

Wearable Sensor Technology and its Applications in the Medical Field

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Abstract. With the development of biomedical engineering and Internet of Things technology, wearable sensing technology plays an increasingly important role in the field of modern medicine. Wearable sensing technology is widely used in biomedical field because of its non-invasive and portable characteristics, especially in laboratory medicine. With the development of wearable sensing technology from traditional rigid structure to flexible patch, its sensitivity, specificity, stability and practicability have been greatly improved. Combined with related research, this study aims to systematically comb three different sensors, reveal the core principles of physical and chemical measurement sensors, and special sensors, and integrate their current applications in intensive care unit, pulse phase and acupuncture effect of traditional Chinese medicine and chronic disease management. This study is expected to provide theoretical reference for the clinical transformation of wearable sensing technology and promote the sustainable development of smart medical care and equipment safety.

Keywords: medical, sensor, biology, Traditional Chinese Medicine

1. Introduction

With the rapid development of biomedical engineering and Internet of Things (IoT) technologies, wearable sensor technology is playing an increasingly important role in the field of modern medicine. Research on wearable sensor technology has,for the most part,concentrated on the performance of single devices or on narrowly defined disease contexts,while a systematic synthesis of the underlying technical principles,present clinical use cases,and likely developmental trajectories has remained comparatively underdeveloped. Out of that imbalance have emerged several implementation and clinical translation bottlenecks—most notably,insufficient battery endurance,risks to data privacy and security,and still-limited accuracy in multimodal signal fusion (a problem that persists even when device-level performance appears promising in isolation). Against the broader progression of science and technology,and with sensing devices themselves continuing to mature,a wide range of sensor types has been adopted across medical settings,with decades of development having produced encouraging results. The present article surveys the current research landscape on sensor applications and the corresponding solutions,addressing both the operating principles and the application protocols associated with different categories of sensors.

2. Classification and principles of wearable sensing technology

2.1. Sensors for measuring physical quantities

Physical quantity measurement sensors constitute the most mature and core category in wearable sensing technology. They are primarily designed to support real-time and continuous dynamic monitoring of basic vital signs, including heart rate, blood pressure, respiratory rate, and body temperature.

In terms of heart rate and ECG monitoring, current approaches primarily rely on two principles: photoplethysmography and ECG signal detection. The former involves illuminating the skin with a green LED light and capturing changes in light intensity caused by blood flow to calculate heart rate, whilst the latter utilises electrodes to directly capture myocardial electrical activity, providing medical-grade accuracy in the detection of arrhythmias. To further enhance measurement accuracy and the depth of information, multimodal signal fusion has become a key area of development. For example, Cardiosense's CardioTag device can simultaneously capture electrocardiograms (ECGs), photoplethysmograms (PPGs) and cardiograms, enabling a comprehensive assessment of heart rhythm, cardiac mechanics and haemodynamics, and has received FDA 510(k) clearance; The TAESS system, based on elastic fabric, integrates ECG and impedance plethysmography into textiles, enabling continuous acquisition of ECG and blood flow signals without the need for precise positioning.

In the field of blood pressure monitoring, traditional cuff-based blood pressure measurement is gradually being supplemented by cuffless technologies, as it fails to provide continuous tracking. Tianjin University has developed a conformable piezoelectric microsystem integrating pulse wave and ultrasound sensors, offering 160-fold improved sensitivity with a systolic pressure error of just 5.22 mmHg and requiring no calibration; Aktia and Valencell have respectively launched FDA-approved cuffless blood pressure devices and a calibration-free cuffless blood pressure measurement solution integrated into earplugs [1]. As an early and sensitive indicator of clinical condition changes, wearable respiratory rate monitoring mainly adopts working principles such as thoracic movement sensing and impedance plethysmography. For example, a smart respiratory monitoring belt based on giant magnetoresistance (GMR) sensors detects thoracic movement via changes in the magnetic field; it has been verified to have a maximum error of only ± 2 breaths per minute and requires no direct skin contact. The PneumoRator patch-type sensor, developed by the University of Southampton in the UK, achieves measurements of equivalent accuracy by detecting frequency changes caused by thoracic expansion, whilst the multimodal system reSPIRE integrates multiple signals such as cardiothoracic oscillography, impedance plethysmography and electrocardiography, providing a continuous monitoring solution for the comprehensive assessment of cardiopulmonary parameters.

With respect to body-temperature sensing, wearable devices most often rely on thermistors, P-N junction diodes, or infrared-based detection principles. Through microfabrication, microstructured thermocouple infrared detectors can be produced on silicon substrates, thereby permitting non-contact measurement; in Ko's 1986 report, the device exhibited a sensitivity of 6 V/W and a time constant of only 15 ms. Along a different technical pathway, high-sensitivity temperature sensors constructed from silicone-ion gel composites draw on ion capture-release kinetic mechanisms to sharpen detection accuracy to 0.008°C, thus exceeding the 0.02°C thermal sensitivity of human skin (a comparison frequently used as a practical benchmark) and, in turn, broadening the range of possibilities for personalised temperature regulation and precise monitoring. Across these developments, the ongoing refinement and combination of such physical-quantity sensors are

steadily moving wearable medical monitoring away from single-point,fragmented recording and toward multidimensional,continuous,dynamic sensing.

2.2. Chemical sensors

Unlike physical sensors,which directly transduce mechanical or thermal variables,chemical sensors are designed to translate concentration shifts in trace chemical markers within body fluids into readable electrical or optical outputs through the construction of specific molecular-recognition interfaces,thereby allowing real-time tracking of dynamic changes in the human biochemical milieu. At present,wearable chemical sensing technologies are concentrated largely in two domains: detection of electrolytes and metabolites,and pH monitoring. The study-defining advances,put more precisely,lie in the engineering of highly selective sensing interfaces and in the development of anti-interference signal-transduction mechanisms [2].

Within electrolyte and metabolite detection,electrochemical amperometric methods and photoelectrochemical (PEC) strategies remain the principal technical routes. For electrolyte ions,all-solid-state ion-selective electrodes provide label-free monitoring of ionic activity by measuring the potential difference across the membrane or at the solution interface; over recent years,these systems have drawn sustained attention because operation is straightforward,response is rapid,and energy demand is low. For key biosignaling molecules—notably ascorbic acid (AA) and dopamine (DA)—functionalised PEC sensors built on heterojunctions and metal-organic frameworks (MOFs) exhibit strong analytical performance. In the specific case of AA detection,heterojunction design exploits bandgap engineering so that the optical response extends into the near-infrablue region,a shift that helps bypass the shallow tissue penetration associated with conventional UV excitation [3]. Once AA is adsorbed onto the heterojunction surface,a reversal in semiconductor band bending is induced; from that inversion follows a corresponding switch in photocurrent polarity,from anodic to cathodic. Particularly in complex biological matrices,this polarity-reversal approach orthogonally couples qualitative information (positive versus negative polarity) with quantitative information (current amplitude),and in doing so improves resistance to interference; accurate determination of AA concentrations in human serum and rat cerebrospinal fluid has already been demonstrated with this scheme [3]. A closely related logic applies to DA: by combining MOF confinement with Au-LSPR,the composite system enriches DA through hydrogen bonding,broadens optical absorption,and accelerates charge transfer,ultimately enabling ultra-sensitive detection—a result validated in rat cerebrospinal fluid [3]. Also relevant here,graphene foam sensors support simultaneous,high-sensitivity detection of uric acid,DA,AA,and other sweat metabolites,which makes them particularly suitable for exercise monitoring and metabolic assessment [4].

As for pH monitoring,sensor operation rests mainly on either the potential response occurring at the sensitive-membrane interface or the optical principle of refractive-index modulation. Electrochemical pH sensors,in most implementations,use pH-responsive materials—such as polyaniline,hydrogen ion carriers,or metal oxides—to modify the electrode,after which the open-circuit potential exhibits a Nernstian response relationship with local pH [5]. Confirmed through in vivo implantation experiments,subcutaneous pH sensors are able to capture accurately the drop in blood pH in a respiratory acidosis model and to maintain a stable response over one week [6]. In wearable applications, integrating such microelectrodes with microfluidic sweat collection systems enables non-invasive, continuous monitoring of dynamic changes in the pH of sweat on the skin surface during exercise.Recent studies indicate that wireless flexible potential sensors incorporating temperature compensation mechanisms are now capable of simultaneously detecting pH levels in sweat and skin temperature, whilst maintaining high measurement accuracy even within extreme

temperature ranges [7]. Furthermore, biodegradable nanostructured pH sensors have been developed for subcutaneous implantation. These devices monitor local pH in real time through fluorescence signal variations and fully degrade within one week after implantation, demonstrating promising prospects of implantable chemical sensors in postoperative monitoring and related fields.

2.3. Specialised sensors

Beyond sensors for physical and chemical quantities, specialised sensor technologies such as needle-type chemical sensors and flexible electronic skin have emerged to meet the specific demands of medical monitoring, including minimally invasive implantation, long-term adhesion, and the comprehensive analysis of complex physiological signals. Such sensors break traditional limitations in structure, functional integration and material design, making them a cutting-edge research hotspot in wearable sensing technology.

Microneedle chemical sensors utilise micro-needle arrays or individual micro-needles as carriers. By penetrating the stratum corneum to reach the epidermis or dermis, they enable minimally invasive or even painless monitoring of key biomarkers in interstitial fluid. Compared to traditional transdermal or implantable sensors, microneedle sensors minimise trauma and effectively mitigate the risks of bleeding and infection. In terms of structural design, microneedles are typically fabricated from silicon, metals, polymers, or biodegradable materials, with their tips loaded with specific sensing elements. For example, the 3D-assembled microneedle ion sensor developed by Huang et al. integrates multi-ion-selective electrodes, enabling dynamic transdermal monitoring of physiological ion waves [8]; Molinero-Fernández et al. constructed a potential-type microneedle patch for simultaneous multi-ion monitoring, achieving real-time tracking of ion concentrations in tissue fluid during *in vivo* experiments [9]. Furthermore, glucose monitoring represents a core application area for microneedle sensors. Sang et al. reported a fluorescence-based, biodegradable microneedle sensor array that, once implanted, can continuously monitor blood glucose levels and completely degrade within the body upon completion of its function, thereby avoiding a second surgical procedure for removal, demonstrating broad prospects for diabetes management [10]. In the future, microneedle sensors are expected to be extended to the continuous analysis of various metabolites and hormones—such as lactate and cortisol—emerging as an important tool for the long-term management of chronic diseases.

Flexible electronic skin, meanwhile, represents a leap forward in wearable sensing, moving from single-function devices to biomimetic multimodal sensing systems. Electronic skin aims to mimic or even surpass the complex sensing capabilities of human skin, integrating physical sensors for pressure, temperature, humidity and strain, as well as chemical and biological sensors for pH, ions and glucose, to enable the simultaneous analysis of multiple physical and biochemical parameters. In terms of materials, electronic skin typically adopts flexible substrates such as polydimethylsiloxane, thermoplastic polyurethane, and hydrogels, combined with conductive or functional materials such as liquid metals, carbon-based materials and metal-organic frameworks. Through microstructural design, these materials are endowed with biomimetic properties such as stretchability, breathability and self-healing. As a significant sub-category, ion-electric electronic skins utilise the ultra-high capacitance per unit area of the ion-electron interface double layer, achieving pressure sensing sensitivity that is up to a thousand times greater than that of traditional capacitive devices. Furthermore, through signal acquisition strategies such as array integration and frequency division multiplexing, they can realise high spatio-temporal resolution mapping of tactile and physiological signals. For example, the embedded ion-electronic sensor array reported by Shi et al. can be affixed to joints to enable real-time visualisation of intra-articular pressure distribution,

providing quantitative evidence for orthopaedic diagnosis and treatment [11]; whilst the fingerprint-like ion-electronic sensing system designed by Bai et al. has endowed robots with the fine tactile ability to recognise surface textures of objects [12]. Electronic skin has demonstrated immense potential in fields such as cardiovascular health monitoring (e.g. continuous blood pressure and pulse wave analysis), wound healing management (e.g. simultaneous pH and temperature monitoring), and sports rehabilitation assessment. It is driving the evolution of wearable devices towards 'epidermal electronic systems', becoming a vital hardware platform for personalised precision medicine.

3. Application scenarios and case studies of wearable sensing technology in the medical field

3.1. Intensive care units (ICUs)

Patients in intensive care units (ICUs) require continuous vital sign monitoring to ensure safety; however, traditional ICU monitoring equipment is bulky and involves complex wiring, which can easily restrict patient mobility and cause iatrogenic skin damage. Wearable devices offer a new solution through their wireless, portable and flexible characteristics: wrist-worn photoplethysmographic devices can assess the total sleep duration of non-intubated patients [13]; finger-cuff continuous blood pressure monitoring shows a high correlation with arterial catheter results, supporting non-invasive dynamic blood pressure tracking; wireless chest-worn photoplethysmographic monitors are comfortable and accurate for post-operative use; and wrist-worn pulse wave analysis devices demonstrate high consistency with heat dilution methods for cardiac output assessment. In pressure ulcer prevention, wearable position sensors increased nurses' compliance with scheduled repositioning from 55% to 89%, reduced the average repositioning interval from 3.8 hours to 2.3 hours, and significantly lowered the incidence of pressure ulcers [14].

Delirium is an acute, fluctuating syndrome characterized by impaired attention and cognition, commonly induced by severe illness, medications, or environmental stressors. In terms of its management, the smart ICU system integrates wearable accelerometers with environmental sensors such as light intensity and noise, enabling the simultaneous collection of patient facial expressions, limb movements and environmental parameters. It has been found that there are significant differences between delirious and non-delirious patients in terms of ambient light intensity, sound intensity and the frequency of night-time rounds, providing a basis for early identification and intervention [15]. In neonatal and paediatric ICUs, wireless skin-interface biosensors can simultaneously measure patients' heart rate, respiratory rate, body temperature and blood oxygen saturation with accuracy equivalent to clinical gold standards, whilst avoiding the skin damage and restrictions on parent-child contact associated with traditional hard-wired devices. Additionally, wearable flexible blue-light garments have been applied to neonatal jaundice treatment. Bilirubin levels drop markedly after three hours of irradiation, effectively reducing the risks of dehydration and retinal injury related to conventional phototherapy. In summary, wearable sensor technology has demonstrated application potential in multiple monitoring tasks within the ICU; however, its clinical adoption requires further validation of data accuracy and the resolution of interference issues in complex environments [16].

3.2. The field of traditional Chinese medicine

Pulse diagnosis in Traditional Chinese Medicine (TCM) relies on the subjective perception of the practitioner's fingertips, leading to limitations such as a lack of objective indicators, low

standardisation, and poor reproducibility. Wearable sensor technology, by quantifying pulse electrical signals and integrating multimodal physiological information, provides crucial support for the objectification of pulse diagnosis, the quantification of acupuncture, and the digital integration of the Four Diagnostic Methods [17].

In pulse pattern detection, piezoresistive, piezoelectric, and magnetoresistive sensors detect changes in pulse pressure at the Cunkou (radial artery) pulse position, enabling the digital recording of the four key pulse elements: location, rate, form, and momentum. Flexible sensors based on PVDF piezoelectric films are widely used due to their wide frequency response, large dynamic range and resistance to bending; their multi-point systems can simultaneously measure signals from the cun, guan and chi positions and perform spectral analysis [18]; flexible capacitive sensors, through microstructural design of the sponge dielectric layer, achieve high-sensitivity detection in the low-pressure range, compensating for the inability of rigid sensors to capture faint pulse forces [19].

In studies on acupuncture efficacy, flexible e-skin sensor arrays combined with fiber-optic Bragg grating (FBG) sensors have reduced needle insertion depth errors to within ± 0.3 mm, thereby improving procedural standardization. E-skins integrating pressure, temperature, humidity and electrochemical sensors simultaneously acquire multi-source data, aiding in the objective quantification of the Eight Principles of Differentiation and the intelligent identification of the nine TCM constitutions, with a cross-validation accuracy rate of 86.4% [20].

Currently, wearable sensors are driving the transformation of TCM from an experience-driven to a data- and intelligence-driven approach; however, breakthroughs are still required in the quantitative modelling of abstract concepts such as 'shen' and 'qi', as well as the long-term stability of flexible materials during prolonged wear [18].

4. Challenges of wearable sensing technology in the medical field

Chief among these constraints is tolerance to interference. Throughout the operationally saturated ICU environment, electromagnetic noise—together with motion artefacts arising from patient movement—can shift the sensor baseline and distort the acquired waveform, a weakness made especially consequential when the clinical demand is accurate, continuous monitoring rather than intermittent spot-check assessment.

No less pressing is the still-unresolved problem of tightly integrated multi-parameter monitoring. In platforms such as electronic skin, the simultaneous acquisition of multimodal inputs, including pressure and temperature, is required; yet, because heterogeneous sensors seldom interface cleanly, signal crosstalk routinely introduces millisecond-scale delays in cross-parameter synchronization, thereby eroding the real-time responsiveness on which diagnosis and early warning depend. With prolonged wear, a different constraint becomes apparent: ageing at heterogeneous material interfaces—gradual in onset, though hardly trivial in effect—progressively compromises device stability over time. Of comparable concern are user-privacy configurations. Where wearable systems continuously collect and transmit sensitive physiological data, regulatory obligations begin to converge with exposure risks, and data breaches may result. Further complicating matters, most systems presently available on the market lack encryption mechanisms or localized privacy-computing architectures; at the same time, unified data formats and security standards have not yet been established by the relevant authorities, a gap that materially complicates compliant medical-data governance and cross-platform sharing.

5. Conclusion

This paper systematically reviews the primary applications of three wearable sensor technologies in the medical field and identifies a dual bottleneck in their current clinical adoption: insufficient accuracy and biocompatibility for long-term monitoring, making it difficult to capture subtle pathological features such as activity-suppressed delirium; and the absence of established data security and interoperability standards. In response to these challenges, researchers are actively exploring the integration of flexible electronics, low-power edge computing and explainable AI to develop low-burden, high-performance smart wearable solutions. The limitations of this paper lie in the absence of clinical validation and quantitative cost analysis. Looking forward, this study aims to provide a theoretical framework for building a closed-loop system of "multimodal sensing—edge computing analysis—clinical early warning", facilitating technological advances in critical neurological monitoring and the standardization of TCM diagnosis and treatment, and accelerating the clinical translation of intelligent healthcare systems.

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