

Post-print Reflections on Research in Wearable Human Body Sensor Networks

Authors: Han Shipeng, Olatunji, Mumini, Omisore, Wang Lei

Date: 2018-01-09T00:00:00+00:00

Abstract

The monitoring, acquisition, and processing of human health information constitute the most direct approach to assessing individual health status and serve as a crucial means for effectively preventing disease threats. Wearable human body sensor network technology enables tracking and intelligent services throughout the entire health process, holding significant importance for dynamic monitoring of human information and disease prevention. This article, based on an analysis of the prospects and current research status of wearable human body sensors, proposes strategic methodologies for addressing the core technologies of wearable human body sensor networks, and presents two key issues related to “human-machine-environment” in wearable medical devices based on human body sensor network technology.

Full Text

Wearable Body Sensor Networks

Topic: Biosensors & Organs-on-Chips

Olatunji Mumini Omisore

Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences

Monitoring, acquisition, and processing of human health information represent the most direct method for assessing personal health status and constitute an important means for effective disease prevention. Wearable body sensor network (WBSN) technology enables comprehensive health tracking and intelligent services throughout the entire health management process, holding significant importance for dynamic monitoring of human physiological information and disease prevention. This article analyzes the prospects and current research status of wearable human sensors, proposes strategic approaches to address the

core technologies of WBSN, and identifies two key issues related to “human-machine-environment” in wearable medical devices based on body sensor network technology.

Keywords: human health, intelligent services, wearable, body sensor networks

1. Introduction

Wearable body sensor networks (WBSN) represent an interdisciplinary technology involving wearables, micro-electro-mechanical systems (MEMS), and biomedical electronics. As one of the prominent development directions in mobile internet in recent years, WBSN offers numerous advantages including portability, wireless connectivity, network integration, and digital information management. Wearable medical devices based on body sensor networks can achieve comprehensive health tracking and services throughout the entire process, while employing medical intelligence technologies for intelligent processing of human health information, which holds significant importance for disease prevention. Smart healthcare, mobile medicine, remote medical services, home healthcare, and community public welfare medicine are all driving rapid development in the medical market. As a breakthrough technology for medical health detection equipment and human health information monitoring, wearable body sensor network technology possesses substantial research value and medical demand.

Body sensor networks and medical health service applications represent one of the development trends in wearable devices. WBSN primarily involves equipment and technologies for physiological parameter detection, exercise statistics, and health status improvement. According to a recent report by Juniper Research, approximately 19 million wearable devices were in use globally in 2014, with usage expected to triple by 2018. Reports from the Consumer Electronics Association (CEA) and the Institute of Electrical and Electronics Engineers (IEEE) project that global wearable device sales will reach 280 billion RMB in 2022, driven primarily by wearable medical health service products. Based on calculations by the Global System for Mobile Communications (GSM) for the mobile healthcare industry, China’s wearable device market sales are expected to reach 60 billion RMB in 2022.

Wearable body sensor network technology for medical health services exhibits three key characteristics. First, competition in the basic medical electronic products market is intensifying. As emerging economies such as China, India, Russia, Brazil, and Mexico take off, medical technology advances have shifted the primary functions of medical electronic devices from diagnosis and treatment to healthcare, gradually making them accessible at the grassroots level. These emerging markets demand more practical new medical device products—from common electronic pedometers, blood pressure monitors, and glucose meters to massage devices, pain therapy devices, and relatively higher-priced home oxygen

concentrators. As international medical electronics giants continue to tighten their grip on high-end markets while extending into relatively low-end basic markets, and as China's medical electronics R&D capabilities improve, market competition between domestic and foreign enterprises in these areas will become more intense.

Second, the domestic production process for both high-end and low-end medical equipment continues to accelerate. In recent years, China has launched selection programs for excellent domestic equipment products, with an increasing number of hospitals beginning to use domestically produced medical equipment, which has promoted the development of China's medical electronics industry. A group of outstanding domestic medical electronics enterprises, including Mindray, Shanghai United Imaging, Wandong Medical, Neusoft Medical, Shenzhen Edan, and Shenzhen Anke, are embracing development opportunities. With support from relevant government policies and funding, these companies will certainly industrialize a batch of advanced medical equipment technologies in the coming years.

Third, mobile healthcare is becoming a new medical model for the future. Smart healthcare, mobile medicine, remote medical services, home healthcare, and community public welfare medicine represent major trends in future medical industry development. They will change traditional healthcare approaches while saving medical resources and effectively addressing issues such as China's imperfect medical management system, high medical costs, and limited coverage. The use of medical electronic products is no longer limited to traditional professional medical institutions; demand for applications in home care is expanding rapidly. This shift in application scenarios places higher demands on the miniaturization and portability of medical electronic products. As society's informatization level continues to improve, medical electronics are developing toward networking, remote connectivity, and wireless capabilities. In the future, mobile healthcare will gradually permeate citizens' daily lives, enabling network interconnection from registration to treatment, which can significantly reduce time costs for patients and hospitals, improve diagnosis and treatment efficiency, and ensure optimal integration and synergy of medical service resources.

2. Current Research Hotspots

In recent years, medical health services have been developing vigorously, particularly in the challenging research field of flexible wearable medical device innovation centered on wearable body sensor network technology. This involves research on "core components—flexible integration—medical intelligence—innovative applications." Current research hotspots mainly include: (1) In biosensing, developing high-performance micro/nano sensors based on semiconductor nanomaterials, wearable active sensors, ultra-thin carbon nanomaterial films, electronic skin with biomimetic functions, and electronic textiles as core devices; (2) In biochemical sensors, developing epidermal biochemical sensors based on high-crystallinity, high-aspect-ratio nanocellulose biomembrane substrates, and

using polyimide and rigid glass as substrate plates with gold and zinc oxide as sensing electrodes to design flexible wearable sweat sensors for monitoring alcohol concentration; (3) In flexible integration, developing highly reliable hardware systems based on biomimetic micro/nano processing, low-power integrated circuit (IC) design, and high-density packaging technology; (4) In human data communication, researching principles of near-body information interaction and information security theory to achieve energy-efficient near-body communication; (5) In health status identification, researching machine learning methods suitable for wearable life and health datasets and their integration with biological information big data; (6) In system power supply, researching nanogenerators, flexible photovoltaic materials, and energy harvesting methods based on temperature gradients to develop prototype devices; (7) In medical health applications, exploring the integration of wearable medical devices with fashion and innovative design, establishing industry and group standards and business models, and new applications such as flexible wearable medical rehabilitation robots.

3. Research Progress

3.1 Physiological and Biochemical Detection

Ryu et al. [?] prepared highly oriented carbon nanotube fiber elastic strain sensors through dry spinning. Yugandhar et al. [?] established simulation models for piezoelectric micro-electro-mechanical systems (MEMS). Yamada et al. [?] prepared aligned single-walled carbon nanotube films that form island-bridge-gap structures when stretched, achieving deformations up to 280%. Tee et al. and Lipomi [?, ?] utilized piezoresistive sensors with conical microstructures to prepare electronic skin that can transmit tactile information to the brain and capacitive transparent stretchable carbon nanotube sensors on elastic substrates that respond to both pressure and tension. Chae et al. [?] prepared highly stretchable transparent field-effect transistors combining graphene/single-walled carbon nanotube electrodes with wrinkled inorganic dielectric layers and carbon nanotube mesh channels. Gong et al. [?] developed practical high-sensitivity piezoresistive sensors by constructing gold nanowire thin layers and electrode arrays on elastic substrates. Liao et al. [?] developed flexible wearable glucose sensors. Bae et al. [?] developed double-layer PDMS composite structures to enhance adsorption force.

Our research team, supported by the Chinese Academy of Sciences Key Deployment Project, focuses on common and key technologies for next-generation wearable medical health services. We utilize enzyme electrodes, nanotechnology, and flexible MEMS to build wearable sweat sensors for detecting multiple health status identification indicators in sweat, including glucose, lactate, uric acid, amino acids, and various ions (such as sodium, potassium, calcium, and chloride ions), establishing connections with human health-related indicators. The sweat sensors employ directed evolution of glucose, lactate, and uric acid oxidases and nanostructure assembly design to improve the sensitivity and sta-

bility of electrochemical detection of glucose, lactate, and uric acid. We develop genetic codon extension methods, design and screen redox enzymes with specificity for specific biochemical molecules, and achieve efficient conversion of biochemical signals to electrical signals by site-specifically coupling redox enzymes to patterned high-density gold and graphite electrodes, thereby improving the sensitivity and stability of bioelectrochemical sensing systems. The integration of glucose, lactate, amino acid oxidases, and various ion detection methods on wearable devices establishes the process flow for arrayed microneedle enzyme electrodes, enabling demonstrations of cardiovascular and diabetes health management. Flexible electrodes developed by our team are shown in Figure 1 [Figure 1: see original paper].

3.2 Medical Device Integration and Health Status Identification

Kim et al. [?] analyzed the design of application-specific integrated circuits for wearable low-power ECG monitoring. Kmon and Gryboś [?] studied low-power, low-noise multichannel neural amplifiers based on complementary metal-oxide-semiconductor (CMOS) processes. Muller et al. [?] developed a physiological signal acquisition IC powered by 0.5 V low voltage. Lee et al. [?] designed a low corner frequency filter structure based on Gm-C architecture, with further improvements in ultra-low corner frequency and power supply noise rejection. Qian et al. [?] analyzed micropower low-noise neural signal detection and recording front-end circuits for epilepsy treatment. Chang et al. [?] focused on the design of low-power, high-performance digital filters. Piwek et al. [?] studied how wearable clothing can provide personalized health data for patients to assist in self-diagnosis and intervention. Poon et al. [?] analyzed the application prospects of wearable sensor technologies in the context of big data applications. McDonald et al. [?] systematically analyzed the correlation between data and disease, health, or behavior. Chaussabel and Pulendran [?] discussed relevant cases of applying wearable data acquisition information to clinical decision-making. Rumsfeld et al. [?] applied relevant wearable datasets and intelligent analysis methods to clinical analysis of specific cardiovascular diseases. Eisenstein [?] combined genetic biological data with health monitoring data for application in community population medical care and rehabilitation demonstrations.

4. Existing Problems and Constraints

While the aforementioned research has significantly advanced the level of individual technologies for wearable body sensor networks, a comprehensive review of related scientific work reveals several shortcomings. First, in biosensing and sensor development, there has been considerable focus on material innovation, types of available vital sign parameters, and research on new parameters. However, research on interface circuits for flexible sensors and ergonomic optimization designs that conform to human physiology is relatively limited, resulting in degraded performance of prototype systems during dynamic continuous monitoring and preventing many sensors from being practically useful. Second, the

above studies have devoted limited attention to the flexible integration of all modules including sensors, IC chips, and electronic circuits. Consequently, although the sensors themselves are highly flexible, the overall system exhibits poor flexibility or is virtually non-flexible, making the term “flexible wearable medical device” centered on body sensor networks a misnomer. This also leads to increased motion artifacts during continuous monitoring and reduced wearing comfort. Third, there are many exploratory studies on principle verification of flexible systems, but relatively few application studies integrated with specific medical health needs.

These three problems severely constrain the promotion of flexible wearable medical devices centered on body sensor networks as technical means for future grassroots medical care and mobile medicine aimed at the general public. How to overcome and solve these problems represents a challenging and important frontier issue in this field.

5. Research Strategy Recommendations

Body sensor network technology is an important technical foundation for wearable medical health devices in health management, portable health monitoring, remote medical care, and other health medical equipment or solutions. Future technological breakthroughs should focus on key technologies, core devices, and solutions for body sensor networks, with research expanding in the following four areas to provide corresponding technical accumulation for wearable medical health applications.

5.1 Graphical Multimodal Flexible Electrode Preparation Technology

Based on ergonomic principles, we should optimize electrode structure and shape. Developing sensor interconnection solutions that maintain good electrical performance and signal acquisition capabilities under different human body states will provide safe, comfortable, stable, and reliable surface interfaces for the acquisition, processing, and analysis of wearable sensor signals.

5.1.1 High-Precision Multimodal Analog Front-End Biosensing IC Chip Design

Graphical multimodal MEMS sensors can measure various parameters on the body surface including electrophysiological signals, force (tactile) sensation, pH values, and lactate [?], imposing higher requirements on interface circuit precision. We can research design techniques for low-noise, low-offset operational amplifiers based on dynamic common-mode feedback and high common-mode rejection ratio, gain-adjustable instrumentation amplifiers based on current-mode technology, as well as high-precision, low-power voltage/current reference sources using all-CMOS structure and power supply voltage and temperature compensation using all-MOSFET structure. These efforts will develop higher-precision, lower-power analog front-end chips for flexible wearable medical devices, as shown in Figure 2 [Figure 2: see original paper].

5.1.2 High-Precision Parameter Extraction and Fully Flexible Microsystem Integration First, considering the actual physical dimensions and spatial layout of self-developed ICs and other functional components, we should research computer-aided design technology for high-flexibility substrates and high-precision wiring. We should study optimization layout and routing methods based on kinematic analysis of flexible substrates and bases. Simultaneously, to reduce interference from digital circuit noise and thermal noise on analog circuits, we should research multi-level isolation structures for layout and routing that minimize noise propagation.

Second, we should explore matching designs for flexible substrates and bases, integrating MEMS technology with electronic technology to achieve fully flexible microsystem integration. Finally, addressing the non-stationary and nonlinear characteristics of physiological parameters, we should employ nonlinear filtering methods with signal quality evaluation, combined with morphological analysis and time-series analysis methods for artifact detection to eliminate severely contaminated unusable signal segments, achieving accurate and reliable extraction of multimodal body surface signals.

5.2 Human Body Communication Technology

5.2.1 Construction of Wearable Communication Systems Based on Human Body Communication Principles Human body communication uses the human body as the communication medium, offering advantages of low power consumption, high security, and minimal impact of body state on the channel. Human body communication principles can be employed to construct wearable communication systems, which differs significantly from conventional WBSN construction methods using Bluetooth, Wi-Fi, etc. [?]. Utilizing the capacitive coupling phenomenon occurring in the human body itself at specific frequencies for high-efficiency and high-security near-field wireless data transmission is of great significance for improving transmission performance of wearable devices and perfecting WBSN theoretical systems.

5.2.2 Acquisition of Human Information Based on Human Body Biometric Characteristics Human biometric information sensing technology based on human body communication involves placing human body communication transceivers at different experimental sites on multiple subjects. The signal generation end produces waveforms with different frequencies, amplitudes, and modulation methods, while the receiving end records corresponding attenuation values. By establishing numerical simulation models, we can study the impact of dielectric changes on signals. Through a combination of experiments and simulations, we can research human biometric information sensing technology based on human body communication to obtain the human body's "biological password." Figure 3 [Figure 3: see original paper] shows the hierarchical security management architecture for human body communication networks.

5.3 Wearable Medical Intelligence Technology

5.3.1 Data Fusion Processing for Medical Intelligence-Based Wearable Medical Devices Based on reliable acquisition of multiple data types and accumulation of massive data, we should develop fusion of flexible wearable medical device data using machine learning. By analyzing multiple complex data sources and scales, we can avoid noise and errors in signals superimposing and reducing prediction accuracy, thereby achieving accurate personalized prediction.

Research should focus on feature engineering and pattern matching for multi-data-stream information, information fusion, consistency and anomaly detection, unsupervised learning methods for massive non-standard datasets, and health monitoring applications and evaluation systems based on flexible wearable datasets. We should analyze the high-dimensional and redundant characteristics of data in wearable datasets, research dimensionality reduction and data embedding-based machine learning methods, and consider the characteristics of electrophysiological/physical/chemical multimodal sensing data in wearable dataset applications and their adaptability in health monitoring applications. We should develop adaptive data embedding dimensionality reduction machine learning computational frameworks and explore data analysis methods and applications for high-dimensional wearable datasets.

6. Thoughts on Key Issues for Future Research

Wearable medical devices based on body sensor network technology must consider the relationship among “human-machine-environment.”

First, how to fully consider the “change” and “motion” of environment and human body to optimize the reliability of core modules is a key scientific issue. Wearable devices operate in variable environments, and the human body itself is basically in motion. Ensuring stable overall performance and reliable core modules of flexible devices is crucial. Moreover, if we can fully utilize this “change” and “motion,” establish theoretical models, and research adaptive reliability improvement strategies, we can lay a theoretical foundation for practical applications of flexible wearable medical devices.

Second, how to improve signal acquisition accuracy of flexible wearable medical devices based on deep understanding of human health information is another key scientific issue. Frequent contact between flexible devices and the human body is inevitable, and electrode sections are particularly affected by the structure and mechanical properties of human wearing sites, with severe signal crosstalk [?]. How to combine human physiology and ergonomics to increase device adhesiveness and improve signal extraction “efficiency” is essential. Meanwhile, the human body is an integrated whole, and how to compensate for insufficient detection accuracy of individual sensors through effective combinations of multi-parameter extraction from the body surface also has important theoretical significance and practical application value.

References

1. Park Y T, Han D. Current status of electronic medical record systems in hospitals and clinics in Korea. *Healthcare Informatics Research*, 2017, 23(3): 189.
2. Ryu S, Lee P, Chou J B, et al. Extremely elastic wearable carbon nanotube fiber strain sensor for monitoring of human motion. *ACS Nano*, 2015, 9(6): 5929.
3. Yugandhar P, Gupta A, Chauhan V S. Design and simulation of piezoelectric MEMS sensor. *Materials Today Proceedings*, 2015, 2(4-5): 1595-1602.
4. Yamada T, Hayamizu Y, Yamamoto Y, et al. A stretchable carbon nanotube strain sensor for human-motion detection. *Nature Nanotechnology*, 2011, 6(5): 296-301.
5. Tee B C, Chortos A, Berndt A, et al. A skin-inspired organic digital mechanoreceptor. *Science*, 2015, 350(6258): 313-316.
6. Lipomi D J, Vosgueritchian M, Tee B C, et al. Skin-like pressure and strain sensors based on transparent elastic films of carbon nanotubes. *Nature Nanotechnology*, 2011, 6(12): 788-792.
7. Chae S H, Yu W J, Bae J J, et al. Transferred wrinkled Al₂O₃ for highly stretchable and transparent graphene-carbon nanotube transistors. *Nature Materials*, 2013, 12(5): 403-409.
8. Gong S, Schwalb W, Wang Y, et al. A wearable and highly sensitive pressure sensor with ultrathin gold nanowires. *Nature Communications*, 2014, 5(2): 3132.
9. Liao X, Liao Q, Zhang Z, et al. Flexible wearable glucose sensors. *Advanced Materials*, 2015, 27(4): 676-681.
10. Bae J, Park Y J, Lee M, et al. Linearly and highly pressure-sensitive electronic skin based on a bioinspired hierarchical structural array. *Advanced Healthcare Materials*, 2013, 2(1): 109.
11. Kim H, Yazicioglu R F, Kim S, et al. A configurable and low-power mixed signal SoC for portable ECG monitoring applications. *Vlsi Circuits*, 2011, 8(2): 142-143.
12. Kmon P, Gryboś P. Energy efficient low-noise multichannel neural amplifier in submicron CMOS process. *IEEE Transactions on Circuits & Systems I Regular Papers*, 2013, 60(7): 1764-1775.
13. Muller R, Gambini S, Rabaey J M. A 0.013 mm² 5 μ W DC-coupled neural signal acquisition IC with 0.5 V supply. *IEEE Journal of Solid-State Circuits*, 2012, 47(1): 232-243.

14. Lee S, Song C, Cho N, et al. A 0.8V low-noise dynamic amplifier for ECG data acquisition. *Biomedical Circuits and Systems Conference*, 2013, 12(4): 318-321.
15. Qian C, Parramon J, Sanchez-Sinencio E. A micropower low-noise neural recording front-end circuit for epileptic seizure detection. *IEEE Journal of Solid-State Circuits*, 2011, 46(6): 1392-1405.
16. Chang C H, Molahosseini A S, Zarandi A A E, et al. Residue number systems: A new paradigm to datapath optimization for low-power and high-performance digital signal processing applications. *IEEE Circuits & Systems Magazine*, 2015, 15(4): 26-44.
17. Piwek L, Ellis D A, Andrews S, et al. The rise of consumer health wearables: Promises and barriers. *PLoS Medicine*, 2016, 13(2): e1001953.
18. Poon C, Lo B, Yuce M, et al. Body sensor networks: in the era of big data and beyond. *IEEE Reviews in Biomedical Engineering*, 2015, 8: 4-16.
19. McDonald D, Glusman G, Price N D. Personalized nutrition through big data. *Nature Biotechnology*, 2016, 34(2): 152-154.
20. Chaussabel D, Pulendran B. A vision for data-enabled medicine. *Nature Immunology*, 2015, 16(5): 435-437.
21. Rumsfeld J S, Joynt K E, Maddox T M. Big data analytics to improve cardiovascular care: promise and challenges. *Nature Reviews Cardiology*, 2016, 13(6): 350.
22. Peng H, Dang W, Cao J, et al. Topological insulator nanostructures for near-infrared transparent flexible electrodes. *Nature Chemistry*, 2012, 4(4): 281-286.
23. Jandhyala S, Walper S A, Cargill A A, et al. Integration of biochemical sensors into wearable biomaterial platforms. *SPIE Commercial + Scientific Sensing and Imaging*, 2016, 9863: 1-6.
24. Selvam A P, Muthukumar S, Kamakoti V, et al. A wearable biochemical sensor for monitoring alcohol consumption lifestyle through Ethyl glucuronide (EtG) detection in human sweat. *Scientific Reports*, 2016, 6: 1-9.
25. Zheng Y L, Ding X R, Poon C C Y, et al. Unobtrusive sensing and wearable devices for health informatics. *IEEE Transactions on Biomedical Engineering*, 2014, 61(5): 1538-1554.
26. Raj P, Raman A, Nagaraj D, et al. *High-Performance Big-Data Analytics*. Switzerland: Springer International Publishing, 2015: 391-424.
27. Laschi C, Mazzolai B, Cianchetti M. Soft robotics: Technologies and systems pushing the boundaries of robot abilities. *Science Robotics*, 2016, 1(1): 1-11.

28. Qiu M. Design and Implementation of a Wearable Remote Health Monitoring System Based on Body Sensor Networks. Hangzhou: Zhejiang University, 2013.
29. Song Y, Lin N, Jiang H, et al. Application research of nanoplatinum black modified microelectrode arrays in neuroelectrophysiological detection. Journal of Southeast University (Medical Science Edition), 2011, 30(1): 29-32.
30. Xu P. Analysis of Mechanical Interaction and Dynamic Noise Between Textile Structured Electrodes and Skin for Surface ECG Monitoring. Shanghai: Donghua University, 2012.
31. Eisenstein M. Wearable monitors get more out of sweat. Nature, 2016, 527(7576): 2-4.
32. Han S, Omisore O M, Wang L. Wearable Body Sensor Networks. ChinaXiv, 2017.
33. Mann S. Wearable computing: a first step toward personal imaging. Computer, 1997, 30(2): 25-32.
34. Gao Y, Zhang Z, Wang L, et al. Flexible electronics: from wearable sensors to implantable devices. Advanced Materials, 2017, 29(19): 1700001.

Han Shipeng is a research assistant at the Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences. His research focuses on flexible sensors and medical robots. He has participated in several projects supported by the National Natural Science Foundation of China, the Chinese Academy of Sciences Key Deployment Project, and other research programs. He has authored or co-authored 4 research papers. E-mail: sp.han@siat.ac.cn

Wang Lei is Deputy Director of the Institutes of Biomedical and Health Engineering, Director of the Center for Medical Robotics and Minimally Invasive Surgical Devices, and a member of the Discipline Inspection Commission at the Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences. He has received numerous honors including the CAS “Hundred Talents Program,” the CAS Wang Kuancheng Leading Talent Program, Guangdong Provincial Leading Talent in Scientific and Technological Innovation, and Shenzhen Municipal Special Allowance. His research focuses on body sensor network (BSN) technology, wearable technology, and medical robotics. He has presided over and participated in major scientific research projects such as the Key National Natural Science Foundation of China, Major National Science and Technology Projects, and the National “863” Program. He has authored or co-authored over 200 scientific papers, including more than 150 indexed by SCI/EI/ISTP, and 10 monographs or book chapters. E-mail: wang.lei@siat.ac.cn

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.