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Wearable bioelectronics based on emerging nanomaterials for telehealth applications

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SUMMARY

Nanomaterial-driven, soft wearable bioelectronics are transforming telemedicine by offering skin comfort, biocompatibility, and the capability for continuous remote monitoring of physiological signals. The devices, enabled by advanced zero-dimensional (0D), one-dimensional (1D), and two-dimensional (2D) nanomaterials, have achieved new levels in electrical stability and reliability, allowing them to perform effectively even under dynamic physical conditions. Despite their promise, significant challenges remain in the fabrication, integration, and practical deployment of nanoscale materials and devices. Critical challenges include ensuring the durability and stability of nanomaterial-based bioelectronics for extended wear and developing efficient integration strategies to support multifunctional sensing modalities. Telemedicine has revolutionized healthcare by enabling remote health monitoring. The integration of nanomaterials within wearable devices is a central factor driving this breakthrough, as these materials enhance sensor sensitivity, durability, and multifunctionality. These wearable sensors leverage various operating principles tailored to specific applications, such as intraocular pressure monitoring, electrophysiological signal recording, and biochemical marker tracking.

INTRODUCTION

Remote health monitoring systems (telehealth) encompass a broad spectrum of services beyond traditional clinical care, including health education, patient movement monitoring, and recording metabolism status.[1–3] They represent an evolving field in healthcare, providing medical services and remotely transmitting user biometric data and health metrics. Telehealth integrates various technological tools, such as wireless data transfer and recording, to offer comprehensive healthcare services to individuals regardless of their geographical location. They allow healthcare providers to diagnose, treat, and monitor

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DECLARATION OF INTERESTS

The authors declare no competing interests.

patients through wireless communications technologies.[4,5] These emerging fields aim to improve access to care, enhance patient outcomes, and reduce healthcare costs, which facilitate radiologic image acquisition and sharing, provision, and management of real-time health-related data to detect symptoms of serious illnesses, such as cardiovascular, diabetes, cancer, and mental illness. It is worth mentioning that telehealth has played a vital role in remote health monitoring (e.g., continuous, real-time cough, body temperature, and vital sign sensing) during the COVID-19 pandemic.[6–10]

In recent years, advances in cutting-edge wearable electronics and wearable sensors have found their way into telehealth.[10–12] Wearable electronics made of flexible and skin-friendly materials can convert biological signals into electrical signals, such as current, voltage, resistance, and capacitance, and transmit the associated data in real time; they have also shown great potential in advancing health monitoring, fitness tracking, and other biomedical applications.[12–14] For instance, wearable strain sensors can accurately sense human body movement and facial expression, thanks to their conformal interface with the human body.[15–17] As another example, wearable pressure sensors can monitor blood pressure and respiration rates in a minimally obtrusive manner.[18–21] Nowadays, wearable sensors and systems have evolved to become increasingly sophisticated and intelligent, with multiple functionalities. Fundamental materials innovations, including design, synthesis, and fabrication of electronic nanomaterials, drive significant advancement in wearable electronics and biosensing applications.

In general, wearable electronics require skin-friendly and flexible substrates. However, electronic components, including sensors, antennas, and circuits, are typically made from metals and rigid glass fabric or ceramic substrates, which may not be suitable for wearable applications due to issues associated with user comfort and biocompatibility with human skins and bodies.[22–25] In this sense, materials should be biocompatible and create a comfortable interface between on-/in-body electronics and human skin without compromising their performance and functionalities. In the past, researchers have used commercial conductive films and the CO_2 laser-outfitted lasing-cutting technique to fabricate soft and multilayered wearable sensors, aiming to illustrate the applicability of wearable skin-compatible sensors.[26,27] However, the laser-cutting technique requires many artificial materials, which are not cost effective or environmentally friendly. Hwang et al. demonstrated a plant-based substrate derived from plant pollen (termed “sporosubstrate”) for its application in flexible and stretchable wearable electronics. The substrate offers advantages over conventional synthetic plastics due to its eco-friendliness and enhanced safety, making devices more suitable for direct contact with human skin and tissues.[28] Nevertheless, more research is needed to demonstrate the stability of these plant-based materials (e.g., low transmittance and high linear coefficient of thermal expansion). Some recent studies have indicated that pencil-paper on-skin electronics may be a good alternative, leveraging flexibility, breathability, the profitability of paper, and the conductivity of pencils (i.e., graphite).[29–32] Xu et al. have proposed various pencil-paper-based wearable biochemical sensors, thermal stimulators, and humidity energy harvesters.[30] Despite several advantages of pencil-paper technologies, their transition from laboratory-based demonstrations into commercial applications remains challenging. The thermal and mechanical stability of paper-based conductive electrodes is yet to be validated and improved for long-term use in soft bioelectronics. In particular, the intrinsic low stretchability of cellulose papers and structural dissociation of paper-based electronics in wet environments remain key challenges.

In recent years, low-dimensional nanomaterials have attracted research attention due to their intriguing properties, such as enhanced mechanical strength, excellent electrical and thermal conductivity, unique optical characteristics, increased chemical reactivity, and tunable magnetic properties. These characteristics stem from their nanoscale dimensions and high surface area-to-volume ratio.[33–35] Electrical conductivity and thermal management capabilities are crucial for high-performance electronic components. The high chemical reactivity and potential for surface functionalization allow nanomaterials to interact selectively with specific molecules, enhancing their effectiveness in sensors and catalytic applications.[34] Nanomaterial-driven soft wireless bioelectronics are a type of soft electronics driven by nanoscale materials with improved or even unprecedented properties (such as electric, optical, mechanic, magnetic, etc.). For example, the rearrangement of silver (Ag) nanomaterials in elastomer substrates could enable the composites to maintain electrical stability even under uniaxial or biaxial strains, which is crucial for the long-term, reliable transmission of measured tissue signals and feedback stimulation signals. So far, various nanomaterials, including liquid metal nanodroplets,[36,37] carbon nanotubes (CNTs),[38,39] and graphene and other 2D nanomaterials,[12,40,41] have been utilized in emerging wearable biosensors, wearable antennas, and wearable wireless power transfer (WPT) and energy harvesting systems, which pave a promising pathway for telehealth and telemedicine. This review article will focus on recent advances and challenges in nanomaterial-enabled wearable electronics used in the next-generation telehealth and telemedicine ecosystems. We start by reviewing the latest research on the mechanical and chemical properties of nanomaterials used in wearable electronics. We then discuss the major design considerations of emerging wearable electronic devices and present the emerging bio-applications of nanomaterial-enabled wearable electronics. Finally, we highlight the challenges and opportunities of nanomaterial-based wearable electronics in telehealth and telemedicine.

MATERIAL SELECTION AND FABRICATION METHODS OF NANOMATERIAL-BASED WEARABLE ELECTRONICS

Conductive materials for wearable electronics

Witnessed by the advancements of nanoscience and nanotechnology, a large number of nanomaterials have been synthesized for wearable electronics, including wearable antennas,[42,43] sensors,[44,45] and WPT systems.[46,47] Nanomaterials, processed from bulk materials by top-down methods, including laser ablation, ball milling, photolithography, e-beam lithography, and wet etching, or synthesized by bottom-up strategies, such as electrochemical deposition, sol-gel synthesis, spray pyrolysis, phase separation, and electrospinning, have been employed to fabricate substrates and conductive parts of emerging wearable electronic devices. Bioelectronic materials are required to maintain the stability of electrical properties under various physical deformations.[48–51] As classified by their dimensions, conductive nanomaterials include 0D nanoparticles, 1D nanowires (NWs), and 2D nanosheets. Notably, although 0D nanomaterials have been explored in bioelectronics, they typically exhibit a higher percolation–indicating the minimum concentration of conductive fillers required in a composite or network to establish a continuous path for electrical conductivity–compared to 1D and 2D nanomaterials, making it more challenging to achieve optimal electrical conductivity without excessive loading. Excessively loading 0D nanomaterials will cause increased production costs, failure of crosslinking, and higher mechanical stiffness, which may affect the flexibility and user comfort of wearable devices. In contrast, 1D and 2D nanofillers with high aspect ratios can form continuous conductive pathways within composites, enhancing electrical conductivity and mechanical properties. Such an effect can be achieved even at low filler concentrations, implying lower amounts of nanofillers used in the composite to enhance specific material properties.

1D nanomaterials have made contributions to soft wearable electronic systems because of their inherent mechanical softness, enhanced optoelectronic performance, and expanded integration possibilities. 1D nanomaterials, with their high aspect ratio, offer enhanced overall conductivity by improving electrical conduction through the materials themselves while minimizing electrical resistance at the contact points between individual NWs or nanotubes. Detailed reviews of the characteristics and fabrication of 1D nanomaterials are reviewed by Gong et al.[52] CNTs are one of the most intriguing 1D nanomaterials due to their high carrier mobility (i.e., ballistic transport), high electrical conductivity, and excellent mechanical performance. Kim et al. proposed a NO_2 sensing system using single-walled CNT (SWCNT) film with one of the highest surface-to-volume ratios, which avoids the shortcomings of traditional CNT-based gas sensors, such as low sensitivity and extended response time.[39] The as-grown SWCNT film can be directly transferred onto a flexible polyimide (PI) substrate for building wearable sensors, as displayed in Figure 1A.

In the same vein, metal NWs with high conductivity, such as silver, copper, and gold NWs, are generally regarded as good candidates for wearable electronics applications.[55–63] Silver NWs (Ag NWs) are widely employed in wearable electronic systems due to their capability to form highly percolated conductive networks. The solution-phase synthesis approaches using polyols (organic compounds containing multiple hydroxyl groups) are commonly employed to synthesize Ag NWs in large-scale production.[64,65] Hu et al. proposed a multifunctional wearable electromagnetic shielding system on an aramid nanofiber/cellulose nanocrystal/montmorillonite nanoplate (ACM) composite substrate,[63] of which the conductive layer is made of the graphene/Ag NW composite. The nanopaper exhibits excellent electromagnetic interference shielding effectiveness (39.59 dB) and reliable heating performance, showing great potential for wearable devices in radio frequency (RF) and telehealth applications. Nonetheless, the synthesis of Ag NWs is rather cumbersome, hindering their potential for large-scale use.[66] Another obstacle to the real-world application of Ag NWs in bioelectronics is their susceptibility to oxidation and corrosion in biological environments. The leaching of Ag ions from Ag NWs can cause harmful effects on human tissues. To address this issue, Choi et al. developed Ag-Au core-sheath nanocomposites (NCs) consisting of ultralong gold-coated silver NWs in a poly(styrene-butadiene-styrene) (SBS) matrix.[67] The inert gold shell layer enhanced the oxidation resistance, biocompatibility, and electrical durability of the bare Ag NWs, thus enabling their long-term use in wearable and implantable biosensing and electrical stimulation.

Alternatively, copper NWs (Cu NWs) are promising for wearable electronics since copper is one of the most common metals. To date, a variety of methods, including solution-phase chemical reduction,[68–70] copper-alkylamine-mediated synthesis,[71] and ethylenediamine (EDA)-mediated synthesis,[72,73] have been developed to synthesize Cu NWs. Gold NWs (Au NWs) emerge as promising candidates for soft wearable electronics applications, as the chemical stability issue may be overcome. For example, Kim et al. employed monolithically patterned Au NWs to build a multifunctional wearable system for monitoring of bio-signals, as shown in Figure 1B.[53] However, similar to Ag NWs, it is rather expensive to manufacture Au NW-based wearable devices.[74]

2D materials, such as graphene,[75–77] MXenes,[78–80] transition-metal dichalcogenides (TMDs),[81,82] and metal thiophosphates (MPS_3),[12,83] have emerged as promising candidates for soft electronics, as they exhibit several unique advantages, such as superior charge carrier mobility, electrochemical activity, mechanical robustness, and flexibility. 2D nanosheets can form a percolated conductive network with area-based contacts, as opposed to the point-based contacts found in 1D nanomaterials, which may effectively lower the device's contact resistance. Furthermore, the conductivity of 2D materials can be flexibly tailored by doping,[84,85] adding multiple layers,[86,87] and regulating structural defects.[88,89] For example, Mu et al. utilized laser-induced graphene (LIG) fabricated on various soft substrates (polydimethylsiloxane [PDMS], PI, and paper) to achieve an innovative sensor,[41] as shown in Figures 1C and 1D.[41] The proposed sensor exhibited a wide operation range of about 30% with ultra-high sensitivity and stability, which can be applied to human motion detection. Liquid metal nanodroplets are emerging nanomaterials for soft and wearable electronics.[37,90,91] Recently, Xu et al. developed a phase-separation-based synthesis of a porous liquid metal-elastomer composite with high leakage resistance and antimicrobial properties,[54] as shown in Figure 1E. The as-developed interconnected porous structures acted as a damper to mitigate leakage and lower percolation thresholds to reduce the use of liquid metals. Benefiting from the large stretchability, excellent stability over deformation and magnetic resonance, and high breathability, these unique porous, soft composite conductors would pave the way for emerging wearable electronics applications. Table 1 summarizes the details and important characteristics of the nanomaterials mentioned above.

Critical design considerations for wearable electronics

Various factors should be considered when assessing the performance of wearable electronic devices. Key evaluative criteria for conventional electronic components on rigid metal materials include power consumption, noises, impedance matching and signal integrity, and reliability.[23–25,93] There are several additional design considerations for wearable electronics. The sophisticated and dynamically changing environments, such as the irregular shape and continuous variations of dynamic body parts, may affect the accuracy, sensitivity, and signal-to-noise ratio (SNR) of wearable devices.[13,94,95] Therefore, it is essential to study the influence of the human body effect on the performance, long-term stability, and durability of nanomaterial-based wearable electronic devices.

For wearable applications, soft and flexible electronic circuits and sensors are inevitably subjected to bending, stretching, and twisting. Physical deformations may alter the dimensions, morphologies, and characteristics of nanomaterials, impacting their electrical and other physical properties.[96] It is imperative that wearable electronic devices should maintain an optimum performance that is independent of physical deformations. So far, many new material and structural innovations have been proposed to enhance the stability and durability of wearable electronic devices. Jung et al. presented mechanically, electrically, and thermally stable wearable electronic devices realized by integrating a PDMS nanofibrous (PDMS NF) cooler with liquid metal conductors,[97] as Figure 2A displays. Figure 2B shows the normalized resistance of the proposed electronic components versus the strain curve, demonstrating negligible variations in the resistance during stretching and, thus, excellent durability and stability. However, Li et al. pointed out the major shortcomings of this material platform, such as the potential electrical failure under large deformations, and proposed the use of dopamine-induced composite fiber bundles (DCFBs) to address this issue.[98] DCFBs exhibit a more stable conductivity even at an ultra-high tensile strain, making them more suitable for building stretchable electronic components. Yang et al. proposed a wearable sensor with excellent flexibility and robustness based on a conductive NC hydrogel obtained using the one-pot polymerization and subsequent solvent replacement.[99] The as-fabricated stretchable hydrogel sensor exhibits excellent sensitivity when monitoring minor strains (10%–40%), as displayed in Figure 2C. Li et al. proposed a self-powered multidirectional strain sensor based on the E-skin composed of novel coiled CNT yarns and an encapsulated electrochemical system in silicone.[100] This multidirectional strain sensor can sense strain changes up to 20% at 0°–90°, with a strain sensitivity of 1.28 mV/% for strains in the 0° direction and an angle sensitivity of 0.4 mV/% for the strains of 20%. Sun et al. presented a wearable sweat sensor to monitor perspiration, providing real-time, non-invasive insights into human physiology. The sensor's stretchable and wettable smart patch incorporates a bilayer laminate of a patterned microfoam and poly(vinylidene fluoride-hexafluoropropylene) (PVDF-HFP) nanofibers, an electrochemical sensor array that measures multiple biomarkers, and an elastomer substrate,[101] as shown in Figure 2D. The patterned microfoam in the membrane pumps sweat unidirectionally into vein-like collection channels and a central detection area for electrochemical analysis, while excess sweat is vented through the outlet port. The patch is attached to the human body with a silicone gel adhesive applied around the edges, providing optimum comfort when in contact with the skin. The sensing patch composed of new compliant materials and structures can maintain stable operations under mechanical deformations and can conform to the curvilinear and dynamic contours of the human body. Figures 2E and 2F display images of the wettable sensing patch at different stretch strains and the *in situ* measurement results of biomarkers, respectively. The wettable patch enables continuous collection of biomarkers such as pH, K^+, and Na^+. Moreover, the cell viability analysis using NIH 3T3 cells from the American Type Culture Collection demonstrated the skin biocompatibility of the wearable sweat-sensing patch.

POTENTIAL BIOMEDICAL SENSING APPLICATIONS

Wearable strain and pressure sensors

Wearable pressure and strain biosensors that enable real-time and long-term evaluation and feedback of individual physiological data have revolutionized telehealth by avoiding the burden of heavy instruments and cables. These wearable sensors are designed to detect various kinds of mechanical variations, such as body movements, muscle contractions, and pressure changes. Small-footprint piezoresistive, capacitive, and piezo-electric sensors, capable of converting mechanical stress in nanomaterials or microstructures into an electrical signal, can enable lightweight wearable biosensors to monitor vital signs of patients and athletic performance, among many other healthcare applications.[18,20,21,55,102] This section delves into the materials, sensing principles, and innovations related to wearable pressure and strain sensors, showcasing their impact on advancing personalized health monitoring and diagnostics.

Xue et al. presented an ultralightweight and ultrathin intronic paper-based pressure (IPBP) sensor based on ionic cellulose nanopaper (CNP) sandwiched by a pair of graphite paper electrodes, as shown in Figure 3A.[103] This structure can be regarded as a supercapacitor (electrical double layer [EDL]), which allows for monitoring of the grip force. Figure 3B shows the standard curve (blue) and the actual test curve (green) of the sensor's capacitance value in response to changes in grip force modulated by the middle finger. The promising experimental results demonstrate the potential of this device in monitoring rehabilitation and physiotherapy.

Liu et al. proposed an innovative strain sensor based on the utilization of tannic acid (TA)@MXene nanosheets.[104] These strain sensors exhibit good sensitivity, with a gauge factor of 3.99 at <400% strain and 7.79 at 400%–700% strain, as shown in Figure 3D. The sensor can be used for real-time monitoring of human emotions, swallowing, and speech (Figure 3E) and can also be readily integrated with on-skin electrodes to detect pressure changes associated with electrophysiological signals, such as electrocardiogram (ECG) and electromyography (EMG). Figures 3C and 3F show the setup and results for ECG monitoring. The experimental results demonstrate the potential of these organohydrogel strain-sensing devices for the early detection of cardiac events and other chronic diseases.

Nanomaterial-enabled wearable pressure and strain sensors can also be applied to the detection of eye-related diseases such as glaucoma.[105,106,107] Kim et al. presented a wearable soft contact lens with an excellent intraclass correlation coefficient for the real-time monitoring of intraocular pressure (IOP).[105] The contact lens incorporates a strain sensor, an antenna made of silver nanofibers and silver NWs, and a near-field communications (NFC) chiplet operating at 13.56 MHz, as Figure 3G displays. The NFC chiplet connected to the nanomaterial-based soft antenna allows for wirelessly transmitting the IOP data to the portable mobile device. Moreover, with the miniature antenna, an external device, such as a smartphone, can wirelessly power the integrated circuits that process and transmit the IOP data in real time. Figure 3H shows the circuit and system block diagram of this contact lens sensor. It is envisioned that real-time, non-invasive monitoring of IOP will be beneficial for glaucoma diagnosis and the detection of ocular hypertension.

Wearable electrochemical sensors

Electrochemical sensors, which allow for detecting chemical substances via electrical signals, serve as vital tools for many biomedical applications, as they offer high sensitivity, specificity, and fast response times.[108–111] Wearable electrochemical sensors based on flexible and stretchable nanomaterials are expected to achieve high-sensitivity, real-time monitoring of various biological signals transduced by the human body.

Mannoor et al. demonstrated a fully passive and highly sensitive graphene-based wearable sensor for the real-time monitoring of respiration and bacteria in saliva.[112] A graphene monolayer transferred onto interdigitated electrodes is connected to a coil antenna, forming a resistor-inductor-capacitor (RLC) resonator, as Figure 4B illustrates. This wearable sensor can be bio-transferred to tooth enamel or tissue to detect bacteria, as shown in Figure 4A. Notably, the biosensitivity of the sensor is achieved through the self-assembly of antimicrobial peptides (AMP)-graphene peptides onto a graphene monolayer, as illustrated in Figures 4B and 4C. When the immobilized peptides bind to specific bacterial targets (Figure 4C), the electrical conductivity of the graphene film is altered, which in turn varies the complex-valued input impedance and resonance frequency of the RLC resonator. Interestingly, this wireless, tooth-wearable biosensor enables battery-free operation, as variations of electrical properties can be wirelessly read (via inductive coupling) by an external interrogator equipped with a coil antenna. Here, high sensitivity (in terms of electrical responses) and bio-selectivity of nanomaterials enable a low-profile wearable device to detect bio-agents, thus benefiting early detection of oral pathogens and dental diagnosis. Likewise, with proper surface functionalization and modification of the antenna and wireless setup, the graphene-based, battery-free, wireless wearable sensor can be applied to monitor a wide range of biological factors, such as viral proteins, ketones, and glucose.

Wearable gas sensors can detect pollutants and monitor hazardous environments to protect individuals and can be used in some biomedical applications.[114–119] Guo et al. reported a lightweight and inexpensive wearable epidermal gas sensor grounded on $MoSe_2$ nanosheets.[113] Figure 4D displays the optical microscope image of the sensing unit, which consists of a $MoSe_2$-based gas-sensing site (highlighted in the inset), thin serpentine Au interconnects (100 μm in width and 150 nm in thickness), comb structures with a finger width and gap (20 μm), and a metal bond pad connected to an external readout circuit. The high sensitivity (down to parts per billion level) and fast response time (up to 300 s) are demonstrated with continuous monitoring of NO_2 and NH_3 (Figure 4E). Moreover, the gas sensor is integrated with a Bluetooth low energy (BLE)-cable flexible printed circuit board (FPCB) for wireless data transmission to the internet. The data generated by the sensor can be first transmitted to a smartphone and subsequently uploaded to a cloud terminal for data analysis, sharing, and documentation. Wearable gas sensors have many applications, including but not limited to tracking minor fluctuations in harmful environmental gases and issuing early evacuation alerts for patients with asthma.

Xu et al. proposed an NFC-compatible, fully stretchable, and battery-free wireless bioelectronic system for multiplexed biochemical sensing.[92] The wireless sensor based on a passive RLC resonant circuit is built on a stretchable phase-separated porous Ag

NW NC (PSPN) substrate, as shown in Figures 4F and 4G. In this RLC resonator, a variable capacitor (or varactor) is connected to a LIG ion-selective sensing electrode (ISE) and a reference electrode (RE), such that potential difference across the ISE and RE can tune the equivalent capacitance of the varactor. Capacitive changes can be detected by contactless (inductive) coupling of the RLC resonator with a coil antenna (Figure 4F) and tracking the resonance frequency shift of the system (Figure 4H). With multiple miniature RLC resonators integrated with bio-functionalized electrodes, *in vivo* (on-body) multiplexed wireless sensing of glucose, pH, NH_4^+, Na^+, and H^+ is showcased. This work opens a new avenue toward rapid, multiplexed wireless biosensing for precise, non-invasive assessment of metabolic function and acid-based balance.

Long-range wireless wearable biosensors

NFC-based wireless sensing techniques generally suffer from relatively short interrogation ranges (typically less than a few centimeters) and the need for close contact, which restrict their practical use in some healthcare applications that require long-term and long-range remote monitoring.[103,117,120,121] Long-range wireless sensing also offers the scalability to deploy numerous sensor nodes and gain more insights from the data, thereby benefiting chronic disease management and remote diagnostics.[122,123] In this regard, passive and maintenance-free radio frequency identification (RFID) sensors have gained remarkable attention in telehealth and telediagnosis.

Traditional passive RFID sensors are often questioned for their immunity to clutters, crosstalks, and self-jamming, which result in deteriorated accuracy and reliability in noisy indoor and urban environments. Recently, nonlinear harmonic RFID sensors have been proposed to suppress these electromagnetic interferences and thus improve the SNR and extend the wireless interrogation distance for long-range tracking and sensing applications.[22–24,118,122,124,125] With the rapid advancement of materials innovations and electrically small antenna designs,[126,127] as well as interfacial engineering on wearable electronics,[128–130] nanomaterial-enabled soft and flexible harmonic RFID sensors have been proposed. Ye et al. reported a fully passive smart face mask based on a soft harmonic RFID tag for real-time wireless monitoring of coughs.[122] The harmonic RFID tag consists of a meander-line antenna (frequency of operation: 1.6 GHz), a modified planar inverted-F antenna (frequency of operation: 3.2 GHz), and a passive frequency multiplier, as shown in Figure 5A. The antennas, interconnects, and RF circuit on the harmonic RFID tag are made of spray-printed Ag NWs coated with a passivation layer of poly (3,4-ethylene dioxythiophene):poly (styrene sulfonate) (PEDOT:PSS) and are deposited on a porous substrate of polystyrene-block-poly(ethylene-ran-butylene)-block-polystyrene (SEBS). As a result, the tag is stretchable, flexible, breathable, reusable, and resistant to deformation and long-term use. When the sensor is away from the human body or in an open-air environment, it receives the radio signal at 1.6 GHz and retransmits the second-harmonic signal at 3.2 GHz to the reader in the far zone. When the sensor is close to the human body (Figure 5B), the parasitic effect from tissues changes the input impedance and resonance frequency of antennas, detuning the signal strength of the backscattered second harmonic. Hence, the recorded second-harmonic received signal strength indicator (RSSI) and its history can be used to monitor cough events and mask-wearing conditions. The proposed cough-detectable sensing system can help healthcare professionals make timely interventions, personalize treatment plans, and improve patient outcomes through remote telediagnosis.

Rauf et al. proposed a screen-printed ECG system consisting of an Ag NW-based, skin-friendly ECG electrode embedded with a scaled-down PCB encapsulated inside a 3D-printed antenna-on-package (AoP).[131] By integrating the antenna directly onto the chip package, the signal loss can be reduced, and the overall system efficiency can be improved. Figure 5C shows the integrated ECG sensor that captures the ECG signal and transmits the data to a designated server through a smartphone intermediator. The PCB readout circuit filters out noises and amplifies and digitizes the signal before sending it to the smartphone app via the BLE protocol. The app displays the ECG waveform to the user and uploads it to the cloud server for data storage and postprocessing. The AoP module has a maximum wireless interrogation distance of 142 m. In addition, the ECG sensor can be expanded to provide a standard 12-lead ECG for long-term diagnosis of cardiovascular conditions.

The concept of human body sensing networks is regarded as a new, promising avenue for collecting physiological signals from multiple sensing nodes at different body locations.[132,133] Niu et al. present an innovative wireless body area sensor network (bodyNET) comprising multiple skin-friendly RFID tags (sensing nodes) that are wirelessly linked to flexible on-textile readout circuits[132] (Figure 5D). Each sensor node (Figure 5E) is constituted by (1) a stretchable on-skin RLC strain sensor composed of a silver nanoflake-elastomer spiral antenna and a strain-sensitive CNT coating (i.e., resistive sensor) on the SEBS substrate (Figure 5G) and (2) a flexible on-textile initiator consisting of an antenna, readout circuits, flexible batteries, and a Bluetooth transceiver (Figure 5H); the two components are wirelessly connected via the RFID protocol. Physiological signals, including respiration, heartbeat, and motion, are first detected by the soft strain sensor and then transformed to the on-textile reader via the RF signal at 13.56 MHz. Finally, communication between multiple sensing nodes and a smartphone is achieved via the Bluetooth protocol, as illustrated in Figure 5F. The data collected in the bodyNET can be transmitted into the remote cloud server through the cellular network. A master-slave communication protocol is adopted for the bodyNET, in which a specific sensing node serves as the master node and the other sensing nodes serve as slave nodes. The data in slave nodes are first gathered to the master node, and the master node will send all the aggregated data to the smartphone, as illustrated in Figure 5F. The bodyNET system can be used for long-term continuous, hands-free, and accurate monitoring of daily physiological signals, making it particularly suitable for telehealth applications. Remote, real-time data collection from patients without the need for frequent hospital visits will significantly improve patient care, especially for individuals with chronic conditions. The ability to transmit data to healthcare providers allows for timely interventions, personalized treatment plans, and intelligent management of health conditions. This telehealth technique can also potentially improve diagnosis outcomes in remote or underserved areas where access to medical facilities is limited.

CONCLUSION AND OUTLOOK

Wearable bioelectronic devices made of low-dimensional nanomaterials have made significant progress in personalized healthcare monitoring and clinical diagnostics.[37,50,134] Here, we have reviewed various nanomaterial-based wearable devices and their applications, which show great promise in revolutionizing the current telehealth and telemedicine systems.[135,136] Nevertheless, the long-term durability of nanomaterial-based wearable sensors, circuits, and other electrical components remains an open question and a major potential challenge.[137] Molecular-level modification, such as surface passivation, appears to be a promising route to get rid of oxidation and electrical failure, thereby increasing the device's durability and lifetime. It is also of paramount importance to accomplish economical large-scale production of nanomaterials,[138] so as to facilitate the clinical translation and commercialization of wearable devices.

A standalone wearable system usually requires many cumbersome and complex circuits. For example, in state-of-the-art 12-lead ECG systems, electrodes are connected using cables, which not only increases the cost and cumbersomeness of the system but also impedes patients' mobility and creates discomfort.[131] Recently, contactless biosensing by incorporating nanomaterial-enabled wearable sensors with wireless protocols (e.g., NFC, RFID, and/or Bluetooth) has been demonstrated. Still, challenges remain regarding the safety, lifetime, and user-comfort issues of batteries and power sources. On the flip side, passive (battery-free) long-range wireless sensors generally suffer from electromagnetic interferences stemming from clutters, crosstalks, and jamming.[139,140] The aforementioned issues may be mitigated by the recently proposed harmonic or intermodulation-based passive RFID systems, which exploit harmonic or sub-harmonic tones in the forward and reverse links.[23,24,122] Furthermore, body-coupled wireless sensor networks and WPT techniques (e.g., simultaneous wireless information and power transfer or SWIPT protocol)[122,123,133,141–143] may allow for monitoring multiple biomarkers at the same time. In the realm of sensor fusion, machine/deep learning-assisted data analysis tools can further enhance the accuracy and reliability of smart health monitoring systems. We envision that the real-time, high-quality physiological data collection enabled by nanomaterial-based wearable electronics, alongside new wireless data acquisition and sensor fusion technologies, will ultimately provide more effective assessments and insightful decision-making for individual and public health.[144–147]

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DATA AND CODE AVAILABILITY

The authors declare that the data supporting the findings of this study are available within the paper. There is no code associated with this paper.

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THE BIGGER PICTURE

Nanomaterial-driven, soft wearable electronics hold great promise for continuous monitoring of bio-signals, efficient collection of physiological data, and on-demand drug delivery. Wearable electronic devices transducing physiological responses into electrical signals have been used in various telemedicine and telediagnosis applications, such as real-time monitoring of vital signs, blood pressure, body temperature, and human motion. Combined with radio frequency (RF) technologies, these devices can transmit health data and be powered wirelessly. In this review, we discuss the recent progress of one- and two-dimensional nanomaterials and their intriguing electrical, biochemical, thermal, and mechanical properties that make them suitable for wearable electronics applications. Human body sensing networks built with nanomaterials may enable long-term, multi-physiological monitoring, thus facilitating comprehensive data collection across various health metrics.

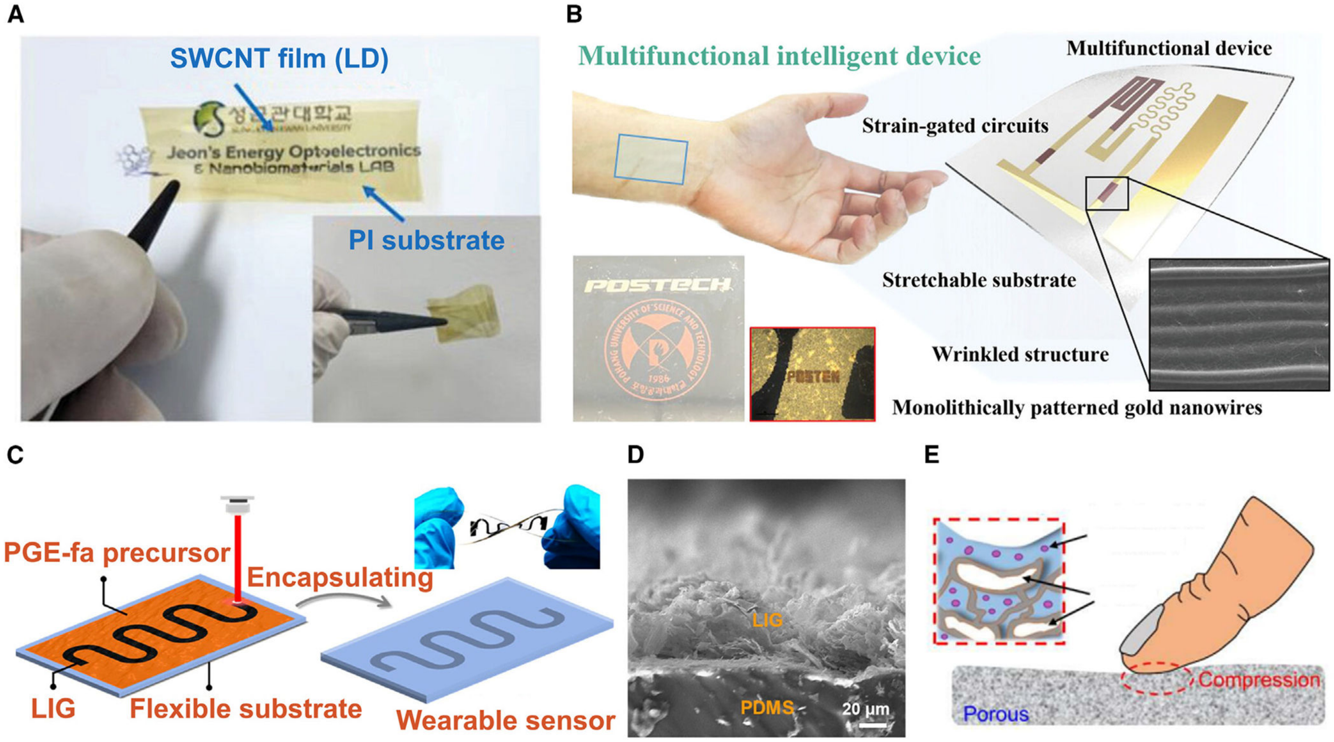

Figure 1. An overview of 1D and 2D nanomaterials applied in existing wearable electronics

(A) The photographs of SWCNTs embedded on PI substrates.[39]

(B) Schematic of multifunctional intelligent wearable devices consisting of sensing part and the strain-gated logic circuits using patterned gold nanowires and microwrinkle structures.[53]

(C) Schematic of the fabrication of flexible LIG/PDMS wearable sensor.[41]

(D) The SEM image of LIG on PDMS substrate of the proposed sensor in the work presented by Mu et al.[41]

(E) Phase-separated eutectic gallium-indium (EGaIn)/SEBS nanocomposites with leakage-resistant properties upon compression.[54]

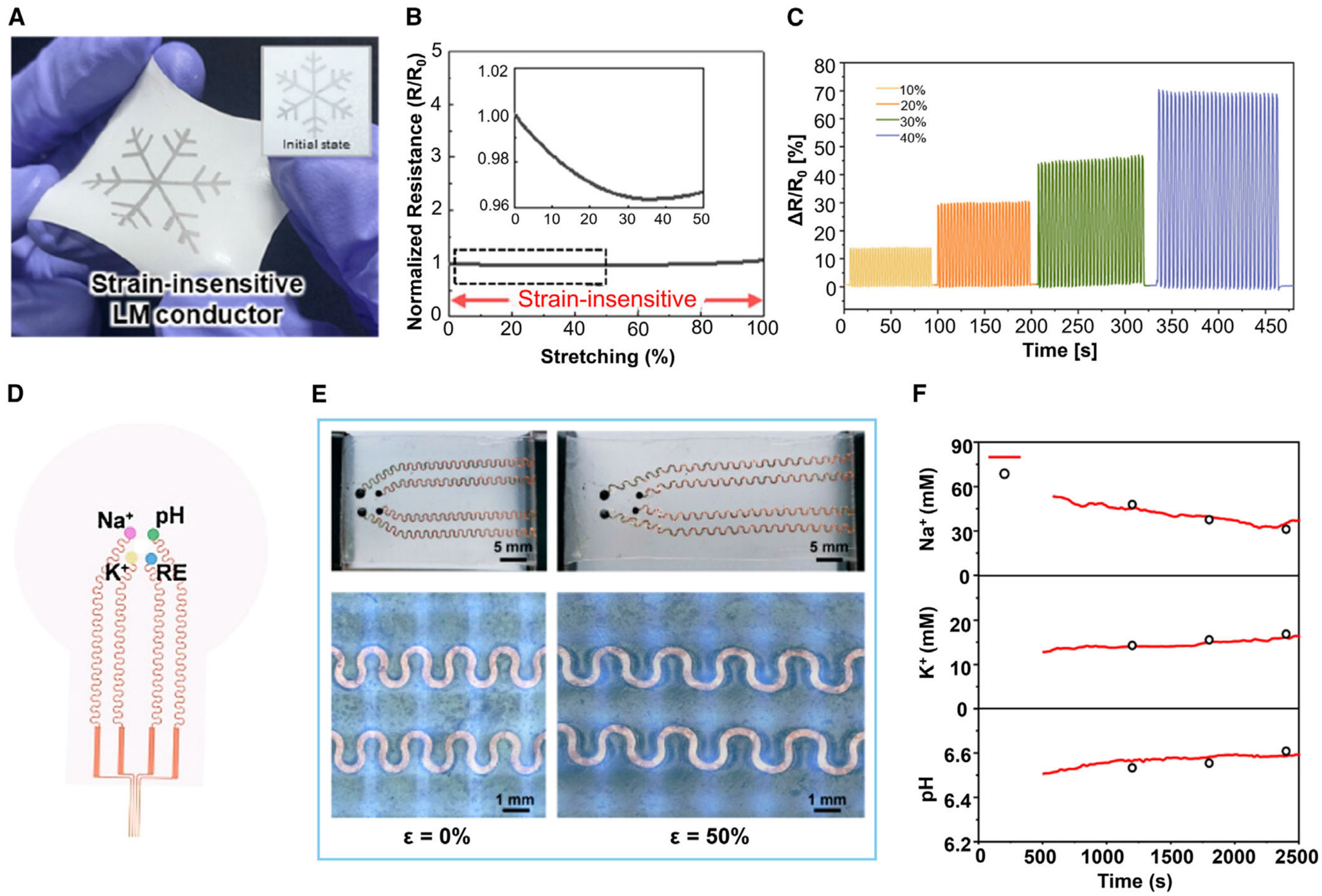

Figure 2. Critical design aspects of nanomaterials in wearable electronics

(A) Photograph of the laser-patterned, strain-insensitive liquid metal conductor on a PDMS NF.[97]

(B) Resistive variation against the alteration in strain.[97]

(C) Resistive variation of the hydrogel sensor under small strains.[99]

(D) Schematic diagram of the stretchable electrochemical sensor arrays for multi-biomarker detection.[101]

(E) Optical images of the stretchable sensor array at different strains.[101]

(F) Demonstration for the presented sensing patch in real-time monitoring of sweat compositions over continuous cycling.[101]

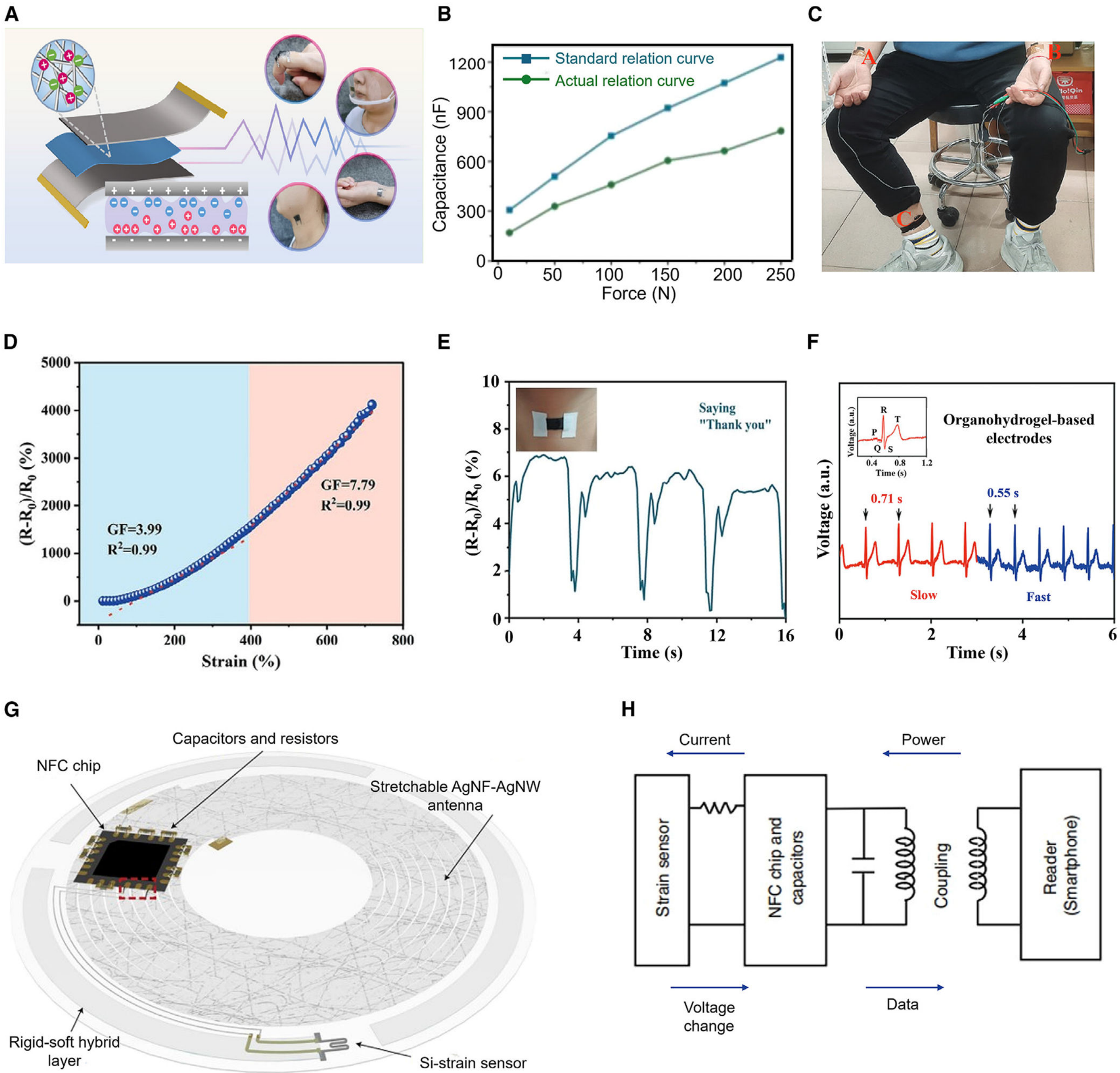

Figure 3. Review of nano-enabled, deformation-based wearable biosensors

(A) The schematic of the proposed wearable pressure sensor grounded on ultrathin ionic nanopapers. Specifically, five cycles of capacitive responses with respect to different pressures are displayed. The bottom figures demonstrate the sensitivities and response-pressure curves of the proposed IPBP sensors.[103]

(B) IPBP sensor applied to grip force monitoring.[103]

(C) The schematic diagram of the setup for ECG detection applying PHEA-TA@MXene organohydrogel electrodes.[104]

(D) Stretching demonstration (including the image and resistive illustration) of the presented sensor grounded on PHEA-TA@MXene organohydrogel electrodes with superior stretchability.[104]

(E) The voice sensing test of this sensor.[104]

(F) The performance of the ECG monitoring using PHEA-TA@MXene organohydrogel electrodes.[104]

(G) Schematic of the integrated sensing system consisting of a Si strain sensor, stretchable Ag NF-Ag NW antenna, NFC chip, passive capacitors, and resistors and stretchable interconnects on a rigid-soft hybrid film.[105]

(H) Schematic of the equivalent circuit models of the presented contact lens for intraocular pressuring monitoring.[105]

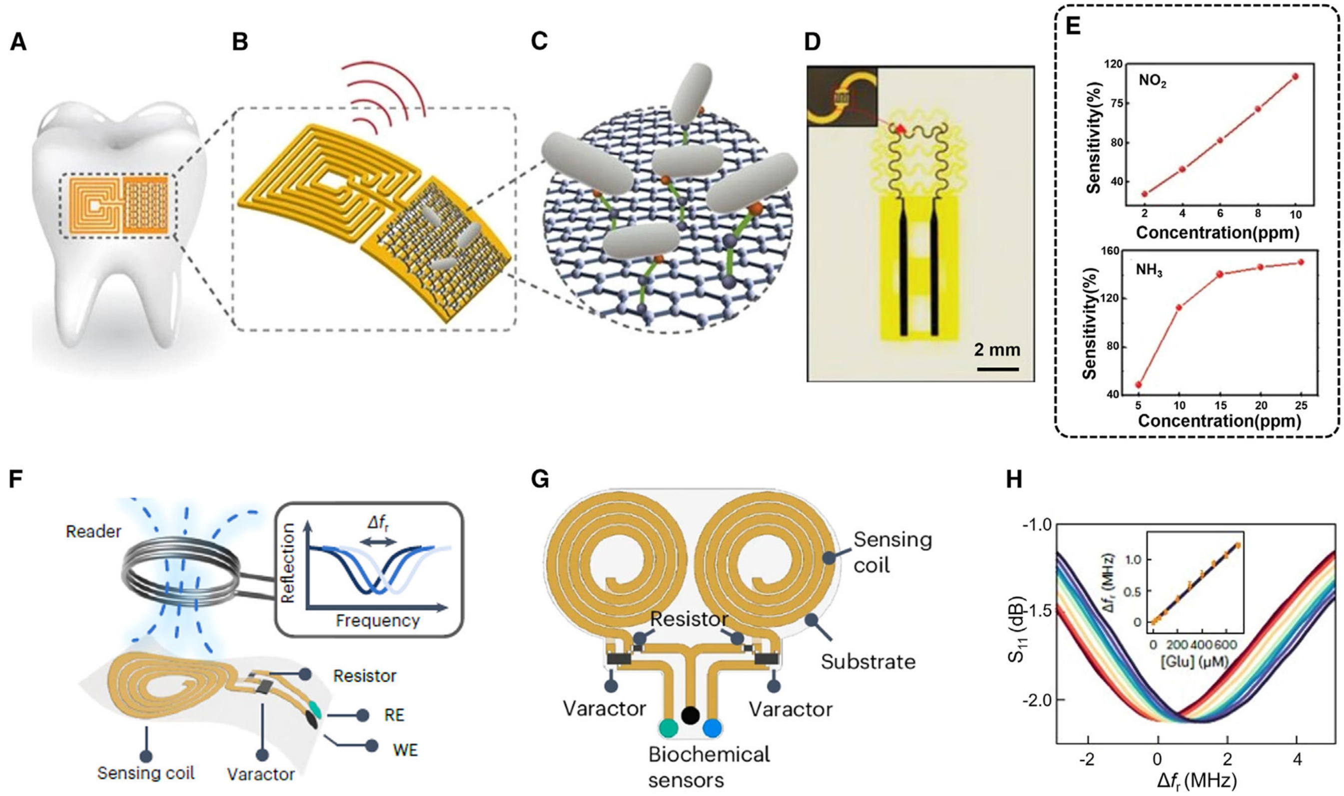

Figure 4. Nano-driven wearable chemical-sensing systems

(A) Placement of the graphene-based nano-sensor on the surface of the tooth. The proposed sensor including a wireless coil is formed onto bioresorbable silk.[112]

(B) Schematic of the sensing element of the proposed nano-sensor for bacteria detection on tooth.[112]

(C) Peptide self-assembly on a graphene nanotransducer for binding pathogenic bacteria.[112]

(D) Optimal image of the MoSe2 nanosheet-based gas-sensing device.[113]

(E) Sensitivity curves of NO2 (top) and NH3 (bottom).[113]

(F) Schematic demonstration of the fully passive biomedical sensor presented in the work of Xu et al.,[92] where RE refers to the reference electrode and WE stands for working electrode.

(G) Circuit diagram of the proposed sensor.[92]

(H) Reflection coefficient shifts for wireless on-body monitoring of glucose.[92]

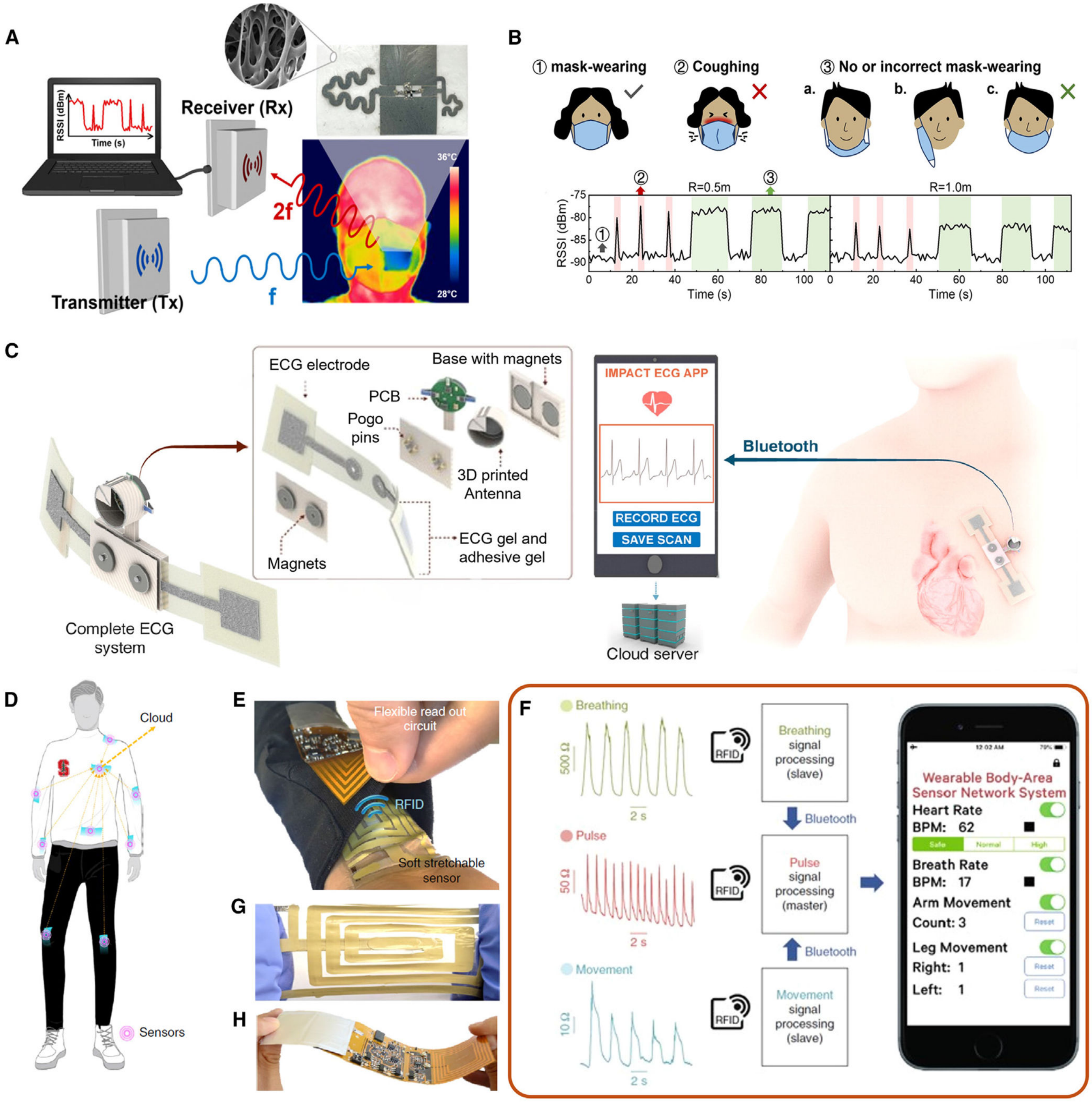

Figure 5. Emerging long-range, nano-based wearable sensing systems

(A) Illustration of the harmonic sensor fabricated on spray-printed Ag NWs.[122]

(B) RSSI signals of the proposed sensor in different situations.[122]

(C) Schematic of the proposed ECG system. This sensing system is mainly composed of a 3D-printed AoP, silver-nanowire-based ECG electrodes, and a Bluetooth module. The ECG system operates by capturing the ECG signal and transmitting the data to a dedicated server through a smartphone app.[131]

(D) Concept schematic of the bodyNET. There are multiple sensing nodes distributed across various body locations. The sensing information from each sensing node is linked to the center cloud and then transmitted to the external wireless device.[132]

(E) Photograph of the fabrication sensing node.[132]

(F) Operation of sensing physiological data transmission. The data are transmitted to the respective initiators via RFID, while the pulse sensor node gathers information from other nodes and sends it to a smartphone via Bluetooth.[132]

(G) Photograph of a stretched target.[132]

(H) Photograph of a bent FPCB initiator.[132]

Table 1.

Significant materials utilized in nano-enabled wearable electronics

References	Conductive material	Substrate material	Electrical conductivity	Mechanical properties		Application	Mechanism	Property
				Stretchability (%)	Durability			
Kim et al.[39]	carbon nanotube	PI	55.2 Ω sq^{-1}	15%	5,000 bending cycles	gas (NO_2) sensor	resistive	low response time, high sensitivity, low defect rates, low noise, stretchable, flexible
Hu et al.[63]	Ag NW/ graphene	ACM composites	1,398.08 S cm^{-1}	24.61%	–	electromagnetic shielding	N/A	robust, thermal and electromagnetically stable
Zhao et al.[70]	Cu NW	PVDF	15.6 Ω sq^{-1}	–	1,000 bending cycles	temperature sensor	resistive	thermal/chemical stable, ultra-thin and transparent, flexible
Kim et al.[53]	Au NW	SEBS	0.39 S cm^{-1}	100%	300 cycles	strain sensor, strain-gated logical circuits, electrical heater	resistive	highly sensitive, flexible, robust
Xu et al.[92]	PSPN	polyurethane	642,000 S cm^{-1}	600%	10,000 cycles	WPT, biochemical sensor	resistive, capacitive	highly conductive, strain insensitive, fatigue tolerant
Mu et al.[41]	LIG	PDMS, poly, and paper	56.65 S cm^{-1}	30%	10,000 cycles	strain sensor	resistive	high sensitivity, good stability, short response time
Cai et al.[77]	graphdiyne	polyethylene terephthalate	–	–	5000 cycles	strain sensor	resistive	high sensitivity, fast response, and long-term stability
Sharifuzzaman et al.[80]	MXene	PVDF	15.6 Ω sq^{-1}	15%	550 cycles	strain sensor	resistive, electrochemical	simultaneous sweat biosensing and electrocardiogram signal recording
Xu et al.[54]	porous liquid metal	polyurethane	1200,000 S cm^{-1}	500%	1,000 cycles	skin-interfaced bioelectronics (monitoring cardiac electrical and mechanical activities)	resistive	high and stable electrical conductivity over deformation, high breathability, magnetic resonance imaging compatibility