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Perspective

The rise of intelligent fabric agent from mass-produced advanced fiber materials

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Artificial intelligence (AI) is crucial in driving scientific, technological, and industrial advancements, and it has given rise to an ambient intelligence that can potentially improve the physical execution of healthcare delivery [1,2]. Among diverse advanced AI technologies, an intelligent agent with multi-parameter perception, decision-making, and execution capabilities demonstrates the potential for facilitating the development of next-generation optoelectronic devices. The intelligent agent is a physical or abstract entity that acts autonomously, perceives and interacts with its environment, and communicates with other agents [3]. It could perceive dynamic environmental conditions, execute actions, and make appropriate decisions. Fabric emerges as an ideal carrier for human-centered intelligent agents, providing various properties such as perceptibility, adaptability, and wearability. Intelligent fabric, known for its unique functionality, has attracted considerable attention from academia and industry. In 2014, Germany proposed a national strategy called FutureTEX to upgrade the entire textile industry by promoting integration between textiles and other fields. Two years later, the United States announced the establishment of the Revolutionary Fibers and Textiles Manufacturing Innovation Institute, which intends to accelerate the revival of fabric manufacturing. Compared with conventional fibers, revolutionary fibers focus on the design of multiple materials and structures, enabling the integration of various functionalities into a single fiber. Particularly in the United States, the advent of the digital revolution, advancements in Internet of Things technology, and mature fiber technology significantly boost the development of the intelligent fiber industry. Notable commercial applications of intelligent fibers are gradually emerging. Project Jacquard, a collaborative effort by Google and Levi's, presents an intelligent jacket that combines the washability and texture of standard fabrics with the interactive functionalities of electronic products. Apple Inc. has developed intelligent garments, accessories, and household items with capabilities to "read" physiological indicators such as weight, body temperature, and sedentary duration on sofas.

Herein, we proposed an intelligent fabric agent based on mass-produced advanced functional fibers with multiple materials and hierarchical structures, which was used to establish a flexible "human-fabric-environment" intelligent system for achieving intelligent health management in complex environments (Fig. 1). The intelligent fabric agents can allow them to detect, monitor, or respond to multiple physical and chemical stimuli within the human body and the surrounding environment. Their adaptability provides adequate protection for the human body in complex and dynamic environments, such as high solar irradiation, harmful substances, and strong forces. Their wearability allows for adaptation to body movements or skin actions while ensuring good air permeability and biological compatibility to prevent skin irritation or discomfort. According to their intelligent functions, intelligent fabric agents are divided into three categories: health protection agents, vital signs monitoring and motion analysis agents, and human–computer interaction agents. They present excellent, intel-

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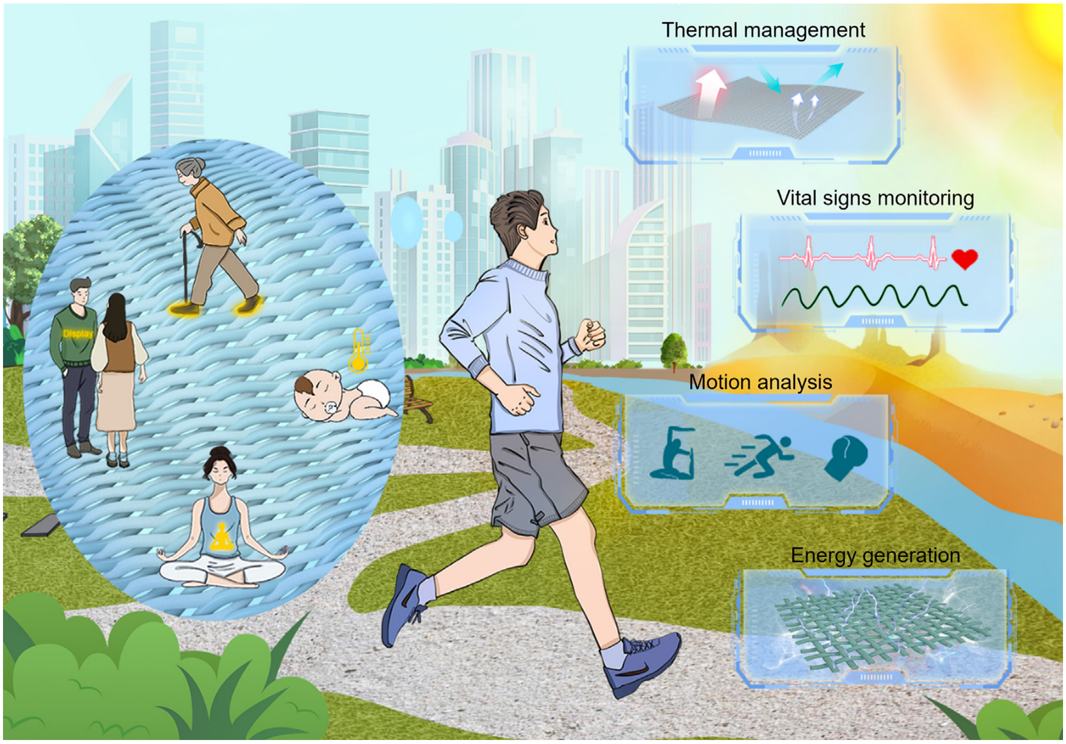

Fig. 1. (Color online) Illustrztion of the real-life applications of intelligent fabric agents from mass-produced advanced fiber materials. Facing complex life scenes in the future, intelligent fabric agents, integrated into essential items such as clothing, carpets, and other objects in daily life, have a variety of functions, such as physiological information monitoring, activity recognition, color change, and temperature regulation. Due to their comfort, aesthetics, and privacy properties, intelligent fabric agents would be utilized as a seamless connection between humans and the environment in living space.

ligent characteristics in different scenarios to expand their health services in real and virtual worlds.

Health protection agents can be established on protective garments, accessories such as headbands, sleeves and gloves, blankets, and other devices. It provides all-around protection for the human body in a lightweight and flexible way and prevents exposure to high-intensity light, heat, impact, poison gas, bacteria, etc. For instance, the intense solar radiation during summer would lead to skin aging and heat stroke [4]. Intelligent fabric agents with spectral selective ability would protect people from solar radiation, exhibiting excellent potential for passive cooling regulation of the human body [5]. The individuals working in high-risk environments are vulnerable to impact-related injuries. Structured fabrics consisting of two layers of interlocked granular particles can solve this problem. They can bend, fold, and drape freely over curved objects, and can switch reversibly between wearing comfort and strong protection in different topologic states [6]. Furthermore, by incorporating copper ions into the cotton structure at the molecular level, intelligent cotton textiles have been prepared that exhibit high antiviral and antibacterial effects and show great potential in household products, public facilities and medical settings [7].

Vital signs monitoring and motion analysis agents create a flexible, intelligent sensing network to achieve long-term and stable acquisition, processing, and real-time physiological signals and motion information analysis. This can be achieved by integrating multifunctional materials into fibers and designing hierarchically structured intelligent fabric agents. They can allow highly sensitive acquisition and analysis of signals and intelligently classify the data via deep neural networks. This enables real-time monitoring and early warning of pulse, breathing, gestures and body posture [8–11]. Furthermore, intelligent fabric agents capable of long-term noninvasive evaluation of cardiovascular disease and sleep apnea syndrome would be developed [12]. They can avert freezing of gait in patients with Parkinson's disease and help them achieve longer strides, significantly expanding their application in medical care [13].

Human-computer interaction agents can function as display and presentation platforms, transmitting information to the external environment through light, color, sound waves, and more. For example, large-scale luminescent fabrics demonstrate their great potential in interaction, communication, and navigation [14–16]. Furthermore, an intelligent fabric microphone would be applied in physiological monitoring and communication [17]. Notably, intelligent fabric can significantly improve the functionality of augmented reality devices, including prosthetics, robotic grasping systems, and human–computer interaction systems [18,19].

With the advancement of materials, electronics, and computer technology, fiber has progressively evolved from a single-function entity to a multifunctional device. Following "Moore's Law" for fibers, various multifunctional materials and devices can be continuously integrated into fiber and fabrics. This progression heralds the emergence of novel multifunctional fabric systems capable of sensing, communication, diagnosis, treatment, and data storage. In addition, the booming fabric industry would promote the rapid development of intelligent fabric agents. Since 2020, global chemical fiber production has proliferated. The global market value of fabric products amounts to USD 961.5 billion, with apparel accounting for approximately 75%, technical fabrics around 12%, and household goods about 9%. Approximately 90 billion articles of clothing, or 62 million tons, are produced and sold annually

[20]. The intelligent fabric agent incorporates advancements in fabric technology, wearable technology, machine learning technology, and intelligent devices into the field of human health. It will significantly impact remote healthcare diagnosis, maintenance, and rehabilitation.

To develop an intelligent fabric agent for everyday use, its fibers should consist of various mass-produced advanced materials to achieve multifunctionality. However, integrating multiple functions within a single fiber presents a significant challenge. Moreover, in multifiber braided fabrics, inter-layer instability and intra-layer device interactions impose limitations on the assembly accuracy and layout design of multifunctional fiber devices. Therefore, regulating the physical and chemical properties of fabrics, yarns, and even fibers becomes essential through modification processes. The realization of the entire process encompassing spinning, weaving, and post-processing of mass-produced advanced functional fibers or any modification within these stages poses an immense challenge. Currently, the main difficulties in designing and fabricating intelligent fabric agents can be summarized as follows: Firstly, the fibers must possess a specific capacity to regulate, quantify, or convert energy (both physical and chemical signals) within the human body and the surrounding environment to achieve multifunctionality within a single fiber. The preparation of multifunctional fabric involves integrating multiple fibers. Secondly, modifying the polymer and inorganic material should not significantly damage its original mechanical and diverse functionalities, thereby ensuring the durability and functionality of fibers and fabrics in multi-scenario applications. Bio-based materials are favored because of their degradability, but their mechanical properties and scalability still need further improvement. In addition, the fabric must maintain its multifunctionality and preserve its inherent flexibility, wearability, and comfort performance. Finally, fiber manufacturing can be rapidly integrated into the traditional textile industry for mass production.

In conclusion, the critical technology of constructing an intelligent fabric agent is to ensure multifunctional performance without decreasing the softness, breathability, or mechanical robustness required for practical use. The precise preparation of multifunctional fiber and the development of highly integrated technology of multifunctional fiber will lay a solid foundation for human-centered intelligent fabric agents. Therefore, this perspective proposes the following suggestions for developing intelligent fabric agents from mass-produced advanced fiber materials: Firstly, achieving multifunctional integration is crucial. To achieve mass-produced advanced functional fibers and fabrics with exceptional performance, hierarchical structures, multi-material composites, and material interfaces should be optimized to facilitate efficient energy conversion. For example, composite materials, such as organic/inorganic hybrids, can achieve structural and functional integration of fibers and fabrics. This effectively addresses the industry challenge of balancing functionality and comfort. Additionally, it is crucial to adapt to the application requirements of multiple scenarios and sustainable development. High-performance and functional fibers are selected to fabricate intelligent fabric agents to protect the human in complex environments. Raw materials should adhere to principles such as "renewable and low-carbon" and focus on expanding the utilization of bio-based materials like polylactic acid in intelligent fabrics. This approach aims to accelerate the sustainable development of the fabric industry. Finally, scientists aim to maintain excellent service performance while developing cutting-edge, original, and innovative intelligent fabric agents. They also consider practical production and application challenges to gain recognition from scientific communities and the public. Collaboration between experts in traditional chemical fiber industries and intelligent fiber technologies is crucial for enhancing service performance aspects such as sensitivity, stability, washability, and flexibility. This will promote the widespread adoption of intelligent fabric agents into people's daily lives.

Conflict of interest

The authors declare that they have no conflict of interest.

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