Body-coupled smart fibers: Enhancing seamless integration and efficiency in medical human-machine interaction

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Human-machine interaction (HMI) has always been at the frontier of technological innovation, making our interactions with technology more intuitive and efficient, as well as driving much of the research interest in this field. Wearable electronic systems can seamlessly and accurately receive, store, process, and output information. This endows them with tremendous potential applications ranging from daily life interactions to monitoring physiological signals and clinical medical treatments. Building upon this foundation, researchers have embarked on a series of innovations concerning textile fibers' materials, manufacturing techniques, and further functional payloads.[1] However, integrating the textile electronic systems, which still primarily rely on the classic von Neumann architecture paradigm, consisting of sensors, actuators, energy storage, harvesters, and rigid silicon-based processors, with dynamic human bodies poses significant challenges.

Yang et al. reported in *Science* that a novel intelligent fiber integrates wireless energy harvesting, information sensing, and transmission functionalities and can

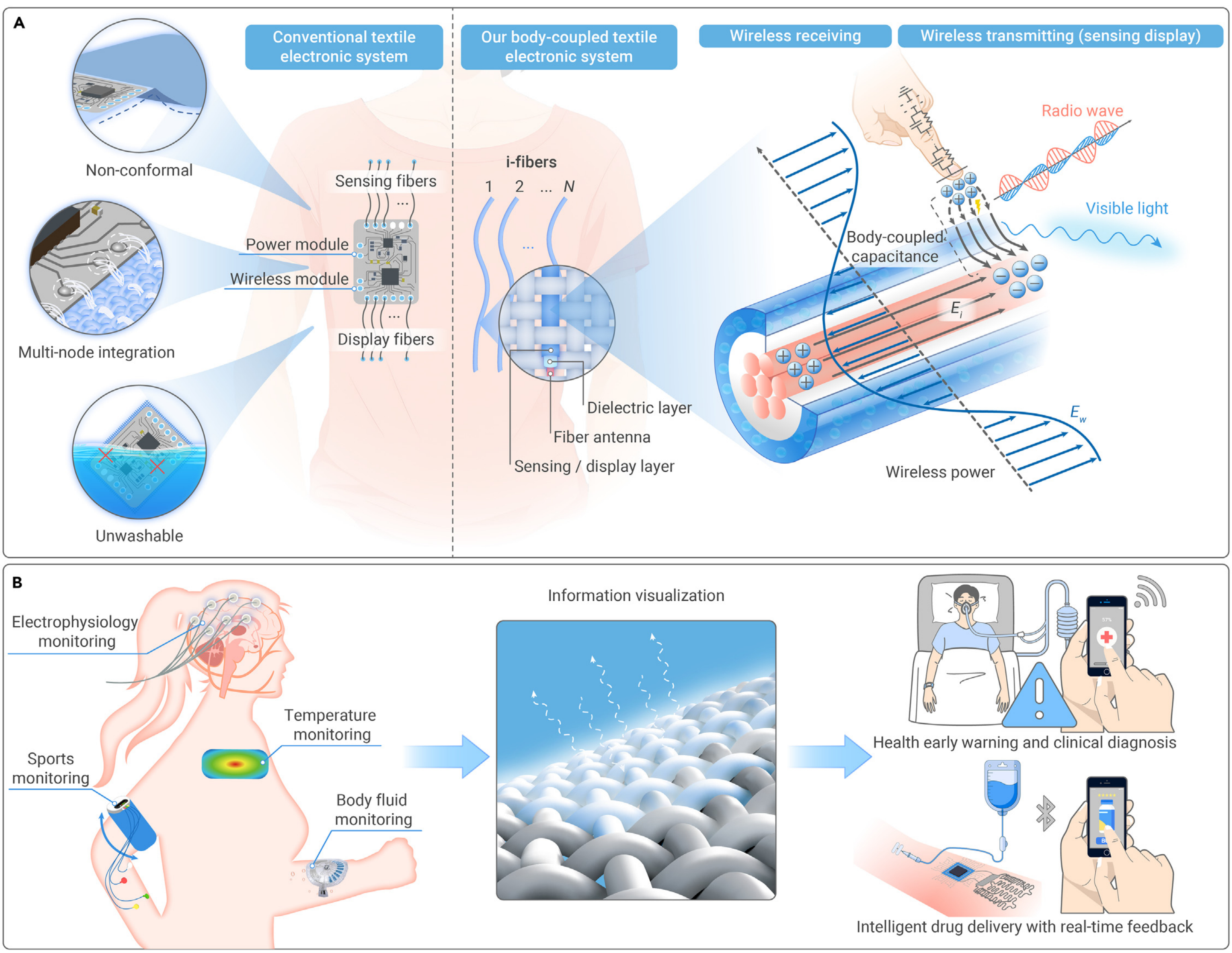

Figure 1. Schematic illustration of body-coupled interactive fiber design and harvesting of ambient electromagnetic energy (A) Comparison between current wireless interactive textile system (left) based on integrated circuit chips and i-fiber system (right). (B) Schematic of i-fiber's applications in the medical human-machine interaction field. Reproduced with permission.[2] Copyright 2024, The American Association for the Advancement of Science.

interact with the human body.[2] This study proposed an energy interaction mechanism based on "body-coupling," enabling smart textiles woven according to this mechanism to achieve touch control, luminous display, and other HMI functions without relying on chips and batteries (Figure 1). This body-coupled optical fiber electronics technology can generate bound charge pairs between the body and electronic optical fibers, which can alternate between bound and radiative states to transmit sensing signals wirelessly. The proposed solution introduces electric-field-sensitive luminescent dielectrics into body-coupled interactive fibers (i-fibers) to utilize the human body's high relative permittivity and conductivity to couple electromagnetic energy. This integrated design strategy efficiently overcomes the constraints of chips, batteries, and other rigid components.

The structure of the optical fiber comprises three functional layers: a silver-plated nylon fiber core to induce alternating electromagnetic fields, a dielectric layer doped with barium titanate ($BaTiO_3$) to store coupled electromagnetic energy, and an optical layer doped with zinc sulfide (ZnS: Cu^{2+}) to display electric fields. When the i-fiber comes into contact with the human body, a capacitive interface is formed between the body and the fiber, acting as a conduit for energy exchange. This allows i-fibers to sense and capture electromagnetic energy from the surrounding environment, such as energy emitted from smartphones or power lines or generated through textile friction. The human body, with its significantly higher dielectric constant ($\varepsilon \approx 78$) and conductivity ($\sigma \approx 0.6$ S m−1) compared to air, acts as an efficient conduit for electromagnetic energy, establishing a closed-loop energy pathway that encompasses the coupling path, the human body path, and the return path to the ground. In this process, the conductive core of the i-fiber functions as a combination of inductors and resistors. Interaction with external power sources and the capacitive pathways formed by the fiber facilitates the transmission of electromagnetic energy. The modulation and transmission of wireless optical and electrical signals are facilitated through the interface contact capacitance generated when the i-fiber comes into contact with the human body. As contact occurs, this capacitance forms, increasing the electric field strength in the contact area. During this process, ions' and electrons' high-speed collision and movement create a transient conductive path in the air. This localized discharge event not only triggers the luminescent material within the i-fiber to produce a visible optical signal but also generates a rapidly changing displacement field, thereby modulating a radio signal. This signal modulation mechanism relies directly on the electrostatic interaction between the human body and the i-fiber rather than on complex analog circuits or multiple electronic components. Furthermore, by altering the thickness of the dielectric layer in the i-fiber, the intrinsic capacitance can be adjusted, thereby modulating the frequency and amplitude of the radio signal. The frequency of the optical signal is typically influenced by the stimulating signal, with an increase in electromagnetic frequency causing a blue shift in the spectral peak wavelength. This signal modulation and transmission mechanism endows i-fibers with vast potential applications in smart textiles and wearable devices.

The core innovation of this study lies in integrating electronic assemblies into a single fiber capable of wireless energy harvesting and signal transmission without additional chips or batteries. This paradigm-shifting development introduces a new era of chipless intelligent fiber technology, underpinned by body-coupling mechanisms, that unlocks many opportunities, particularly within medical monitoring and patient care. This body-coupling mechanism revolutionizes the landscape of medical applications, with potential uses including real-time monitoring of patient physiological signals; continuous health tracking for individuals with chronic illnesses; and facilitating rapid, effective interventions in emergency medical scenarios. Integrating sensors into garments, enabling the wireless transmission of health data without the need for batteries or chips, significantly enhances patient compliance and comfort during extended monitoring periods. These smart fibers could be further functionalized to produce nanofibers with tailored properties for specific medical applications when integrated with electrospinning techniques.[3] Electrospun fibers, favored for their exceptional surface area-to-volume ratio and porosity, are already utilized in drug delivery systems and tissue engineering scaffolds.[4,5] The combination of body-coupled smart fibers with electrospinning could lead to the development of smart bandages that not only monitor wound-healing progress but also deliver targeted medications to the wound site, ensuring optimal dosage and minimal side effects. Moreover, these intelligent fibers can be employed in non-invasive treatments, such as promoting wound healing through electrical stimulation or administering medication via microfluidic technology, providing patients with more comfortable and personalized treatment options. These advancements are expected to enhance care standards by equipping medical professionals with high-tech, user-friendly tools that facilitate diagnosis, monitoring, and treatment. Beyond revolutionizing medical monitoring and patient care, the fibers hold vast potential in applications ranging from intelligent clothing and security surveillance to human-computer interactions, smart home automation, environmental sensing, military communication, educational tools, artistic installations, and transportation monitoring. The wireless nature and body-coupling mechanism of i-fiber technology promise to deliver comfortable and personalized smart solutions across various domains, underscoring its significant role in enhancing user experiences and quality of life in the future.

Despite its groundbreaking features, i-fibers face challenges and limitations in real-world applications. Firstly, the functionality of the i-fiber depends on harvesting energy from environmental electromagnetic fields and transmitting wireless signals, which can be disrupted by external environmental factors. Ensuring the stability of these signals is a crucial issue that needs to be addressed. Moreover, the wireless power transmission component of i-fibers relies on capacitive coupling generated by the contact between human skin and the luminescent materials on the fiber's surface, which presents design challenges for non-body-hugging textile products.

In conclusion, by harnessing the natural properties of the human body to couple with environmental electromagnetic energy, chipless body-coupled smart textiles provide a feasible pathway to surpass the limitations of traditional silicon-based systems. The potential of this technology for seamless integration, energy efficiency, and enhanced user comfort holds it as a promising candidate to advance the development of the next generation of human-machine interfaces.

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DECLARATION OF INTERESTS

The authors declare no competing interests.