity. In recent years, however, rapid advances in technology have begun to fundamentally transform this perception. The convergence of textile engineering, electronics, material science, and digital innovation has given rise to smart functional clothing, a new generation of garments capable of sensing, processing, and responding to both the wearer and the surrounding environment. These intelligent textiles represent a significant shift from traditional apparel, redefining clothing as an active and adaptive interface between humans and technology (Jiang *et al*., 2021).

Smart functional clothing, often referred to as smart textiles or electronic textiles (e-textiles), integrates components such as sensors, conductive fibres, microprocessors and communication modules directly into fabric structures. Unlike conventional wearable devices that are worn as accessories, smart clothing offers continuous and intimate contact with the human body, enabling more accurate data collection and seamless user experience.

Recent technological breakthroughs have addressed early limitations related to rigidity, durability and washability, allowing smart

garments to retain comfort, flexibility and aesthetic appeal while performing complex functions (Majumdar *et al*., 2019; Wu *et al*., 2022).

The growing interest in smart clothing is driven by increasing demands across multiple sectors, including healthcare, sports, defence and everyday consumer applications. Continuous health monitoring, performance optimization, environmental adaptability, and enhanced safety are now achievable through garments that people already wear as part of their daily routines. As smart functional clothing moves from experimental research into practical implementation, it is poised to play a pivotal role in shaping the future of wearable technology and redefining the relationship between clothing, technology and human well-being (Behera *et al*., 2024).

Technological Foundations of Smart Functional Clothing

i. Electronic Textiles and Embedded Systems

At the core of smart clothing technology lies the development of electronic textiles. Unlike conventional wearables that attach electronic modules onto garments, modern smart textiles integrate conductive fibers, sensors and microelectronics directly into the fabric structure. Conductive yarns made from silver-coated fibers, graphene or carbon nanotubes allow electrical signals to flow through textiles without compromising flexibility or comfort. Recent research has demonstrated the possibility of embedding entire computing systems within individual fibers. These fiber-based systems can store data, perform calculations and communicate wirelessly, enabling garments to function as distributed computing platforms. Such integration minimizes bulk and enhances durability, making smart clothing more suitable for everyday use (Lee, 2020).

ii. Advanced Sensors and Actuators

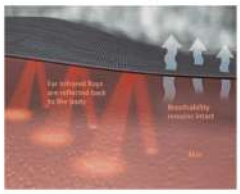
Smart clothing relies on a wide range of sensors capable of detecting physiological, biomechanical and environmental parameters. These include heart rate and electrocardiogram (ECG) sensors, temperature and sweat sensors, motion and posture trackers, pressure sensors, and gas or chemical detectors. The latest developments focus on improving sensor accuracy while maintaining softness, stretchability and breathability. Actuators components that respond to sensor data enable garments to actively adjust their behavior. Examples include heating elements for thermal regulation, shape-memory materials that alter fit or support, and haptic feedback systems that provide tactile cues. Together, sensors and actuators transform clothing into responsive systems rather than passive coverings (Kim, 2025).

Applications of Smart Functional Clothing

i. Aerotherm Technology from Peak Performance

Aerotherm technology is based on aerogel insulation used in ski jackets and pants. Aerotherm was originally developed for NASA and space travel and is therefore capable of blocking both extreme heat and extreme cold. It offers upto 8 times better thermal performance than any other material in the world. It offers excellent breathability and durability, mechanical stretch for great mobility and a 20000 mm water column.

ii. Energear™ Technology (Schoeller)

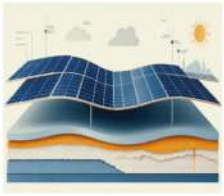


Far infrared rays have numerous positive influences on energetic processes in the body. Far infrared treatments (coatings, prints) with a special titanium and mineral matrix on textiles ensure that the wearer 's energy is reflected back to the body bringing health and fitness benefits. This reflection can increase circulation and oxygen levels in the blood. The new technology allows the heat balance to be optimized and promotes various energetic processes in the body without having an effect on fabric proprieties such as breathability and elasticity. The technology is well fitted in clothing for all sports, summer and winter mountain activities, trekking, work wear and military, as well urban wear (Kruse *et al*., 2024).

iii. Intelligent Compression Sportswear

The development of their woven "intelligent compression" fabrics for swimwear like power skin carbon pro, the first racing suit integrating a carbon cage to deliver intelligent muscle compression, combined with unprecedented fit.

iv. Powered and Warmed by the Sun



Researchers at Georgia Institute of Technology recently developed a fabric that generates electricity from the sun and the wind surrounding the wearer. Garments made from the material could one day power the smartphones or global positioning systems their wearers use every day. To create the material, the researchers used lightweight polymer fibers, photoanodes (the anode of a photoelectron cell), and fiber-based triboelectric nanogenerators. The latter use the triboelectric effect, a type of electrification at contact, and electrostatic induction to generate a small amount of electrical power from mechanical motion, in this case, the wind that blows across the nanogenerators. The photoanodes are used to harvest the sunlight. The anodes, fibers, and nanogenerators are then woven with strands of wool into a 320-micrometer thick fabric that can

be used to make tents, curtains, or wearable garments (Zhang *et al*., 2023).

v. Clothed Cooling

The engineers at Stanford University have developed a low-cost, plastic clothing material that could cool the body more efficiently than natural or synthetic fabrics. The researchers found a type of polyethylene with a specific nanostructure that makes it opaque to visible light, for modesty, yet is transparent to infrared radiation, to let body heat escape. So, in addition to letting perspiration evaporate through the material, something ordinary fabrics already do, the three-ply polyethylene allows thermal radiation, air, and water vapor to pass through, and it is opaque to visible light. They modified industrial polyethylene by treating it with benign chemicals to enable water vapor molecules to evaporate through nanopores in the plastic, allowing the plastic to breathe like a natural fiber. Those who wear the clothing made from the material feel nearly four degrees Fahrenheit cooler than if they wore cotton clothing (Postolache *et al*., 2016).

vi. Artificial-Light Energy Jacket

ThermalTech, from the company of the same name, calls upon energy-absorbing technology embedded in fabric to transform the sun's ultraviolet rays as well as energy from artificial light into heat to warm wearers in minutes. The fabric is made of a 100 percent stainless-steel mesh coated with a solar technology similar to that used for solar water-heaters. The jacket resembles a common lightweight winter coat and warms wearers up to 20 degrees Fahrenheit within two minutes.

vii. Electronic Skin

Xenoma, a company spun-out from the Someya lab at the University of Tokyo in 2015, integrates stretchable circuit and sensor technologies with traditional textiles to remotely monitor the user's motion, respiration, and body temperature for the virtual reality gaming, healthcare, and fitness apparel markets. The stretchable circuit technology allows more than 30 sensors to be integrated into a shirt. The number, type, and location of sensors can be fully customizable. E-skin can be worn like a typical shirt and is machine washable (Shi *et al*., 2020).

viii. One Size Fits All

This is adaptive clothing that grows with children up to seven sizes. This innovative pattern is made from pleated lightweight fabric which machine-washable and recyclable and water and play proof.

ix. Musical Jacket

It has a touch sensitive MIDI keyboard embroidered directly into the fabric using conductive thread. It contains stainless steel filaments, which makes it conductive. The keypad is polyphonic; thus, several keys can be hit simultaneously. Sound is generated by a single-chip General MIDI wavetable synthesizer, and sequences are generated in a microcontroller. The jacket is entirely battery operated, with powered speakers in the pockets.

x. Speedo Fabric (Shark Skin)

SPEEDO Intentional, Japan has developed mimic of sharkskin, which ensures easy swimming. The fastest aquatic creatures have one thing in common: sleek, durable skin that lets them slice through the water. Following their lead, the speedo fabric has been developed. The sharkskin is made from specially developed polyamide and Lycra fibre coated with Teflon to prevent water penetration.In addition, this fabric is knitted with 3-dimenssional V- shaped groove with 3-D knitting principal. With help of this V-shaped groove, the friction between water and swimmer is negligible and drag up to zero. This increases the efficiency of the swimmer by 8-10%. These fabricated textiles are water repellent, chlorine resistant and super-quick to dry (McCann, 2023).

xi. Jogging Suit

The Brussels, Belgium based research lab, Star Lab has developed a suit which monitors the heart

beat, and then plays certain type of music, adopting the rhythm to push the wearer faster or slower. A mobile phone in clothing can send the data by e-mail to wearer's club. This suit has several layers with heat sensor and microphones embedded in cuffs and collars to measure light and sound. From outside it measures the weather and from inside it monitors wearer's biophysical state by analyzing this internal and external characteristics, the jogging suit can suggest the duration and intensity of exercise. A microchip card inside the suit can sense when jogger is tired and suggest him to continue or rest. In addition, if something dangerous does happen it can intimate a doctor.

xii. Wind Stopper Fabric

These types of fabrics are used during trekking on mountain in windy weather. Windproof clothing prevents convective heat transfer. Convective heat loss is a significant factor in causing discomfort. In cool or cold, windy condition windproof clothing keeps us warmer by preventing convective heat loss (the wind chill effect) and the discomfort associated with it. When wearing a windproof layer, we can maintain our warmth with less insulation in windy conditions. Wind stopper products are typically coated with DWR (Durable Water Repellent), which provides them with a modest degree of water resistance (Ramlow *et al*., 2021).

xiii. Cool Shirt Refrigerated T-shirt

Cool Shirt is a company that make a neat refrigerated shirt. This company offers many different solutions for cooling from small scale to industrial solutions. The cooling comes from a non-flammable CFC-Free solution that flows through about 50 feet of tubing. The fluid is stored in a replaceable 12oz Port-a-cool can. It offers instant relief on hot days.

xv. Touch Sensitive Fabrics

Imagine a roll-up QWERTY keyboard, a jacket that interfaces with your mobile phone, a television remote control sewn into the arm of a sofa or light switches embedded in curtains and carpets. A unique technology developed to enable textiles to function as interfaces to control any type of electronic device also called SOFT Switch. Essentially, this means that soft flexible fabrics can be used in place of conventional hard switches, keypads, keyboards, buttons or knobs. Soft switch fabrics can interface directly with any type of electronic device without the need for signal processing or complex software (Behera *et al*., 2024).

xvi. Thermochromic Colour

Thermochromic textiles change colour with heat. They are engineered to change colour at a particular temperature. There are serious medical uses as well as novelty ones, e.g. liquid crystal fabric strip thermometers, & baby sleep-suits to monitor temperature.

Challenges and Limitations

Despite remarkable progress, smart functional clothing still faces challenges. Manufacturing complexity, high production costs, and limited standardization hinder large-scale commercialization. Durability under repeated washing, long-term comfort, and reliable power management remain critical technical hurdles. User acceptance is another key factor. Consumers must perceive clear benefits without sacrificing comfort, style, or affordability. Addressing these challenges requires collaboration between engineers, designers, healthcare professionals, policymakers, and industry leaders (Kruse *et al*., 2024).

Conclusion

Recent developments in smart functional clothing technology mark a significant shift in how we perceive and interact with apparel. By merging textiles with electronics, artificial intelligence, and advanced materials, clothing is evolving into an intelligent interface that enhances health, performance, safety, and everyday comfort. While technical and ethical challenges remain, ongoing research and interdisciplinary collaboration

continue to push the boundaries of what smart clothing can achieve. As innovation accelerates and costs decline, smart functional clothing is poised to move from specialized applications to mainstream adoption. In the near future, garments may become as intelligent and indispensable as smartphones seamlessly embedded in daily life, quietly working to support human well-being, efficiency, and expression.

References

Behera, S.A., Panda, S., Hajra, S., Kaja, K.R., Pandey, A.K., Barranco, A., Jeong, S.M., Vivekananthan, V., Kim, H.J., & Achary, P. G. R. (2024). Current trends on advancement in smart textile device engineering. *Advanced Sustainable Systems*, *8*(12), 2400344.

Jiang, S., Stange, O., Bätcke, F. O., Sultanova, S., & Sabantina, L. (2021). Applications of smart clothing–a brief overview. *Communications in Development and Assembling of Textile Products*, *2*(2), 123-140.

Kim, S. H. (2025). Integration of flexible solid-state thin-film batteries for smart functional clothing applications. *Journal of the Korean Ceramic Society*, *62*(1), 13-45.

Kruse, K., Sauerwein, W., Lübben, J., & Dodel, R. (2024). Smart technologies and textiles and their potential use and application in the care and support of elderly individuals: A systematic review. *Reviews on Advanced Materials Science*, *63*(1), 20230174.

Lee, H. (2020). A study on the development of a user-focused multi-functional convergence-smart-fashion product. *Heliyon*, *6*(1).

Majumdar, A., Gupta, D., & Gupta, S. (Eds.). (2019). *Functional textiles and clothing*. Springer Singapore.

McCann, J. (2023). Collaborative design principles for smart clothing. In *Smart Clothes and Wearable Technology* (pp. 283-325). Woodhead Publishing.

Postolache, G., Carvalho, H., Catarino, A., & Postolache, O. A. (2016). Smart clothes for rehabilitation context: technical and technological issues. In *Sensors for everyday life: healthcare settings* (pp. 185-219). Cham: Springer International Publishing.

Ramlow, H., Andrade, K. L., & Immich, A. P. S. (2021). Smart textiles: an overview of recent progress on chromic textiles. *The journal of the textile institute*, *112*(1), 152-171.

Shi, J., Liu, S., Zhang, L., Yang, B., Shu, L., Yang, Y., Ren, M., Wang, Y., Chen, J., Chen, W., & Tao, X. (2020). Smart textile-integrated microelectronic systems for wearable applications. *Advanced materials*, *32*(5), 1901958.

Wu, S., Zeng, T., Liu, Z., Ma, G., Xiong, Z., Zuo, L., & Zhou, Z. (2022). 3D printing technology for smart clothing: A topic review. *Materials*, *15*(20), 7391.

Zhang, Y., Xia, X., Ma, K., Xia, G., Wu, M., Cheung, Y.H., Yu, H., Zou, B., Zhang, X., Farha, O.K., & Xin, J. H. (2023). Functional textiles with smart properties: their fabrications and sustainable applications. *Advanced functional materials*, *33*(33), 2301607.