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Multifunctional Fiber-Enabled Intelligent Health Agents

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The application of wearable devices is promoting the development toward digitization and intelligence in the field of health. However, the current smart devices centered on human health have disadvantages such as weak perception, high interference degree, and unfriendly interaction. Here, an intelligent health agent based on multifunctional fibers, with the characteristics of autonomy, activeness, intelligence, and perceptibility enabling health services, is proposed. According to the requirements for healthcare in the medical field and daily life, four major aspects driven by intelligent agents, including health monitoring, therapy, protection, and minimally invasive surgery, are summarized from the perspectives of materials science, medicine, and computer science. The function of intelligent health agents is realized through multifunctional fibers as sensing units and artificial intelligence technology as a cognitive engine. The structure, characteristics, and performance of fibers and analysis systems and algorithms are reviewed, while discussing future challenges and opportunities in healthcare and medicine. Finally, based on the above four aspects, future scenarios related to health protection of a person's life are presented. Intelligent health agents will have the potential to accelerate the realization of precision medicine and active health.

1. Introduction

The World Health Organization defines health technology as "devices, drugs, medical, and surgical procedures—and the knowledge associated with these—used in the prevention, diagnosis, and treatment of disease as well as in rehabilitation, and the organizational and supportive systems within which care is provided".[1] The realization of precision medicine and personalized healthcare on the edge is key to promoting a comprehensive health ecosystem.[2] Currently, bulky and rigid medical and health devices are widely being used, but the end user experiences discomfort in protection, diagnosis, surgery, and treatment processes. For instance, during gastroscopy, the use of a conventional examination device can cause difficulty in swallowing, thus affecting its examination performance. In contrast, due to their flexible form and strong adaptability, fibers can be navigated through complex anatomical structures of human body and access deep lesions, whereas fabrics can form a close and comfortable network around the body, adapting to healthy people, patients, and medical staff. In recent years, the use of multifunctional fibers and fabrics has led to significant progress in the fields of physiological signal monitoring,[3] rehabilitation and treatment,[4] health protection, and minimally invasive surgery (MIS).[5] In brief, fiber materials with highly adaptable functionalities have the potential to further promote development of health technology toward more

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imperceptible and comprehensive methods for protection, diagnosis, surgery, and treatment.

Multifunctional fibers that can see, hear, sense, and communicate were proposed in 2007.[6] Following their introduction, multifunctional fiber and fabric technology based on multimaterial fiber manufacturing[7] has attracted great attention of both academia and industry. The rapid progress in flexible electronic technology and development of materials, electronics, medicine, and computer technology, functional fibers, and fabrics has led to their gradual evolution from a single function[8] to multifunctional integration with intelligence.[9] Progress has been made in harnessing intelligence for fibers and fabrics, such as weaving conductive weft and luminescent warp fibers to form micrometer-scale electroluminescent units in large-scale fabrics,[10] embedding high-performance semiconductor chips in flexible polymer fibers for short-haul optical communication, and basic physiological state detection of the human body.[11] The improvements include knitting piezoresistive fibers into tactile fabrics and using machine learning for haptic correction and calibration, to reveal human–environmental spatial information and discover biomechanical characteristics.[12] Also, electroactive materials and electrodes have been integrated via thermal drawing[13] and continuous coating,[14] to form ultralong flexible battery fibers that provide universal energy to the arbitrary geometrical electronic systems mentioned above.

The integration of physical, cyber, and biological spaces witnesses a new generation of technological revolution. More profound and personalized healthcare requires health technologies to penetrate our daily activities with imperceptibility, versatility, and intelligence. For instance, clinical medicine, biomedical engineering, statistics, and information technology engineering have been integrated to develop the "COVID-19 Intelligent Diagnosis System" based on Internet of Things (IoT) technology for rapid diagnosis, convenient detection, and precise treatment of diseases under COVID-19 pandemic. The access of computer science and medicine to daily activities necessitates pervasive interfaces for intelligent health.

The comprehensive solution of the healthcare system has been presented from the perspective of intelligent matter.[15] However, three fundamental challenges in intelligent health should be addressed in order to create an active user-oriented health model: 1) Imperceptible interaction: Long-term health monitoring, protection, MIS, and treatment require system maintenance, diagnosis, treatment, and decision analysis from physicians, surgeons, and professionals. The substantial cost of human resources and maintenance has prompted the need for medical and health equipment to conduct multimodal acquisition and multi-perspective cognition. A more comprehensive medical and health system requires self-adaptive learning of equipment from multi-environment and scenes, physicians, and surgeons in judgment and decision-making during the interaction process. In accordance with the health and medical logic of people, imperceptible interaction reduces the discomfort of the user as much as possible. 2) Cost-effective manufacturing: The manufacturing technology of devices with diverse demand and fine functionality needs to be closely integrated with the fundamental manufacturing industry, aiming to realize cost-effective, reliable, and high-quality production. Their affordability can reduce the difficulty of users in obtaining system services, improving the system application range. 3) User-friendliness: An intelligent medical system must be able to achieve efficient, massive, and long-term information exchange among physicians, surgeons, nurses, patients, and management personnel. In view of this, the intelligent medical system should conduct data-driven service iteration and optimization to deal with various in-depth and user-friendly medical and health scenarios.

To address the aforementioned challenges, here, an intelligent agent is proposed, which is based on multifunctional fibers as a key sensing unit and artificial intelligence (AI) as a cognition unit that is autonomous, perceptual, miniature, and adaptive, serving for the field of healthcare. In addition, combined with the requirements of human healthcare, the latest progress of multifunctional fibers and AI algorithms in the four health fields of health monitoring, therapy, protection, and MIS is summarized. Based on multifunctional fibers and AI technology, "intelligent health agents" offer accurate perception, collaboration, and interaction to support the medical and healthcare field. Through life-long learning and multitechnology integration assisted by these agents, human–computer interaction can be realized in various forms and scenarios.

The contributions of this paper can be summarized as follows: 1) An intelligent health agent driven by multifunctional fibers is proposed and its performance is analyzed in four areas, that is, health monitoring, physical rehabilitation and treatment, thermal comfort management, and fiberbots. 2) The structure, characteristics, and performance of current multifunctional fibers used in the medical and health field are summarized in four areas, that is, health monitoring, therapy, protection, and surgery. Functional categories, system limitations, system integration, and platform deployment are discussed. 3) Future development, opportunities, and challenges of intelligent health agents are presented.

2. Intelligent Health Agents

An agent in the field of AI[16] has evolved from human archetypes to perform actions for certain goals. Since their introduction, intelligent agents have been utilized in various fields, such as autonomous driving, industrial automation, and healthcare.

Traditional healthcare relies on the expertise of physicians and surgeons, as well as short-term instrument-oriented measurements. Additionally, data-collection methods are limited to a short time window, leading to subjective deviation in certain cases. Multifunctional fibers bring health technology closer to the human body for multimodal data collection under long-term imperceptible interaction. Thus, more accurate results and predictions with more reference values can be obtained. Therefore, intelligent health agents based on flexible fibers with multiple forms of appearance, deployment methods, and multitechnological cores, have been proposed to satisfy the needs of intelligent human–computer interaction in the medical and healthcare fields. With physical science as a bridge, intelligent health agents connect medicine and computer science, and promote efficiency, intelligence, and convenience in the medical field, as illustrated in **Figure 1**a.

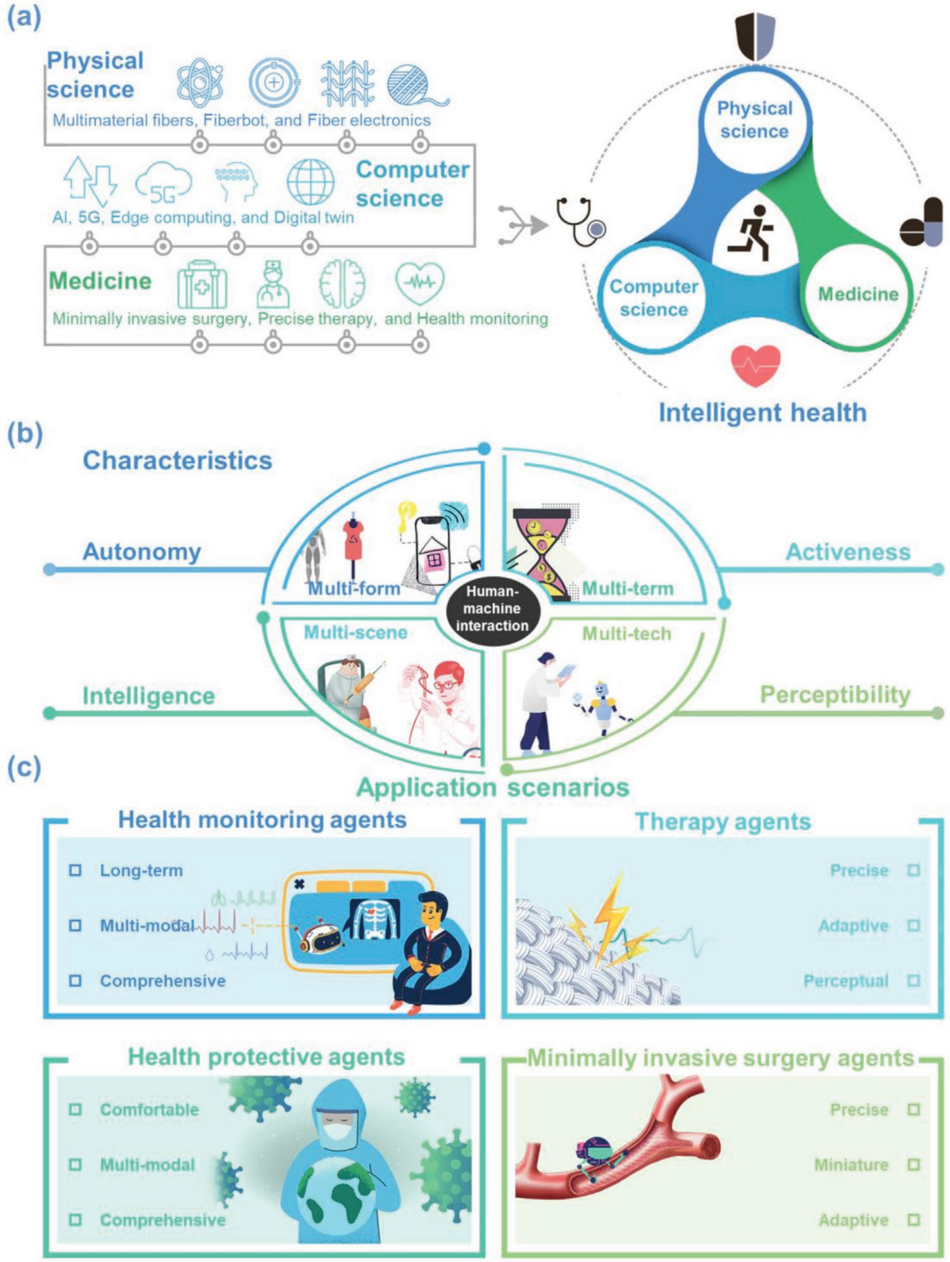

Figure 1. Intelligent health agents. a) With physical science as a bridge, intelligent health agents connect medicine and computer science to promote high efficiency, intelligence, and convenience in fields related to intelligent health with fusion of technologies such as multimaterial fibers, fiberbots, fiber electronics, AI, 5G, edge computing, digital twins, minimally invasive intervention, precise therapy, and health monitoring. b) The primary characteristics of multitech-based multiform intelligent health agents deployed in multi-scenes for long-term companions are autonomy, activeness, intelligence, and perceptibility. c) According to the main application scenarios, intelligent health agents are divided into four categories that provide services: health-monitoring agents, therapy agents, health-protection agents, and MIS agents.

The main features of intelligent health agents are presented in Figure 1b: 1) Autonomy: An agent decides and controls its own behavior derived from its internal state and environmental information acquired through its own resources and operation mechanism for autonomy. 2) Activeness: An agent can voluntarily perceive its operating environment and can actively respond to relevant events based on the requirements of a specific scenario. 3) Intelligence: An agent is equipped with a series of AI algorithms to have a strong cognitive ability. 4) Perceptibility: An agent based on flexible multifunctional fibers can be indiscernibly integrated around or deployed inside the human body; an agent can conduct wide-range and high-precision perception.

Distinct scenarios demonstrate various service characteristics, such as long-term, completeness, and multimodal aspects. With intelligent agents as specific service carriers, this paper proposes health-monitoring agents, therapeutic agents, health-protection agents, and MIS agents that can expand over both real and virtual worlds for intelligent health, as shown in Figure 1c.

3. Health-Monitoring Agents

Current health-monitoring devices include conventional diagnosis devices, wearable electronic devices, and fiber electronic devices. Conventional diagnosis devices require in-hospital treatments, which are time-consuming and include redundant steps.[17] Wearable electronic devices paved us a way to sense the real-time health status of the user via prolonged, efficient services. Patch-derived sensors provide multimodal data acquisition close to the human body with enhanced flexibility for mechanical matching with skin. However, the compatibility of patches with daily activities of wearers poses inherent compliance challenge for long-term monitoring contributing to potential wetting effects. To further prolong the time window of health monitoring, fibers, yarns, and fabrics are old yet ideal candidates for wearables due to their light weight, good air permeability, and ability to ensure user comfort. With a multimaterial fabrication scheme, materials with distinct properties can be integrated into fibers, to enable various vital sign sensing, such as force, temperature, humidity, respiration, and pulse. Through well-developed fabric techniques, functional fibers can be seamlessly integrated into daily clothing and home furnishings, such as jackets, shirts, socks, and mattresses.[18] Moreover, the incorporation of deep learning can promote the adaptability of functional fibers during health monitoring. Health-monitoring agents enabled by multifunctional fibers can acquire, process, and analyze real-time multi-signals in the long term (**Figure 2**). The latest progress of multifunctional fibers in the area of health monitoring is summarized in this section, and interdisciplinary system integration and prospects of health-monitoring agents, are introduced. Finally, the challenges faced by health-monitoring agents will be analyzed.

3.1. Multifunctional Fibers for Information Acquisition

Physical and biomedical signals close to body can directly reflect human health conditions in the prophase, which enables timely warning and recognition on subclinical diseases. Multifunctional fibers with extreme aspect ratio can be constructed with multiple stimuli-responsive materials. When exposed to human–matter interfaces, the designed multifunctional fibers

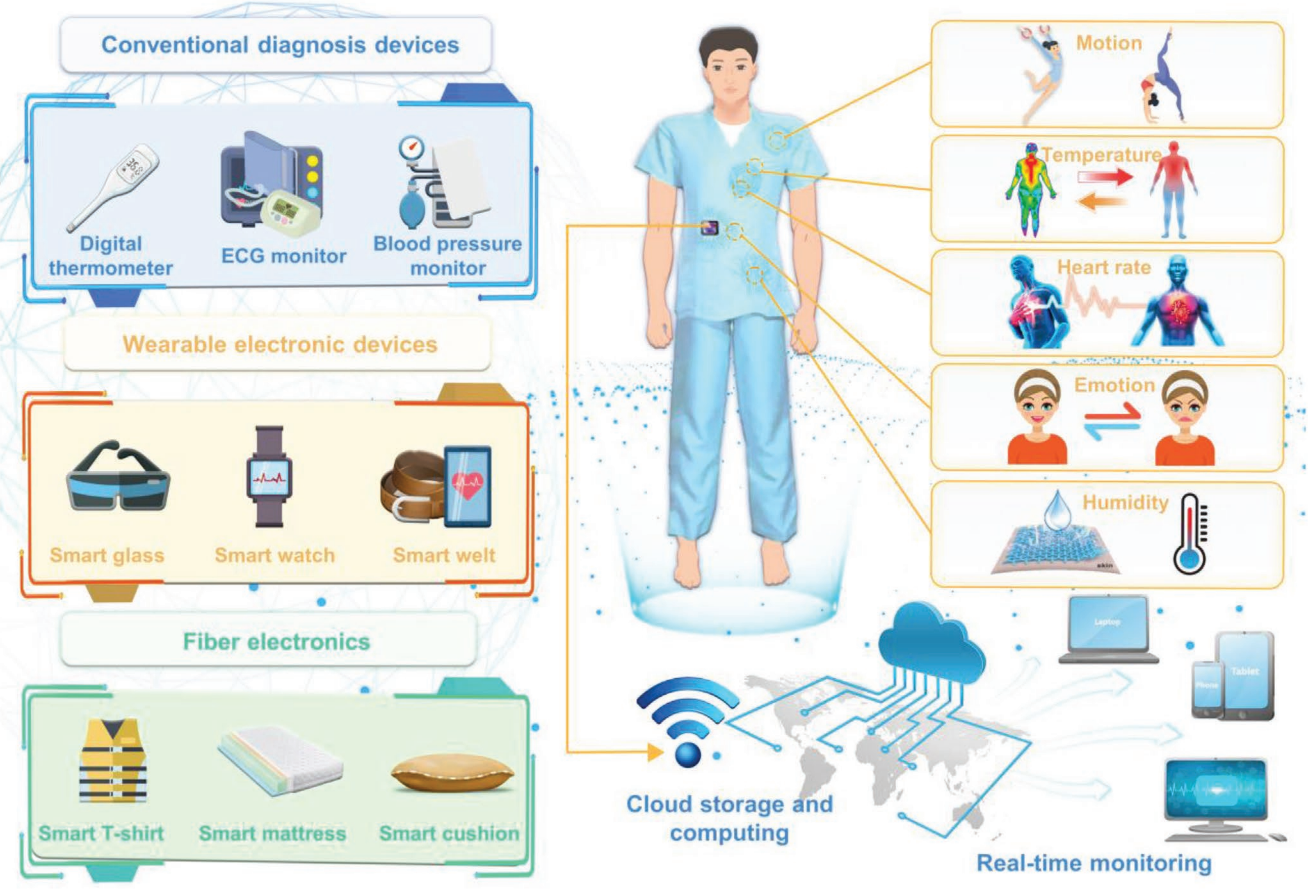

Figure 2. Health-monitoring agents. Representative health-monitoring devices and conventional clothing seamlessly integrated with multifunctional fibers, which can collect body signals that are then wirelessly transmitted and analyzed using deep learning and big data technology for human–machine interaction.

can sense target parameters such as force, heat, humidity, and physiological signals. With sufficient flexibility and encapsulation on fiber design and fabrication, multifunctional fibers can be amalgamated into traditional textiles with indistinguishable appearance from those commercial ones. By integrating seamlessly into everyday clothing, clothing empowered by multifunctional fibers can acquire multimodal information close to body during daily activities, which is of great significance for constant health monitoring. This section will summarize multifunctional fibers for physiological, motion, thermal, and humidity-related applications.

Sensing of faint mechanical signals demands extremely high sensitivity resulting from dedicated stimuli-responsive structures. Therefore, multifunctional fibers for small signal sensing are commonly based on susceptible mechanisms, such as piezoelectricity,[19] triboelectricity,[20] or optics.[21] Contributing to the nanoporous structure, the piezoelectric nanofiber sensor exhibits high sensitivity and accuracy in detecting weak physiological and mechanical stimuli.[22] When deployed on human skin and in mice, the nanofibers responded under weak physiological signals from blood pulses and diaphragm motions in vivo, simultaneously. Based on a biconical silica microfiber probe, an optical neuron was fabricated with a composite structure for finger motion detection for fast angle perception.[23] For integration into daily clothing, leveraged on the shear motion between parallel nylon yarn and conductive yarn for the charge transfer, the triboelectric all-textile sensor array can be machine-knitted and stitched into normal clothing for local physiological signal monitoring. With high pressure sensitivity, enhanced comfort, and robustness, a health-monitoring system for long-term and noninvasive assessment of physiological index in steady state was developed based on all-textile sensor array.[20]

Despite small mechanical signals, motion tracking is essential for analysis of daily activities, such as joint kinematic monitoring,[24] rehabilitation training,[25] and diagnosis of chronic diseases.[26] Differing from small mechanical signals, complex human motion can be divided into abundant mechanical components. Ferromagnetic fabrics and coils were sewn on both sides of the garment for swinging-motion-based electricity generation.[27] Based on the relative orientation between ferromagnetic fabrics and coils, more sophisticated motion can be interrogated. Microstructured elastomeric fibers that integrate tens of liquid metal electrodes are proposed for an ultraelastic transmission line.[28] Complex mechanical stimuli can be deciphered using a time-domain reflectometer, by integrating a single soft transmission line with one port into a target structure. Based on the same distributed sensing principle, distributed intelligent fibers with high spatial resolution are studied for temperature and pressure.[29] Plastic optical fibers and fabrics-based optical sensors have emerged with the advantages of miniaturization, ultrahigh sensitivity, and non-electromagnetic interference. Optical sensors composed of parallel assemblies of elastomeric light guides incorporate continuum or discrete chromatic patterns. The combination of total internal reflection and absorption enables a stretchable distributed fiber-optic sensor that can distinguish and measure locations, magnitudes, and modes of mechanical deformations.[30]

For in-fabric integration, tactile textile was created via digital machine knitting of piezoresistive fibers, which was later combined with machine learning to reveal human–environment interaction.[31] To harness more mechanical components, an “all in one” e-textile with dual tactile and tension stimuli responses can accurately monitor human behavior and movement,[32] with potential applications in taekwondo and high-order physical-training analysis. Besides mechanical parameters, humidity and temperature are also important health indicators. Humidity and temperature sensors are integrated into wearables to detect human sweat, breath, moisture, and temperature level, simultaneously. The electrical resistivity of a temperature and humidity-active material varies with temperature and humidity, respectively. Thus, the status and characteristics of the engaged masks can be determined on-the-fly, which is desired for indicating wearing comfort of fabrics to the skin. [33] In such an intelligent fabric space, medical students could receive operation training based on multifunctional fibers and digital-twin technology to evaluate their manipulation performance and physical conditions in real time.[34]

Considering that physical sensors based on multifunctional fibers can only monitor vital signs and physical activities, biochemical sensors are essential to assess the human health state at the biomolecular level.[35] Biofluids, such as saliva,[36] tears,[37] sweat,[38] and interstitial fluids,[39] are ideal analytes, as they can be retrieved noninvasively and contain a wealth of physiological information. In all the bodily liquids, sweat is the most accessible to fabric. As one of the most readily available biological body fluids, information about the human body can be obtained by monitoring the properties of sweat electrolytes. However, due to the lack of directional transmission of sweat in the fabric, only a small portion of the absorbed sweat can reach the sensing area, which results in low efficiency.[40] Therefore, multifunctional-fiber-based biochemical sensors usually need to work stably under heavy sweating conditions, such as strenuous exercise. An integrated sports shirt system integrating a core–sheath sensing yarn-based electrochemical fabric sensor for powerful sweat capture and stable sensing with an integrated chip was prepared. It can perform real-time monitoring of multiple chemical information (e.g., glucose, Na^+, K^+, and pH) of sweat for users at the states of both intense exercise conditions such as badminton and relatively mild conditions like walking and eating.[41] Daily monitoring and analysis of personal physiological data, aided by AI for medical care, can define healthier and smarter lifestyles. A non-printed integrated-circuit textile via a weaving method, with both wireless monitoring and logical computing capabilities for continuous on-body AI monitoring, was presented. The multifunctional fiber-based sweat sensor was woven with strain- and light-sensor fibers for simultaneous monitoring of hypoglycemia, metabolic alkali poisoning, and other emergencies.[42]

3.2. Multifunctional-Fiber-Based Systems for Health Monitoring

A basic health-monitoring system consists of a sensor module, a data-analysis module, and a visual-interaction module. The sensor module is responsible for collecting data from the environment and monitoring objects based on the aforementioned fiber sensors. Then, the data are locally filtered, processed, analyzed, and forwarded by computational result feedback through wireless transmission to user terminals. Finally, the resulting data is visualized and can be interacted with on smartphones or computers with appropriate user interfaces. A fabric-based health-monitoring system was developed in a previous report for long-term and non-invasive assessment of cardiovascular diseases and sleep apnea syndrome, which includes a fabric sensor, an analog conditioning circuit, an analog-to-digital converter, a Bluetooth module, and a smartphone as the user terminal.[20] An application on a smartphone is powerful enough to execute simple algorithms, such as band-pass filtering[20] and support vector machine analysis to act as the data-analysis module. For instance, a fabric-based tactile learning platform has been reported to record, monitor, and learn human–environment interactions.[12] The development of deep-learning and big-data technology has enabled more advanced algorithms to be effective in different fields. High-performance computers were used instead of smartphones to train a computation-intensive convolutional neural network with multiple hidden layers, and data collected offline were used to verify the proposed method. A multilayer communication system, which involves IoT, edge-computing, and cloud-computing technologies, is additionally needed to enable real-time service, in addition to high computational power. Fabrics and garments with integrated stimulus-active materials serve as conformal sensors for data collection. The electrocardiogram collected in proximate sites was uploaded to the cloud and processed using machine-learning methods.[43] A three-tier architecture consisting of a perception layer, an integrated cloud layer, and a data-analytics layer was used, and 12-lead record could be identified with an accuracy of 97.1% using the data collected by wearable sensors.[44] In particular, a wearable affective robot was studied to collect multimodal data, including video, audio, tactile, and electroencephalogram, for dynamic human-behavior monitoring. The fitbot can enhance the user experience on affective and social interaction.[45] Meanwhile, wearable devices can also be employed to monitor emotional data to recognize factors that influence mental health.[46] A traditional solution for the visual interaction module is a screen through the graphical user interface on one machine, such as a common medical monitor. Another relatively simple solution is to separate the user terminal from the monitor offering the convenience of status checking through a portable device. For more intuitive visual interaction, large-scale display fabrics can be incorporated into daily life with changed motions.[10]

Therefore, an IoT- and cloud-based multilayer architecture, integrating materials science and computer science, represents a digitalization and intellectualization direction for health-monitoring systems.

3.3. Challenges and Opportunities of Health-Monitoring Agents

Invisible, intelligent, and interactive agents are used to provide higher quality of service due to the characteristic that multifunctional fibers are closer to the living space. The agent is expected to be used for real-time health monitoring of different groups of people, including hospitalized patients, patients on home medical treatment, and medical staff at work. However, health-monitoring agents face five main challenges, which include fiber usability, data-acquisition accuracy and stability, hardware circuit integration, and algorithm result reliability: 1) Fiber usability relates to comfort, washability, and durability of the fabric/garment. The hardness, flexibility, stretchability, air permeability, and skin affinity of a fabric determine its comfort. Washability determines the potential of the wearable fabric to be washed multiple times and still retain the functionality of data acquisition. Durability means that fabric function and performance remain relatively stable many times under multiple users. It should be noted that achieving a balance between usability and functionality of fabrics is a great challenge. 2) Data acquisition accuracy and stability. Maintaining high accuracy and stability of collected data in different environments under various operating modes is critical. In addition, various adhesion levels between the fabric and human skin caused by human movement, changes in temperature and humidity caused by sweating, the optical impact caused by the hot summer sun, and other environmental parameters can affect the function of a fabric sensor. The development of robust fabric sensors in extreme environments has also become a significant challenge. 3) Hardware integration refers to the integration and encapsulation of the related hardware connected to the fabric in a health-monitoring system to improve user experience. At present, most fabrics need to be connected to a printed circuit board to obtain the signal, which realizes senselessness and portability. Due to the characteristics of miniaturization, flexibility improvement, and ultrahigh integration, flexible circuits are the most promising solution for the hardware integration challenge at present. 4) Reliability refers to the accuracy and reliability of the AI algorithm used for data analysis. Deep modeling needs to be strictly and comprehensively verified before being put into application, especially in the medical field, due to its black-box characteristics.

For more comprehensive and more imperceptible health services to people, the aforementioned issues are present and future challenges and opportunities. The rise of fiber electronics and AI enables health-monitoring agents derived on multifunctional fibers to direct future medical and health management to intelligent health.

4. Health-Therapy Agents

When the human body is subjected to trauma, treatment is required to alleviate or eliminate associated symptoms. Conventional treatment programs include physical rehabilitation therapy, such as thermotherapy, electrotherapy or phototherapy, and chemotherapy, which includes oral administration, subcutaneous injection, or intramuscular injection. Currently, the treatment process relies on the professional knowledge and clinical experience of physicians and surgeons. The existing treatment instruments are mostly rigid mechatronic instruments, which often bring strong foreign-body sensation and psychological stress to soft tissues and can often leave scars that are difficult to remove after the treatment. Precise therapy can be realized with multifunctional fibers, where appropriate treatment methods are selected and applied via

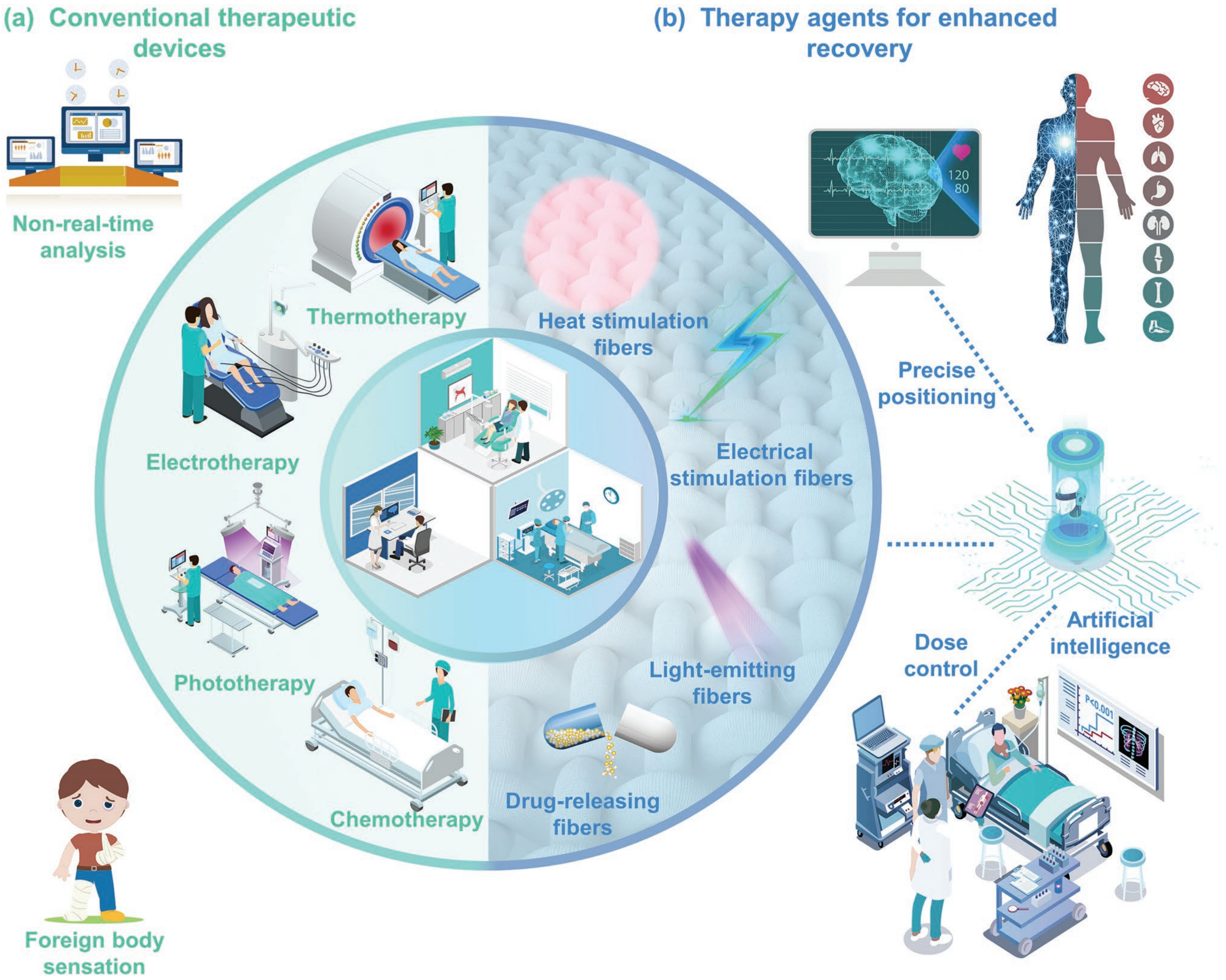

Figure 3. Health therapy agents. a) Conventional therapeutic devices. The existing treatment instruments are mostly rigid metal mechatronic instruments, which often bring strong foreign-body sensation, psychological stress to patients, and likely leave scars difficult to remove after the treatment. b) Schematics of therapy agents for enhanced recovery. Precise therapy can be realized with multifunctional fibers, where appropriate treatment methods are selected and applied via AI learning according to the needs of patients.

machine learning according to the patient needs. A treatment scheme derived from multifunctional fibers is introduced in **Figure 3**. According to biological information, clinical symptoms, and signs of a patient, healthcare and clinical decisions are customized in real-time, thus improving the treatment efficiency and reducing both risk and cost. Meanwhile, owing to the superior flexibility and programmability of fiber materials, the discomfort caused by conventional therapeutic instruments can be greatly reduced. Thus, therapy agents based on multifunctional fibers are the ideal solution for personalized medicine.

In this section, the latest progress on the application of multifunctional fibers in several typical treatment technologies and the beneficial effects of using therapy agents formed by multifunctional fibers and AI technology on rehabilitation treatment are discussed. Finally, the challenges and opportunities of therapy agent applications are given.

4.1. Multifunctional Fibers for Therapy Agents

In this subsection, several treatment technologies are introduced, and the latest research on multifunctional fibers in the corresponding fields is summarized.

Thermotherapy is a treatment method that involves heating human tissues to achieve therapeutic effects. Currently, it has been proven that thermotherapy has considerable effects on the treatment of rheumatoid arthritis, muscle spasms, inflammation alleviation, joint-stiffness reduction, and blood-circulation improvement.[47] However, conventional thermotherapy equipment is bulky, and achieving uniform local heating is difficult because of the physical contours of the human body. By harnessing conformal fibers or fabrics, both local heating stability and daily comfort of patients can be achieved. Many researchers have been devoted to designing and manufacturing high-performance thermotherapy fabrics, aiming to realize high flexibility, large area, and high temperature performance using a low voltage and rapid thermal response. A multifunctional fabric by combining nanomaterials with cellulose was presented,[48] and the electrothermal effect could be used for wound repair. A copper-nanowire-based composite fiber with a unique hierarchical structure was designed to realize personal heat management using an integrated microcontroller and Android phone,[49] and joint thermotherapy with a heating kneepad was demonstrated.

Electrical stimulation is widely used in clinical surgery, adjuvant therapy, and post-operative rehabilitation. The positive effect of electrical stimulation on regenerative medicine,[50] rehabilitation medicine,[51] neural engineering,[52] and other aspects has been demonstrated. The fibers and fabrics used for electrical stimulation can not only meet the intra-operative demands for certain parts of the electrotherapy cure effect, but also assist in post-operative analgesia, healing, and rehabilitation.[53] More critically, with fibers or fabrics, the invasion of devices in the human body can be minimized, and the daily comfort of patients can be improved. Several studies have focused on the development of fibers and fabrics for electrical stimulation. The electric field provided by electrical stimulation can promote cell migration potential, guide cell growth, and accelerate wound healing. As a skin-friendly material, conductive silk microfibers were used to fabricate a conductive flexible silk fibroin patch.[54] Combined with the ability to scavenge reactive oxygen species, it delivered physiological electrical signals and synergistically accelerated diabetic wound healing. Triboelectric nanogenerator[55] fabrics were combined with conventional electrical stimulation therapy for extensive applications, aiming at self-powering and self-adaptability. A wearable ion triboelectric nanogenerator patch, consisting of a fully stretchable gel platform,[56] can further improve the patch wearability.[57] Fabrics with electrical stimulation are also involved in neural engineering. A silk woven composite scaffold with high conductivity, good thermal stability, and appropriate mechanical properties has been reported.[58] The conductivity of the scaffold ranged from 0.62 to 1.72×10^{-3} S cm^{-1}, providing an ideal conductive parameter for nerve regeneration. Electrical stimulation is also essential for muscle strengthening and rehabilitation. A screen-printed flexible and breathable fabric electrodes array was presented[59] for clinical-related healthcare and rehabilitation.

Phototherapy has been widely used in the treatment of psoriasis,[60] neonatal jaundice,[61] bacterial infection,[62] seasonal affective disorder,[63] skin cancer,[64] and other diseases owing to its advantages of being non-invasive, safe, effective, and selective. However, due to the irregular shape of the human body, traditional photobiomechanics and photodynamic therapy methods using external light sources illuminate human skin uniformly (e.g., at the top of the head and hands). To address this, a polymer optical fiber with dispersed fillers has been woven into fabrics to achieve transverse emission of incident light. Flexible light sources could be integrated into flexible fabric structures by knitting or weaving for the treatment of skin diseases, such as actinic keratosis.[65] Typically, a luminous fabric could achieve a high output power of 50 mW cm^{-2} and selective destruction of tumors, but a separate high-power laser and reflector are required.[66] A neonatal jaundice phototherapy equipment called the "O-Blanket" has been developed with a layer of luminous fabric placed between a cover fabric composed of a surface layer and a reflective back fabric. The mid-fabric is composed of a polymer optical fiber and fabric yarns and can provide light radiation with a wavelength of 440–460 nm to treat newborn jaundice.[66b]

Traditional disease-treatment strategies mainly adopt oral administration, subcutaneous injection, intramuscular injection, and intravenous injection. However, these strategies may be severely detrimental on the human body. For example, the degradation of drugs by enzymes in the human body makes high-dose systemic administration to achieve sufficient therapeutic effects potentially lead to increased drug resistance. Simultaneously, the drug accumulation in vital organs, such as in the heart or liver, may cause serious side effects.[67] Numerous studies have been conducted on fabric-based local drug delivery systems for disease treatment. A local drug delivery system enables on-demand drug delivery at the treatment area, controls drug dosage, improves the overall quality of treatment, and minimizes systemic side effects.[68] Different carrier fibers and drug materials and their combination will result in diverse functions. Biodegradable polymers are the main fiber-matrix materials, while drugs include various biologically active compounds, such as antibiotics, therapeutic growth factors, and active antibacterial particles. There are four main types of fiber structures combined with drugs, that is, surface drug-loaded fibers, core–shell-structure fibers, stimulus-responsive fibers, and biodegradable fibers. Surface drug-loaded fibers are produced by a modified coating on the fabric surface, which has antibacterial and anti-ultraviolet functions.[69] The thickness of the core–shell layers dictates the rug release rate of the core–shell structure fibers.[70] The drug release of stimulus-responsive fibers is controlled under external stimuli.[67a] Lastly, biodegradable fibers can be implanted in the body for targeted cancer treatment.[67b] The varied fabric microstructure of fibers and drug carriers can induce active drug-release under external stimulation.

4.2. Multifunctional-Fiber-Based Systems for Enhanced Recovery

Conventional treatment instruments require labor-intensive operations and fixed postures during operation, which may lead to inappropriate or severe effects due to undesired motion. Nevertheless, flexible fiber materials with therapeutic properties can meet the required therapeutic distribution and time, owing to their programmability. Derived from the above requirements for personalized medicine and from the AI system abilities, quantitative indicator assistance can be provided to enhance the treatment programmability of therapy agents. The electrical signals in a fabric array can be recorded and transmitted to the edge node that receives the signal. Analysis and computing tasks can be conducted from these signals. The pre-trained model provides useful theoretical and empirical references for physicians. Moreover, by endowing multifunctional fibers with skin-friendly properties and combining them with daily clothing, mental and physical discomfort in daily activities can be minimalized.

In a joint study by Mayo Clinic and Google on digital health analytics, an AI-assisted algorithm was developed that can accurately map the most suitable regions of brain for neural stimulation. Tests with electrical impulses were conducted to determine the best regions for a broad response. AI-based methods are not only more efficient than traditional ones but also more accurate to locate the areas required to treat. Derived from therapy agents, clinical data including drug concentration data, signal-strength data, operation data during treatment, and patient signs data after treatment can be collected remotely, objectively, and accurately. These data can be shared by following general data-safety protection regulations through a data-transmission system that complies with the Health Insurance Portability and Accountability Act. A physician can then obtain more accurate exclusive information, which can effectively help diagnose and formulate an individualized treatment plan for high-precision treatment. Patients, physicians, and surgeons can realize remote communication and treatment guidance to ensure convenient and efficient healthcare using therapy agents.

4.3. Challenges and Opportunities of Health-Therapy Agents

Although the therapy agents utilizing multifunctional fibers can offer conformal and precise treatment, they still face application challenges. The main challenges are as follows: 1) Cost-effectiveness, reusability, and stability of multifunctional fibers. The cost and quality of multifunctional fiber materials are important factors for production. New strategies should be developed for the production and modification of these materials to promote their manufacturing and practical applications in the future. Since most multifunctional fibers need to be worn close to the body, eliminating viruses and bacteria effectively is key to ensure high reusability. In addition, to provide safe and efficient treatment, the stability of multifunctional fibers also requires further attention. 2) Data privacy. Although the data collected by therapy agents can provide effective treatment to patients, use out of the intended scope must be avoided. To prevent data misuse, strict regulations should be formulated by governments and leading healthcare organizations to protect privacy and personal security. 3) Interpretability of AI algorithms. Although many AI systems used in a surgery scene have emerged, insufficient representativeness, accuracy, and generalization of the AI prediction results can surface due to the systematic bias in collection of clinical data. Moreover, the neural network is a "black box" technology.[71] Although the automated nature of neural networks can learn features and patterns that outperform human beings, it is hard to assess how a machine realizes such intelligence. The accountability of algorithms, the safety and ability to verify automatic analyses, and the impact of these analyses on human–computer interaction may affect the effectiveness of therapy agents in the clinic.[72]

The abovementioned issues are not only the current challenges but also the future research trends. Though in early stage, therapy agents based on multifunctional fibers with great flexibility and programmability and AI learning can push precise therapy to a new frontier for personalized medicine.

5. Health-Protection Agents

The human body is influenced by light, heat, force, germs, dust, etc., when exposed to external environments. For the general public and medical staff, hazard sources can be classified into three categories: 1) electromagnetic waves, such as ionizing, solar, and thermal radiation; 2) pollutants, such as bacteria, viruses, and inhalable particles; 3) external factors, such as body collision with objects or falling down. Therefore, physical barriers are essential for ensuring human safety and health. A wearable device, in a close-fitting way, is the last and essential line to protect against external injuries. However, traditional cloth has weak protection performance. Therefore, scientists have focused on improving and enhancing wearable materials and equipment. Clothes with excellent protective performance and comfort are being developed. For the types of injuries people are prone to suffer, the corresponding protective equipment is presented in **Figure 4**. In addition to physical protection, the prevention alarm before the occurrence of danger and the adjustment after the occurrence of danger also play an important role in human health and safety. A flexible fabric sensor enables a textile with various functions, such as detection, transmission, and feedback. Its characteristics of high sensitivity, flexibility, and stability allow its application to various fields, such as electronic skin, tactile sensing, health and movement detection, and environmental stimulation,[73] which promote the multifunctional development of wearable protection systems.

In the following section, wearable protective devices are introduced to prevent external injuries for the general public, medical staff, and special staff. The roles of health-protection agents corresponding to the above three categories are discussed. Finally, the challenges and opportunities of medical protective intelligent agents are analyzed.

5.1. Multifunctional Fibers for Extreme Environments

Individuals, according to their profession, are exposed to excessive electromagnetic radiation and take severe health risks. Firefighters exposed to high temperatures could be harmed by thermal radiation. For workers in extreme environments, radiation-protection suits and heat-protective clothing are essential to their safety. Traditionally, lead shields have been used in radiation-protection suits and covers,[74] but their heavy weight causes inconvenience to healthcare workers and patients.[75] Therefore, people have turned to seeking convenient and safe alternatives. Glass materials can be easily modified during composition and preparation techniques,[76] and thus it has become a common material for radiation shielding. However, the intrinsic rigid and fragile properties of glass demand special processes for it to be used on wearables. A tungsten double-layered composite yarn was co-manufactured with textile fibers containing shielding nanoparticles in fabrics to minimalize skin discomfort in low-dose shielding.[77] Aircraft crew uniforms and thyroid protection scarves made from this material neither restrict movement nor cause skin discomfort. Excessive heat stress in the outdoors is a common occurrence in daily lives. To protect people from UV radiation, cooling the

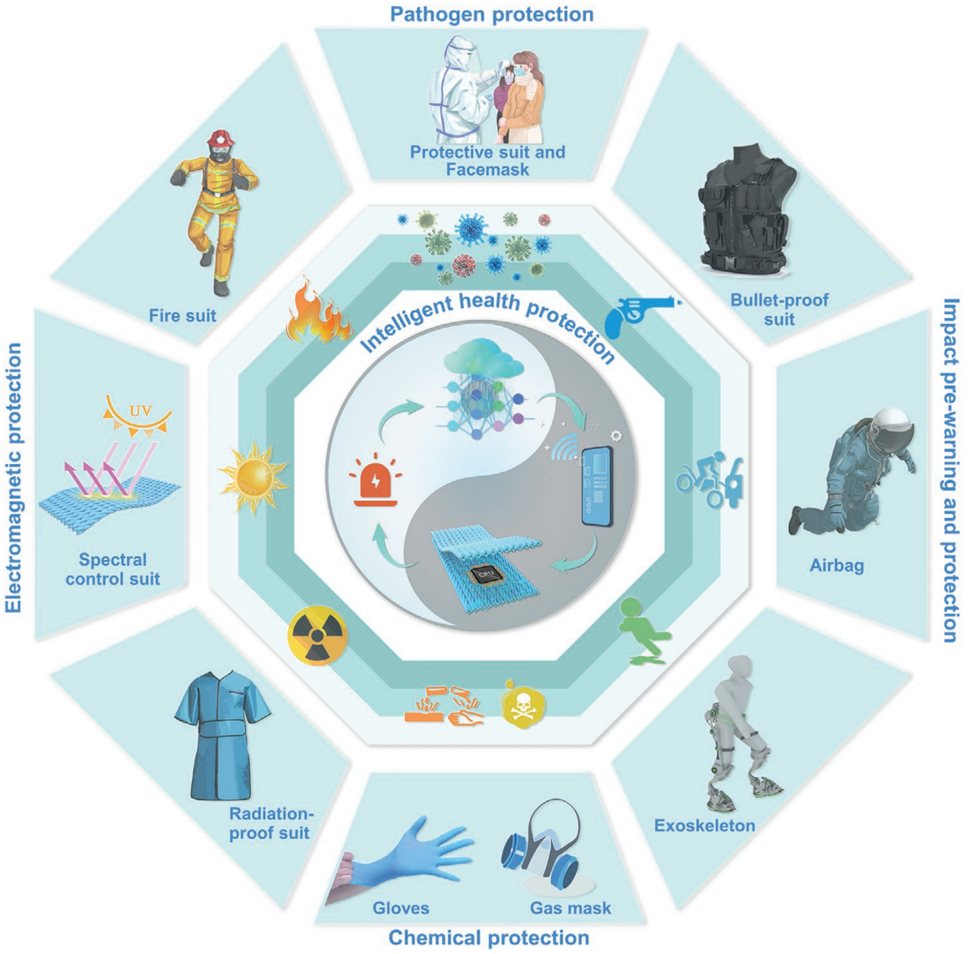

Figure 4. Health-protection agents. Health-protection agents for extreme environments, including microbial invasion, impact injury, and chemical poisoning. Future medical clothing for all-round protection.

body through clothing could be an effective solution. A spectrum-selective nanocomposite fiber and fabric that can be used for outdoor radiation cooling has been developed. It can reflect more than 90% of solar radiation and has high transparency to human thermal radiation. Compared with cotton fabric, it is more effective in cooling the human skin under midday sunshine conditions.[78] A metamaterial fabric was designed by morphological classification. The reflectivity of the fabric is 92.4% in the solar-radiation band and has high emissivity in the mid-infrared band. Compared with cotton, it can decrease the temperature of human body by nearly 5 °C under outdoor exposure, while guarding against solar radiation.[79] Furthermore, a health-monitoring and early-warning function can be integrated to the clothing, increasing the intelligence and initiative of health-protection agents; health-protection agents detect danger signals in real-time through flexible sensors on the protective garment and provide intelligent early warning to reduce the occurrence of accidents and enhance the protection of special professionals.[80] An intelligent, protective garment system for hazardous-environment workers, such as firefighters, is studied, with sensors added to the fabric to measure physiological parameters, such as temperature and heat flow, to assess the thermal status of workers. Once the safety threshold is exceeded, warning signals are sent to workers through vibration, visual, or auditory signals.[81]

5.2. Multifunctional Fibers for Microbial Invasion

The outbreak of the COVID-19 pandemic has increased the awareness of the existence of life-threatening viruses. Medical protective fabrics such as protective garments and masks have become indispensable in daily life. Therefore, it is urgent to develop novel antivirus and antibacterial medical protective devices, which are the first line of defense to resist the invasion of unknown viruses and protect the life and health of the population.

Conventional medical protective fabrics are commonly made of polypropylene with a melt-blown spinning forming the key filtration structures.[82] A medical protective fabric with permanent antistatic, antibacterial, waterproof, and oil-resistant properties was developed by functional fabric laminating technology, which was used to protect people from SARS virus infection.[83] Recently, a biodegradable microfiber pad that can effectively block particulate pollutants and pathogenic particles in the air was manufactured.[84] However, shortcomings of the materials, such as reduced thermal management performance, low wearing comfort, and the absence of detection or adjustment functions, should be considered.

Protective functions can be expanded and improved by the incorporation of health-protection agents, while ensuring comfort and compatibility. To improve the thermal-management performance and comfort of protective fabrics, integrating masks with light thermoelectric ventilation modules can protect users from viruses and other toxic particles, promote breathing, and ensure comfortable wearing.[85] In addition, to overcome the current problems such as slow diagnosis and inability to identify infections accurately, quickly, and quantitatively, the wearable collector is integrated into the protective mask to collect viruses in the exhaled air. Finally, a real-time and closed-loop control system is formed by adding a feedback regulation function to the protection device.[86] Airborne particulate matter sensors could sense airborne particles of different sizes near the mask, and then the misty spray would subsequently be utilized to load aerosol particles in the vicinity and cause them to fall to the ground quickly, thus intelligently mitigating the threat.[87] Furthermore, remote smartphone control can also be integrated into the system to receive real-time mask charging, refilling, and cleansing alerts.

5.3. Multifunctional Fibers for Impact Injury

People who need post-operative rehabilitation and those who work in dangerous environments are vulnerable to impact injuries. The best-case scenario would involve flexible, strong, and comfortable body armor that can effectively protect the human body and ensure safety without influencing their daily activities. Through 3D printing, nylon chain fabrics were constructed with a jamming transition mechanism with both wearing comfort and strong protection in different topologic states.[88] In addition to protective performance, health-protection agents utilize sensing and response properties to realize feedback and early warning after a certain degree of impact injury is perceived or predicted in order to reduce the risk of injury. In addition, health-protection agents with computing ability can intervene in human behavior and aid in the rehabilitation of individuals with movement disorders.

People working in demanding professions, such as police officers and soldiers, are provided with appropriate suits to arm their bodies. Non-Newtonian fluids and shear-thickening fluids were introduced into Kevlar fabrics[89] for robust protection in bulletproof vests. Since people cannot visually identify the degree of attack damage, the perception of bulletproof clothing to external impact is critical.

In medical rehabilitation, exoskeletons are especially important for children who require upper limb intervention and assistance in daily activities.[1] The iterative design and development of aerodynamic actuated and wearable soft exoskeletons were developed based on shape-memory alloys, where soft strain sensing was used to track shoulder motion.[90] In rehabilitation training, intelligent fabrics play a supervisory and motivating role of the medical personnel. Smart trousers were designed to motivate children and adolescents to practice gait therapy and enable them to continue rehabilitation training at home, outdoors, and at work.[91] This garment contains embedded sensors and actuators that are connected by an embroidered conductive yarn track. While measuring the activity of a user to detect specific action performance, the wearable device responds accordingly in real-time using the form of feedback and positive reinforcement. The overall goal is to increase enjoyment and compliance during the treatment process and to foster autonomy, self-empowerment, and positive user prospect.

5.4. Challenges and Opportunities of Health-Protection Agents

Protective garments enabled by health-protection agents are important for health protection. Intelligent agents with autonomy, perceptibility, intelligence, and adaptability empower medical protective garment upgrade and optimization with functions such as real-time detection and intelligent feedback. Wearable fabrics with sensing ability are adopted to perceive external physical quantities such as light, heat, and force in real-time, and the status of the user is transmitted to the cloud server automatically. The predictions and warnings are executed to prevent the occurrence of potential dangers.

However, there are some challenges on health-protection agents as follows: 1) Variability of protective sources and protected objects. A wide variety of protective sources and objects require improved adaptability and performance of protective intelligent agents for comprehensive protection. 2) Insolvability of protective sources. Heat management using multifunctional fabric can be realized for masks, but for many dangerous injury sources, such as viruses and X-rays, intervention and regulation cannot be timely conducted. In addition, a simple warning might not provide effective protection. 3) Anti-interference of flexible fabric sensors. Protective agents are required to function in extreme environments, such as environments with electromagnetic radiation and high temperature, which brings high requirements for the anti-interference, integration, and robustness of sensors. Health-protection agents provide wearable protection and alarms with flexibility, convenience, and imperceptibility and thus can monitor and transmit the condition of objects in environments with interference.

6. Minimally Invasive Surgery Agents

Since Feynman introduced the design of a swallowable microsurgeon in his famous talk, the concept of robotic microsurgery has paved a new way for assisting and even replacing surgeons with higher accuracy, faster repetition, superior dexterity, adequate stability, and less invasive access in MIS. Aiming to develop smaller and smarter devices, the 30-year development of surgical robots[92] has focused on smaller, more flexible devices with higher maneuverability, more advanced embedded intelligence, reduced invasiveness, and better adaptability. As a form factor with an extreme aspect ratio, fiberbots possess intuitive features for MIS.[93] Some of the well-known surgical instruments are designed to have a fiber shape to minimize invasiveness, such as flexible endoscopes, catheters, and guidewires.[94]

In this section, the challenges and merits of fiberbot miniaturization and pliability are summarized, and the current

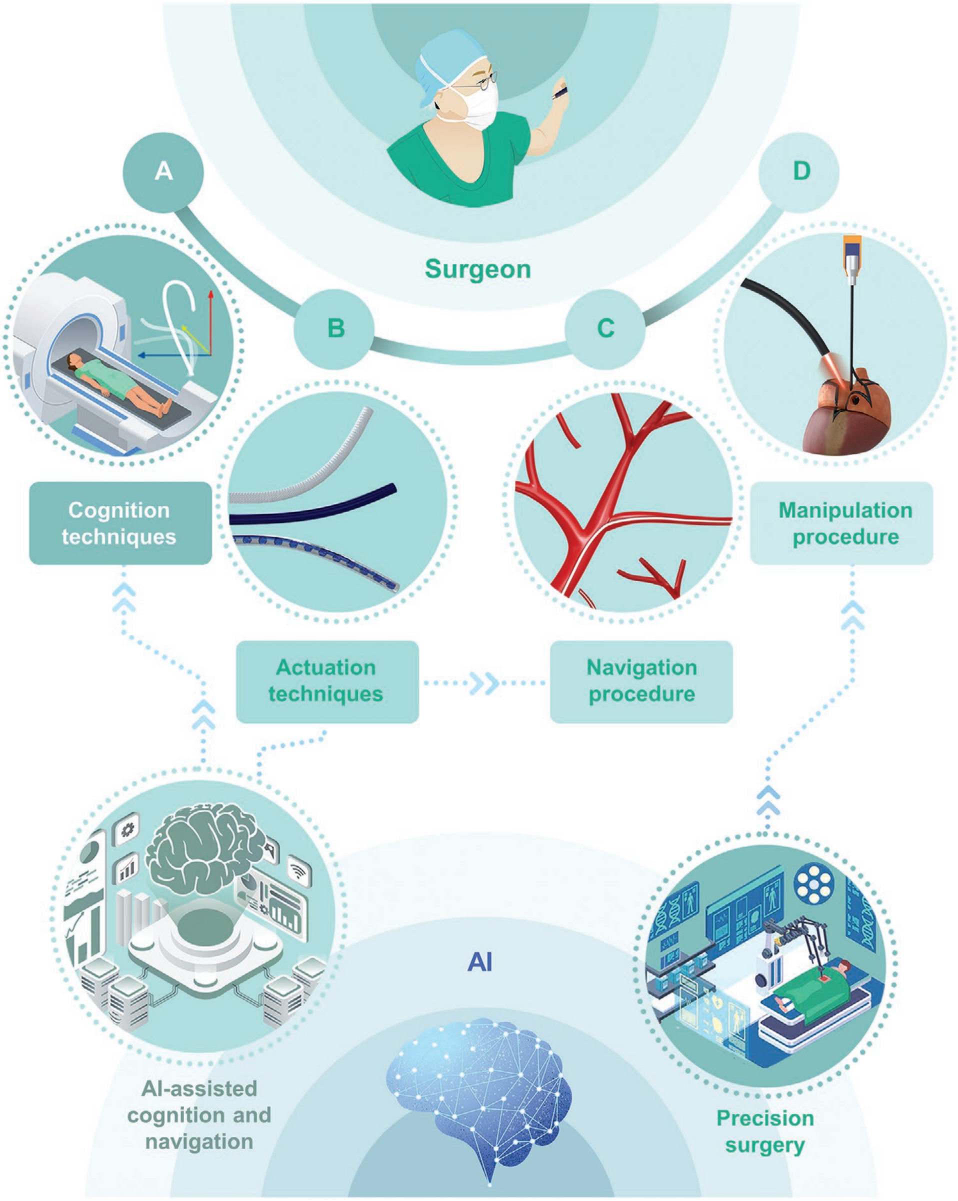

Figure 5. MIS agents. The architecture of an MIS agent consisting of a fiberbot for navigation, target manipulation, and imaging and sensing techniques for in vivo cognition under the supervision of a surgeon and AI system.[116,125]

progress in flexible miniature fiberbot application in dynamic, unstructured environments in vivo is highlighted (**Figure 5**). In addition, different aspects of MIS agents are discussed in detail, including sensing and imaging schemes, robotic actuation and navigation methodologies, as well as target manipulation. Furthermore, the perspective of the next-generation MIS agents for clinical interventions is introduced.

6.1. Multifunctional Fibers and Related Techniques for Minimally Invasive Imaging and Sensing

In surgical applications, the perception and imaging of fiberbots represent the frontend technology, beyond which are two backend technologies, namely, feedback and learning. The advanced functions of three technology groups: imaging and sensing, visual and haptic feedback, and learning and prediction are introduced in this section.

In MIS, perception and imaging work as the frontend basis for subsequent procedures. A fiber-based structured lighting probe[95] has been proposed for its synergy with flexible endoscopes. The image-fusion framework based on confocal laser endomicroscopy and optical coherence tomography images using the da Vinci system has been proposed for real-time micrometer-scale mapping of a dynamic tissue surface.[96] Helically arranged fiber Bragg grating fits well with curved nitinol tube robots for routinely used shape sensing.[97] However, the weakening effect on actuation performance resulting from the relatively rigid nature of silica should be considered. Simultaneously, an original image is preprocessed by means of image filters and weight maps to reduce noise in image fusion.[98] At the data-fusion level, the image is reconstructed using multidimensional multiangle data to achieve a complete visual effect.

Visual and tactile feedback represents the interaction between an intelligent agent and an ultimate object, for example, a surgeon. Since it records the operations and manipulation of the surgeon as the core of a surgical workflow, visual and haptic feedback are vital. The detailed technologies related to haptic feedback can be found at haptics reviews.[99] Haptic feedback is sensitive to delay, and considering the end-to-end performance of "influence–perception–adaptation" and analyzing the interaction of direct causal perception when interacting with materials is necessary.[100] If the feedback covers a long distance, cellular-supported wireless connections through 5G or 6G networks are promising.[101]

For those operations that are not critical or complex, the in situ learning and prediction of surgical lesions by an intelligent agent can improve the accuracy of surgery and enrich the understanding of surgeons. Thus, a combination of AI and fiberbots can promote in situ learning with enhanced adaptability and superior surgical performance. Under an AI-aided closed-loop system, robot locomotion is considered in a quasi-static state with predictive control under the dynamic and unstructured environments in the human body. Sound information acquisition with convolutional neural networks can achieve parallel and independent monitoring to guarantee multidevice operation quality in two preset environments.[102] Nevertheless, during clinical operations, complex and dynamic environmental elements can easily disrupt single modal sensing. Thus, the method that combines multimodal cognition technology and reinforcement learning has shown great potential for in situ real-time monitoring of operation quality. The experimental demonstration of an improved reinforcement learning algorithm tailored using a hybrid analog–digital platform on a three-layer one-transistor one-memristor network has been reported.[103] The results showed that it has the robust ability of in situ training, providing a novel source of data collection and processing. Furthermore, with real-time information acquisition from surrounding data processing and edge computing, fiberbots can learn from and respond to their surroundings.

6.2. Multifunctional Fiberbots for Navigation

Precise and dexterous actuation is the basis for intervening in an MIS environment and realizing further operations. From industrial application to academic research, many studies have been conducted on applying fiber and precision actuation to the rugged human-body channels in MIS, for instance, tendon actuation, fluidic actuation, concentric tubes, and magnetoactive actuation.

From open surgery to MIS, such as laparoscopic surgery, thoracoscopic surgery, endoscopic surgery, and natural orifice transluminal endoscopic surgery, surgical tools include various equipment, from rigid, articulated arms to semi-rigid actuation structures. Even entirely soft robots,[104] which can decrease the mechanical-stiffness mismatch between the surgical tools and the soft human body, are used to provide increased adaptive surgical access, particularly endoluminal and transluminal. The da Vinci master–slave surgical system, which is the most commercially successful surgical system that has received approval for a variety of procedures by the Food and Drug Administration, adopts rigid but precise and stable articulation motions for surgeon-like tele-manipulation. To obtain access to hard-to-reach areas in deeper sites, several commercial endoscopic robotic platforms, such as master and slave transluminal endoscopic robots,[105] have been proposed for flexible instrumentation[106] in larynx, cardiac, colonoscopy, and natural orifice transluminal endoscopic surgeries. However, tendon-driven and hydraulic master–slave robots with a large footprint face considerable limitations on the instrument and device downsizing, due to their inherent mechanically anisotropic structures and fabrication restrictions; a typical robot size is often tens of millimeters.

Aiming at microsurgery in deeper sites, miniature robots with novel actuation mechanisms (e.g., chemicals, light field, ultrasonic field, electrical field, and magnetic field) have been proposed.[107] Nonetheless, we focus here on the essential operations of fiberbots and enhanced flexible navigation and steering. Using the most widely adopted actuation mechanism in surgical robots, tendon-driven robots rely on one or multiple force-transmitting tendons to exert force and/or motion on the distal tip from the external sources. However, a structured distal tip and tethered large proximal driver units hinder tendon-driven robots from further miniaturization.[108] Meanwhile, a pre-designed curvature of tendon-driven robots impedes 3D access to natural orifices with multiple curvilinear geometries,[109] eliciting non-intuitive theory and complicated models. Miniaturization and structural pre-digestion are two appealing and complementary evolutionary directions of tendon-driven fiber robots. Downsizing auxiliary motors and simplifying deformable structures could promote the installation of tendon-driven fiber robots to more extensive surgical procedures.

Pneumatic and hydraulic actuators leverage embedded fluidic chambers and external fluidic sources to achieve the desired level of manipulation. Fluidic actuation methods have been the mainstream strategy in the field of soft robotics, due to their intrinsic soft and compliant quality. In addition to the regulating medium difference, the actuation schemes of fluidic robots are characterized by structural asymmetry, for example, non-uniform distribution of the stiff framework,[110] and temporary asymmetry, such as cascaded bi-chamber unit[111] and multiple-chamber modules.[112] Similar to the tendon-driven actuators, fluidic actuators can output great stress and strain with light weight. The presence of embedded supporting materials, such as fabric and sponge, limits the scalable production and miniaturization of the fluidic module, due to its structural complexity. Nevertheless, a delicate multilayer design can be achieved using bespoke fabrication technologies. The smallest scale can be reduced to catheter size, and fluidic catheter-based guidewire-free access and coil deployment in vivo has been demonstrated.[113]

In contrast to the abovementioned methods, the emerging magnetoactive actuation is untethered, remote, and fast (response frequency up to 100 Hz). Meanwhile, magnetic fields have been widely used in clinical settings, for instance, in magnetic resonance imaging. The external time-varying magnetic field generation empowers small-scale magnetoactive robots with a compact body. In addition, the intense interactions (torque and force) between the external field and the embedded magnetic dipoles allow a thin catheter or a guidewire with a tiny magnetoactive tip to exhibit collective macroresponse,[114] achieving navigation and steering capability for endoluminal MIS.[115] Moreover, the integration ability of magnetoactive fiberbots further enriches its fundamental functions, such as compliance control by variable stiffness,[116] laser delivery with the embedded optical fiber,[117] and detection by a thermal flow sensor.[118] Nevertheless, the application of magnetoactive robots still heavily relies on a diversity of custom magnetic field generators. The compatibility of magnetoactive fiberbots with the clinical magnetic apparatus remains low. Namely, further research of deeper sites in the human body, such as lenticular arteries and scala tympani of the cochlea, remains to be conducted. The use of a fiberbotic platform could provide transformative functionality, as well as multiple functionalities for tissue removal and construction.

6.3. Multifunctional Fiberbots for Target Manipulation

The critical challenges in implementation of MIS are as follows: leveraging an intelligent MIS agent as a smaller, more flexible, and more intelligent extension of a surgeon's will, and helping surgeons to assess lesions and their environment on a smaller scale to achieve the required operation quickly and accurately.

In vivo removal and construction are two basic functionalities achieved by invasive instruments. The integration of fiberbots and these two functionalities are discussed here. In open surgery, tissue removal has typically been conducted using handheld scalpels, drills, and saws. However, in MIS, due to the confined space, limited visualization, and a lack of haptic feedback, this approach is not applicable. Conduction and perception of force are difficult for a fiberbot, in addition to the aforementioned problems, due to the fiber structure characteristics of a small section and no joint. Hence, it is important to develop non-mechanical technologies for tissue removal. Since the invention of laser technologies in 1960s, their applications in the medical field have been widely studied. Compared to the traditional mechanical cutting methods, laser ablation, which evaporates tissue via photothermal or photochemical process, enables a non-contact, precise, and selective incision.[119] Meanwhile, silica optical fibers represent a robust and flexible medium for laser delivery. In urology, a fiber-delivered Ho laser has become a common treatment option of subjects with urolithiasis, bladder tumors, and genitalia lesions.[120] Laser coronary angioplasty was developed to modify atherosclerotic plaque and relieve the acute and longer-term limitations of balloon angioplasty.[121] In neurosurgery, laser-induced thermal therapy can be used to remove brain tumors, whereas percutaneous laser disk decompression is a new solution for diseases induced by the degeneration of intervertebral disks.[122] However, both flexibility and high power cannot be simultaneously achieved for infrared laser delivery.[123] Therefore, lasers used in medicine have been mostly limited to foreign body removal from the surface of tissues. As the volume of ablation increases, the low efficiency of laser ablation can be fatal.[124]

Even though lesions are removed in the majority of surgeries, in vivo construction via in situ delivery and printing could be beneficial in numerous ways, for instance, applying bioglues, implanting electrodes for neural interfaces, and printing bioscaffolds in situ to repair or replace injured body parts.[125] Synchronous with the rapid development of 3D printing and AI, fiber robots have great application potential for use in conformal instruments and devices at deeper sites.[78] Currently, MIS is performed using devices operated manually or remotely by surgeons, so the result of the procedure depends on the operating skills, hand feeling, and experience of the surgeon. The introduction of intelligent agents in MIS has made going deeper into the human body through the original cavity under a smaller body wound possible. AI has been used to support cognition of the body's internal environment and localization of lesions for intelligent health agents in the process of surgery. The intelligent health agents can learn the operation principle and thus convey the will of surgeons in situ at a smaller scale in two ways, laser removal or material delivery. A semiautomatic or automatic operation can be realized in surgical operations that are not critical or complex using MIS agents with high precision.

6.4. Challenges and Opportunities of MIS Agents

Although MIS agents are expected to serve clinical applications due to their features of miniaturization, perceptibility, and high accuracy at a smaller scale, the following challenges remain: 1) Technological mismatch. There are major optical and mechanical mismatches between the current imaging and sensing solutions and the emerging small flexible fiberbots. In addition, a lack of large-scale and structured assembly and fabrication technology, and the introduction of shape-sensing fiber reduce the flexibility of fiberbots. At the same time, high-resolution medical imaging requires expensive equipment. Thus, integrating AI-assisted image-processing technology in agents could be a potential alternative. 2) Manipulation scheme. In current MIS, no large-scale and efficient laser or material transmission scheme exists in vivo that can meet the demand for large-volume ablation and construction at depth. 3) Surgery ethics. MIS is performed by devices under the remote control of surgeons, so the surgical effect depends on the operating skills, hand feeling, and experience of surgeons. Automated and semiautomated operations require multimodal data input for environmental observations. Moreover, accuracy is hard to be guaranteed just through camera observations obtained by endoscopes, which can lead to ethical issues.

In future MIS, the agent can be used as a sharp tool for navigation and steering in the human body, traveling through a narrow and irregular body cavity to reach a particular lesion. It can also be used remotely to perform multimodal perception and stimulation in a targeted environment and to assist surgeons in diagnosis through in-depth body-signal collection and analysis. It can be also used as a smaller hand for surgeons to cut and pulverize the lesion area efficiently, while bio-printing can be performed for configurational tissue regeneration in situ. Finally, a group of MIS agents can communicate, analyze, and summarize the surgical experience with group knowledge.

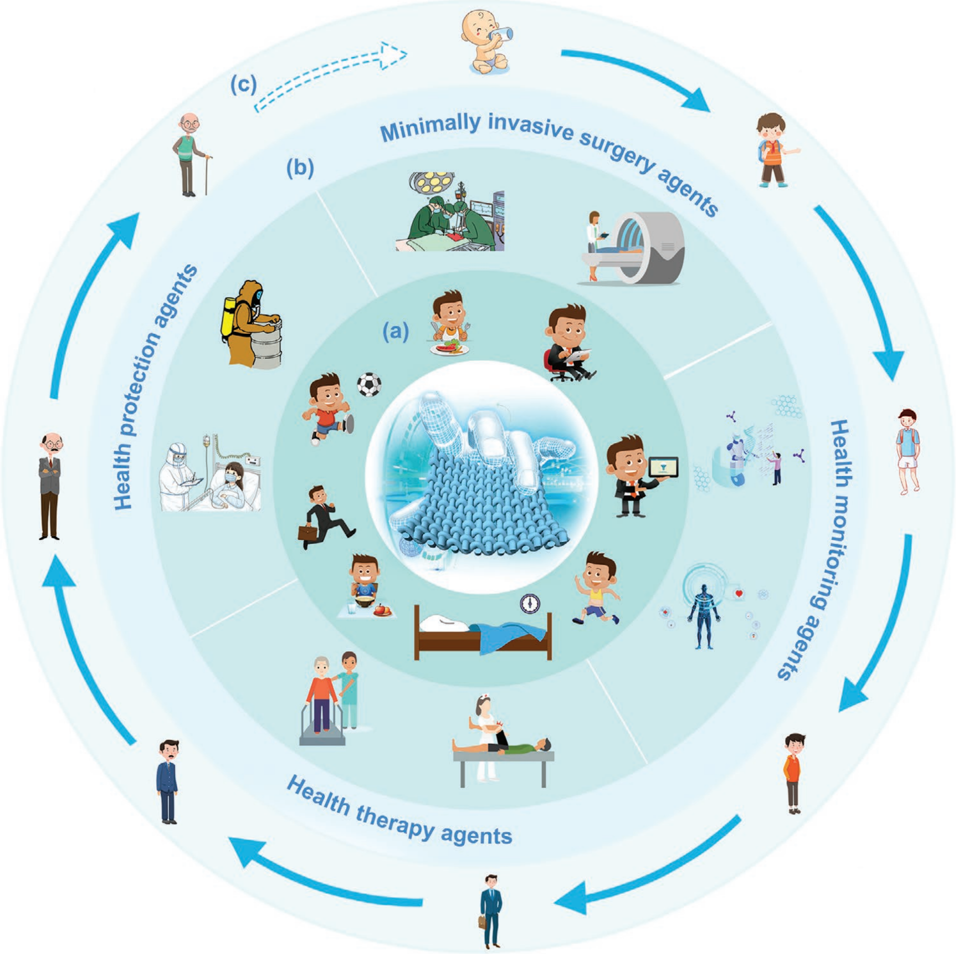

Figure 6. A person with intelligent health agents. a) Daily activities of a child. b) Intelligent health agents such as MIS agents, health-monitoring agents, health therapy agents, and health-protection agents are embedded in all aspects of life. c) Intelligent health agents accompany a person through their lifetime.

7. Summary and Future Perspectives

Numerous studies have investigated the application prospect of flexible sensing materials in the field of life and health. Here, we focus on the four main requirements of healthcare and present challenges and opportunities of future development. From extensive health monitoring to receiving therapy and surgical treatment to active self-protection, a new generation of healthcare systems must be created to suit future scenarios. The design of an innovative healthcare system requires a deeply interdisciplinary paradigm that combines medicine, materials science, and computer science. **Figure 6** shows a person supported by intelligent health agents. In daily activities, flexible and imperceptible intelligent health agents can be embedded in all aspects of life, managing physical and mental health, such as sleep monitoring, physiological index evaluation, sitting posture monitoring, and motion status evaluation. Health-monitoring agents will monitor physical health in various environments. When people are exposed to a harsh environment, intelligent health agents with protective properties, such as adjustable body temperature and antibacterial functions, can protect the body from hazardous external conditions. Meanwhile, a multifunctional fiberbot can enter deeper lesions, broaden the field of vision of surgeons, and conduct complex surgical procedures. After surgical operation, an invisible therapeutic agent can develop a personalized treatment scheme, including electric field, light, and other stimulation techniques to enhance the therapeutic effect.[126] Intelligent health agents will accompany people during their entire lifetime, and will be committed to maintaining life and health in non-interference fashion. The challenges and opportunities in the field of medical health coexist. For an intelligent health agent, medicine is the cornerstone, materials science its physical manifestation, and computer science its core. The main future direction can be the democratization of comprehensive health. Intelligent health agents are expected to play a pivotal role in the overall improvement of the length and quality of life.

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Conflict of Interest

The authors declare no conflict of interest.

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health monitoring and protection, intelligent agents, minimally invasive surgery, multifunctional fibers, precise therapy

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