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The 2026 global roadmap for textile-integrated wearable technologies in health

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The 2026 Global Roadmap for Textile-Integrated Wearable Technologies in Health

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Abstract

Wearable and textile-based technologies are transforming health monitoring by enabling continuous, non-invasive, and context-aware assessment of physiological and biochemical signals in daily life. Advances in flexible electronics, conductive fibers, smart materials, and artificial intelligence have driven a shift from rigid, device-centric wearables toward textile-integrated and garment-based systems capable of distributed sensing, actuation, energy harvesting, storage, and communication. This roadmap provides a textile-centric overview of the current state and future trajectory of wearable technologies for healthcare, with electronic textiles positioned as a distinct and strategically important class within the broader wearable ecosystem. We synthesize progress across textile-integrated sensing, therapeutic and protective garments, textile body-area networks, energy-autonomous systems, and embedded computing, while critically examining challenges related to signal reliability, manufacturability, scalability, data governance, regulation, and equity. Market trends and adoption patterns are discussed to contextualize translational pathways from laboratory prototypes to clinically deployable and scalable textile systems. By identifying key scientific, technological, and societal priorities, this roadmap outlines actionable directions to accelerate the integration of textile-based wearable technologies into preventive, personalized, and decentralized healthcare.

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Section 1: Introduction

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Status

Wearable and textile-based technologies have undergone a profound transformation over the past two decades, evolving from discrete, device-centric sensors into integrated, garment-based systems that support continuous health monitoring, diagnostics, and rehabilitation. By bridging engineering, materials science, and medicine, these technologies enable real-time, non-invasive, and context-aware assessment of physiological signals in everyday environments. Early developments were largely limited to fitness trackers and basic biometric devices; however, recent advances in flexible electronics, conductive fibers, and smart materials have driven the emergence of textile-integrated wearables, including smart garments capable of measuring electrocardiography (ECG), electromyography (EMG), respiration, motion, and sweat-based biomarkers with high wearability and long-term user compliance [1,2].

Electronic textiles (e-textiles) constitute a specialized subset of wearable technologies in which sensing, actuation, energy, and communication elements are structurally integrated into textile substrates such as fibers, yarns, or fabrics. Unlike conventional wearable devices that are attached to the body as discrete components, e-textiles enable seamless, body-conformal integration while preserving flexibility, breathability, and user comfort. Accordingly, this roadmap places particular emphasis on e-textile systems, as they offer unique advantages for continuous, unobtrusive, and long-term physiological assessment in real-world and clinical settings.

The significance of wearable and textile-based health monitoring has been further underscored by the growing demand for decentralized and preventive healthcare models. The COVID-19 pandemic further highlighted the need for contactless and continuous monitoring systems—an area where wearables and smart textiles are uniquely positioned. Advances in sensor miniaturization, flexible electronics, energy harvesting, and machine learning have opened doors for applications across cardiovascular, neurological, metabolic, and mental health domains [3].

Yet, despite promising developments, full integration into clinical workflows remains limited. Challenges such as signal reliability, user comfort, data security, and clinical validation persist. Nevertheless, the field continues to thrive, driven by interdisciplinary collaboration, growing investment, and societal demand. Continued innovation promises to shift healthcare from reactive treatment to proactive prevention and real-time personalized care [4].

From a temporal perspective, as shown in **Figure 1**, the evolution of wearable and textile-based health technologies can be viewed through successive milestones. Early developments (2000–2010) focused on rigid, device-centric wearables primarily targeting activity and fitness monitoring. The subsequent decade (2010–2020) saw the emergence of flexible electronics, conductive yarns, and

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early electronic textile prototypes capable of continuous physiological sensing. Since 2020, the field has rapidly advanced toward multifunctional smart garments integrating sensing, wireless communication, energy harvesting, and embedded artificial intelligence. Looking ahead, the next phase (2025–2035) is expected to emphasize large-scale manufacturing, regulatory approval, clinical validation, and integration into digital health ecosystems, marking the transition from laboratory prototypes toward clinically deployed e-textile systems.



Figure 1. Timeline illustrating the evolution and projected roadmap of wearable and electronic textile technologies in health. Early developments (2000–2010) focused on rigid, device-centric wearables for fitness and activity tracking. The subsequent period (2010–2020) marked the emergence of flexible electronics, conductive yarns, and early electronic textile (e-textile) prototypes enabling continuous physiological sensing. Recent advances (2020–2025) emphasize multifunctional smart garments integrating artificial intelligence, wireless connectivity, and energy harvesting. Future developments (2025–2035) are expected to prioritize scalable manufacturing, clinical validation, regulatory approval, and integration into digital health ecosystems.

Current and Future Challenges

One of the main challenges in wearable and textile health technologies is ensuring signal quality across diverse users and dynamic conditions. Factors such as garment fit, sensor displacement, motion artifacts, and skin properties can degrade data integrity. Designing universal and adaptive sensing systems that account for these variables is critical for real-world deployment [1].

Manufacturability and scalability pose another significant challenge. While proof-of-concept prototypes demonstrate feasibility, producing cost-effective, durable, and washable smart garments at scale remains unresolved. Additionally, integrating complex electronics with fabrics while maintaining breathability, flexibility, and user comfort requires further breakthroughs in materials science and design [2].

From a data perspective, standardization of sensor outputs, cross-platform interoperability, and privacy-preserving data analytics are lacking. Furthermore, regulatory and ethical concerns—particularly those involving AI-driven diagnostics and continuous biometric tracking—are underdeveloped, leading to barriers in clinical adoption and commercialization [5].

Finally, ensuring equitable access to wearable health technologies is a growing concern. Solutions must be affordable, accessible, and inclusive, addressing the needs of diverse populations, including the elderly, rural communities, and individuals with disabilities [3].

Advances in Science and Technology to Meet Challenges

Recent advances in conductive and stretchable textiles have shown promise in addressing the mechanical mismatch between human skin and conventional sensors. Developments in screen printing, embroidery with conductive threads, and coating techniques allow the fabrication of multifunctional textiles with embedded sensors for ECG, EMG, temperature, hydration, and movement [1,2].

Emerging AI algorithms—including lightweight neural networks and federated learning frameworks—enable on-device data analysis with reduced latency and privacy risks. These models can detect anomalies, personalize feedback, and adapt to individual baselines. Additionally, cloud-AI hybrid systems are enabling longitudinal health tracking and early detection of deterioration patterns [4,6].

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In terms of energy autonomy, breakthroughs in triboelectric and thermoelectric generators integrated into garments are powering low-energy electronics without the need for frequent recharging. Combined with energy-efficient Bluetooth and Near Field Communication (NFC) protocols, this supports seamless, long-term data transmission and storage [4].

Cross-disciplinary platforms are also promoting translational research and rapid prototyping. Collaborative projects between clinicians, engineers, and designers are leading to clinically validated systems with improved usability and integration into electronic health record (EHR) systems [5,6]. These collective advances hold promise to bridge the current gap between experimental prototypes and real-world health solutions.

Concluding Remarks

The field of wearable and textile innovations is entering a pivotal phase, where interdisciplinary collaboration and technological breakthroughs are beginning to translate into practical health applications. While challenges remain in signal reliability, manufacturing, and regulatory frameworks, the trajectory is promising. By addressing these gaps, wearable and textile systems have the potential to transform healthcare delivery, making it more continuous, personalized, and preventive [1,4]. Table 1 provides a structured overview of the roadmap, mapping each section to its primary thematic focus. This organization is intended to guide readers through the manuscript, clarify the scope of each section, and highlight how materials, sensing modalities, system intelligence, healthcare applications, and translational considerations are integrated across the roadmap.

Table 1. Overview of the roadmap structure and thematic coverage.

Roadmap Theme	Key Sections	Focus
Foundations and Scope	Sections 1–2	Scope definition, trends, quantitative context
Materials and Textile Integration	Sections 3–5	Fibers, fabrication, durability, material–system translation
Sensing Modalities	Sections 6–7	Physiological, biochemical, and multimodal sensing
Systems and Intelligence	Sections 7–8	Edge AI, body-area networks, embedded computing
Healthcare Paradigms and Applications	Sections 9–11	Healthcare 6.0, clinical use cases, interfaces
Translation, Regulation, and Ethics	Sections 12–14	Regulatory pathways, challenges, roadmap priorities

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References

Accepted Manuscript

[1] Y. Peng et al., "Multimodal health monitoring via a hierarchical and ultrastretchable all-in-one electronic textile," Nano Energy, vol. 110, p. 108374, Mar. 2023, doi: 10.1016/j.nanoen.2023.108374.

[2] M. Azeem, M. Shahid, I. Masin, and M. Petru, "Design and development of textile-based wearable sensors for real-time biomedical monitoring: A review," J. Text. Inst., vol. 116, no. 1, pp. 80–95, Feb. 2024, doi: 10.1080/00405000.2024.2318500.

[3] C. Wang *et al.*, "E-textiles in healthcare: A systematic literature review of wearable technologies for monitoring and enhancing human health," *Neural Comput. Appl.*, vol. 37, no. 4, pp. 2089–2111, 2025,

[4] A. Libanori, G. Chen, X. Zhao, Y. Zhou, and J. Chen, "Smart textiles for personalized healthcare," Nat. Electron., vol. 5, no. 3, pp. 142–156, Mar. 2022, doi: 10.1038/s41928-022-00723-z.

[5] S. M. A. Iqbal, I. Mahgoub, E. Du, M. A. Leavitt, and W. Asghar, "Advances in healthcare wearable devices," npj Flexible Electron., vol. 5, no. 1, Apr. 2021, doi: 10.1038/s41528-021-00107-x.

[6] Y. Fei et al., "Privacy-aware edge computation offloading with federated learning in healthcare consumer electronics systems," IEEE Trans. Consum. Electron., vol. 71, no. 2, pp. 4628–4638, Jan. 2025, doi: 10.1109/TCE.2025.3535753.

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Section 2: Current State of Wearable Technology and Smart Textiles

2.1 - Overview of existing technologies

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Status

The field of wearables innovations has undergone significant evolution. Initially focused on basic wearable devices like fitness trackers and simple smartwatches, the industry has expanded to include sophisticated systems capable of comprehensive health monitoring and personal data tracking [1], [2]. These technologies have increasingly blurred the lines between fashion, technology, and function, embedding advanced technical capabilities into everyday clothing and accessories.

Textiles have been an essential part of human civilization for millennia. Today, they are produced from a variety of materials, both natural—like silk, wool, and cotton—and synthetic—including peptides, polyamides, and polyesters. These materials grant textiles biocompatible, biodegradable, and bioabsorbable qualities, enhancing their utility as platforms for on-body healthcare that offer increased comfort[3]. The integration of biomedical electronics with textiles has led to the development of electronic textiles (e-textiles). These e-textiles combine point-of-care diagnostic and therapeutic functions while maintaining breathability, comfort, durability, environmental stability, and mechanical robustness.

Textile-integrated sensing systems for health monitoring

Textile-integrated sensing systems represent the most mature and widely deployed class of e-textiles. These devices embed various sensors directly into yarns, fabrics, or garments to continuously monitor physiological signals during daily activities [4], [5], [6]. Depending on the targeted biomarkers, textile sensors can be broadly divided into biophysical and biochemical platforms. Textile sensors, seamlessly integrated with the human body, enable the continuous long-term monitoring of both biophysical and biochemical signals. This capability is pivotal in the field of biomonitoring, where e-textiles equipped with a diverse array of sensors—including biomechanical, optical, biopotential, temperature, and biochemical—are utilized to continuously track vital signs. **Figure 2** illustrates a representative integrated smart textile architecture, in which textile-embedded biophysical and biochemical sensors are co-designed with energy harvesting, storage, communication, and display modules to enable continuous, self-powered health monitoring. These physiological signals serve as crucial health indicators, aiding in the early diagnosis of diseases, monitoring chronic conditions, and evaluating real-time body states. Physical sensors in textiles utilize technologies such as triboelectricity, piezoelectricity, and magnetoelectricity [7], [8], [9]. These sensors are highly compliant with human anatomy, allowing for the persistent monitoring of clinical parameters that are critical for disease surveillance and diagnosis. For example, pulse wave analysis can help diagnose cardiovascular diseases, respiratory rate monitoring is vital for detecting

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conditions like COVID-19, body temperature measurements can indicate fever, oxygen saturation levels can warn of sudden cardiac events, and biopotentials are used for diagnosing cerebrovascular diseases. Beyond biophysical data, a comprehensive assessment of personalized health also requires the analysis of biochemical signals. Textile biochemical sensors, which are biocompatible and conform comfortably to the skin or can be implanted in the body, facilitate this process. For instance, monitoring sweat glucose levels can assist in diabetes management, sweat pH can indicate dehydration, urea levels can signal kidney failure, and acetone concentrations in breath can diagnose acute kidney injuries. These advancements in textile sensors not only enhance the ability to monitor health conditions in real-time but also contribute significantly to preventive healthcare measures, making early diagnosis and timely intervention possible. This integration of biophysical and biochemical monitoring tools into everyday wearables represents a major leap forward in medical technology, combining convenience with critical care capabilities.

Textile-based therapeutic and protective devices

Textile-based therapeutic and protective devices extend the role of e-textiles from passive monitoring to active intervention. By integrating actuators and functional coatings into fabrics, these systems can deliver mechanical assistance, thermal regulation, electrical stimulation, or biochemical agents directly at the body–textile interface. Beyond their capabilities for real-time monitoring and diagnostics, e-textiles also enhance healthcare by providing controlled, on-demand therapy and protection [10]. These advanced textile therapeutic systems can significantly reduce health risks and long-term medical expenses by aiding in the early diagnosis of diseases. To deliver sustained and precise therapy, these systems employ a combination of physical and biochemical methods, meeting the growing demands for convenience and accessibility in medical treatments. Textile-based electronics have incorporated physical therapy capabilities to address urgent needs in various clinical settings. Devices such as exosuits, soft robots, heart pacemakers, and wearable heaters are gaining prominence due to their practical applications in patient care. This integration of assistive therapy, phototherapy, electrotherapy, thermotherapy, and protective measures into textiles forms a comprehensive discussion on the state-of-the-art in implantable and wearable smart textiles for physical therapy and protection. Given their prolonged direct contact with the human body, smart textiles are uniquely positioned to offer personalized healthcare solutions anywhere and at any time. Biochemical therapy and protection within these textiles involve the controlled release of functional compounds or the execution of chemical reactions. This capability enriches everyday clothing with precise medical treatments, sterilization, disinfection, and personal protection, effectively transforming garments into active participants in health management. Moreover, e-textiles enhance user safety by offering protective functions such as shielding from electromagnetic waves, filtering harmful air particles, and degrading toxic substances. These features ensure that smart textiles not only cater to individual health needs through personalized 24/7 treatment protocols but also provide a fundamental barrier against adverse environmental conditions. This dual role of therapeutic and protective functionalities underscores the transformative potential of smart textiles in shaping the future of personalized healthcare and environmental safety.

Textile body-area networks and closed-loop operation

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While individual e-textile devices can monitor or treat specific conditions, a truly personalized healthcare platform requires system-level integration and closed-loop control. For a comprehensive and integrated approach to personalized healthcare, it is envisioned that wearable devices will communicate with each other, forming a sophisticated closed-loop system. This vision involves the creation of a textile body area network (TBAN)—a network of textile-based electronics that wraps seamlessly around the human body, maintaining consistent wireless connectivity with existing mobile devices [11]. This network is crucial for continuously collecting multiple physiological signals, enabling timely health data transmission, processing, and feedback for immediate therapeutic intervention. In the initial stage of this two-tiered system, devices-to-devices (D2D) communication within the TBAN utilizes both wired and wireless methods to ensure robust and efficient interactions. Wireless technologies, especially, play a vital role in transferring power from energy nodes, such as energy harvesters or batteries, to the monitoring and therapeutic nodes. Additionally, these technologies establish reliable information connections essential for seamless network operation. Wireless methods including near-field inductive, far-field radiative, and ultrasonic technologies are widely employed in practical applications due to their effectiveness in maintaining communication without physical connections. The subsequent stage involves the transmission of aggregated data from the TBAN to a gateway node or remote servers, such as smartphones, central control units integrated into clothing, or healthcare providers at hospitals and medical centers. This stage is responsible for comprehensive data processing, D2D communication, and interactions with the Internet. When selecting a wireless communication protocol for transmitting data from a TBAN to personal service devices, several factors need consideration: transmission range, data rate, power consumption, and bandwidth are all critical to ensuring efficient and effective communication. Wireless communication technologies such as NFC, Bluetooth, and ZigBee are integral to this system. They facilitate the seamless transmission and processing of clinical data, including updates on treatment progress and user feedback. The integration of these technologies not only streamlines the operation of the TBAN but also significantly enhances the delivery of precise, personalized medical services. This technological synergy fosters an environment where patients can actively participate in managing their health, making informed decisions based on real-time data and insights provided by their interconnected wearable devices.

Energy harvesting and storage textiles

Continuous operation of e-textiles critically depends on sustainable power management. Wearable technologies are therefore increasingly harnessing energy from the human body and its surrounding environment [12], [13], [14]. The human body is a rich source of renewable energy, with biomechanical movements, body heat, and body fluids offering significant energy potential. For instance, body heat can provide up to 4.8 W, biomechanical motions up to 67 W, and body fluids can contain energy levels as high as 100 W. Additionally, the environment around the body also presents renewable sources such as solar irradiance, which can reach an energy density of up to 100 mW/cm^2. The energy demands of contemporary body-worn electronics, which range from 200 µW to 1 W, can be entirely satisfied by these available energy sources [13]. This alignment of energy supply and demand has spurred the development of various energy harvesting technologies designed specifically for wearables. Among these, triboelectric nanogenerators (TENGs) capitalize on static electricity generated from friction, converting mechanical energy into electricity. Piezoelectric nanogenerators (PENGs) harness mechanical stress or vibrations, thermoelectric generators (TEGs)

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utilize temperature differences between the body and the environment, and biofuel cells (BFCs) derive electrical energy from the chemical energy in body fluids. Additionally, solar cells (SCs) capture solar energy, and hybrid generators (HGs) combine multiple technologies to optimize energy harvesting. These advancements in energy harvesting not only extend the operational life of wearable devices but also enhance their efficiency and contribute to the sustainability of wearable technology. This integration of energy harvesting mechanisms ensures that wearables remain functional without frequent recharges, promoting their seamless and continuous use in everyday life.

The effectiveness of wearable technology heavily relies on advanced energy storage solutions that meet the demands for flexibility, safety, and efficiency. Recent innovations in battery technology, such as the development of ultra-thin lithium polymer batteries and supercapacitors, have significantly improved energy densities and charging speeds. These advancements enable the creation of slimmer, more flexible battery designs that can be seamlessly integrated into textiles, thereby maintaining the comfort and wearability of smart garments. A pivotal area of research that has gained momentum is the development of fiber batteries [15]. These are highly flexible, one-dimensional energy storage devices designed to endure various mechanical deformations, such as bending, folding, and twisting. Unlike traditional rigid energy storage devices, fiber batteries are not constrained by the weight limitations typical of portable batteries. This characteristic allows them to be woven into different types of flexible textiles, resulting in compact, lightweight, and wearable power solutions. This shift towards fiber batteries is catalyzing the growth of wearable electronics, as these energy sources can be easily incorporated into everyday clothing and accessories without adding bulk or restricting movement. The integration of such innovative energy storage options is crucial for the continued expansion and practicality of wearable technology, offering users enhanced convenience and functionality in their daily lives.

Quantitative landscape and outlook

To complement the qualitative overview above, we summarize key quantitative indicators that contextualize the current wearable and textile-integrated device landscape. As shown in **Figure 3**, which provides a contextual benchmark of the overall wearable market, recent reports estimate that the global consumer and medical wearable device market reached approximately USD 84–85 billion in 2024, with an implied compound annual growth rate of ~14%. Within this landscape, smart textiles account for approximately 6–8% of total market value and are projected to reach USD 12–15 billion by 2025 [16].

From a deployment perspective, more than 1.1 billion wearable sensor units are estimated to be in active use worldwide, among which approximately 70–80 million units involve textile-integrated electronics. Adoption of textile-based systems is particularly prominent in sports and fitness (~43%), personalized health monitoring (~31%), and medical rehabilitation (~16%) [17].

Current and Future Challenges

Despite considerable progress, several significant research issues and challenges remain. One of the primary concerns is the integration of technologies into comfortable, durable, and aesthetically pleasing designs. Wearables must balance technical functionality with practical, everyday wearability

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to ensure user adoption and satisfaction. Additionally, energy efficiency and battery life continue to be major hurdles. While energy harvesting offers a promising solution, the variability in energy availability and the efficiency of conversion technologies can affect device performance. Developing more reliable energy storage solutions that can handle quick energy fluctuations is a critical area of focus. Finally, data privacy and security are increasingly important as wearables collect and store vast amounts of personal information. Ensuring the security of this data against unauthorized access and breaches is paramount. Moreover, as these devices become more capable and collect more sensitive data, ethical considerations around their use will become even more complex. Addressing these challenges through innovative research and development will be crucial for the future expansion of wearables and textile technologies.

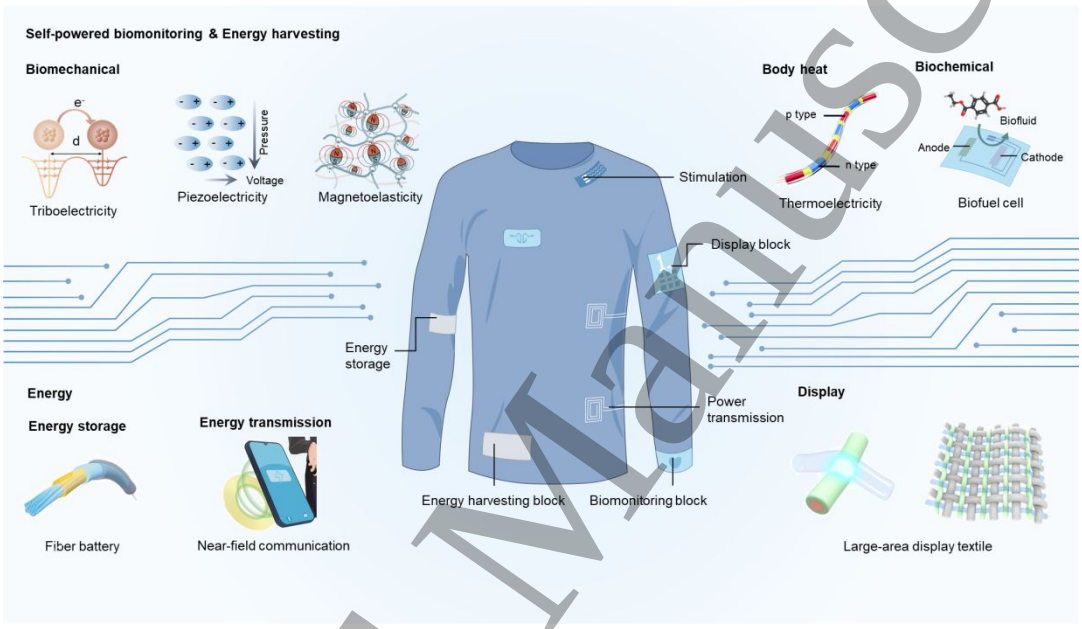


Figure 2. An integrated smart textile system showcases various technologies embedded within a smart garment designed to enhance health monitoring and energy efficiency. The system includes mechanisms for energy harvesting, energy storage, and energy transmission, all integrated into a wearable format. It highlights how biomechanical movements, body heat, and biochemical processes can be utilized for power generation and health monitoring. Key components such as thermoelectric generators for capturing body heat, biofuel cells for converting biochemical energy, and a large-area display textile are detailed, emphasizing their roles in continuous health monitoring and data display. Reproduced with permission from Ref. [18], [19], [20].

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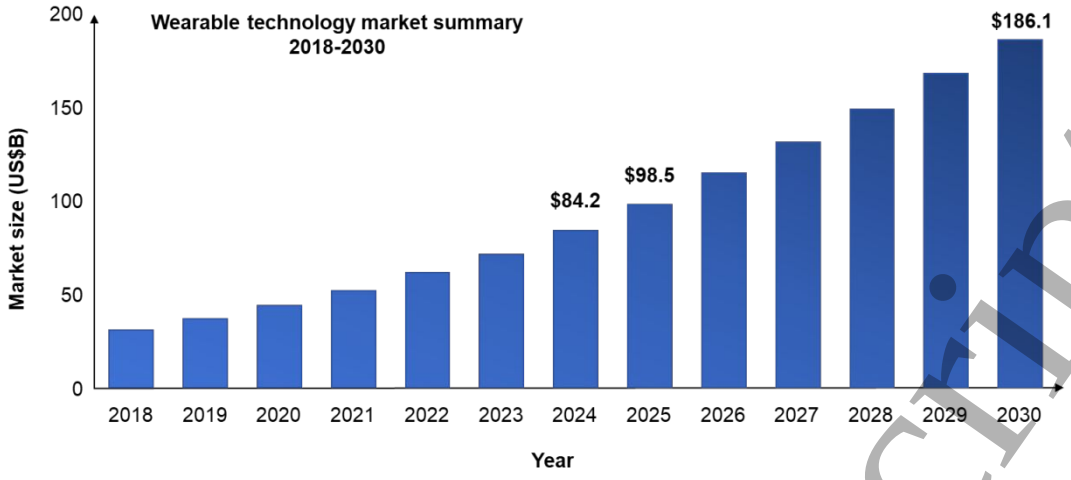


Figure 3. Global wearable technology market size from 2018 to 2030 (contextual benchmark). The chart shows the historical and projected growth of the global wearable technology market, increasing from ~USD 35 billion in 2018 to USD 84.2 billion in 2024, with forecasts of USD 98.5 billion in 2025 and USD 186.1 billion by 2030. The figure was created by the authors using publicly available market data (Grand View Research) [16].

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References

[1] J. Yin, S. Wang, T. Tat, and J. Chen, “Motion artefact management for soft bioelectronics,” Nat. Rev. Bioeng., vol. 2, no. 7, pp. 541–558, 2024, doi: 10.1038/s44222-024-00175-4.

[2] X. Xiao, J. Yin, J. Xu, T. Tat, and J. Chen, “Advances in machine learning for wearable sensors,” ACS Nano, vol. 18, no. 34, pp. 22734–22751, 2024, doi: 10.1021/acsnano.4c05851.

[3] A. Libanori, G. Chen, X. Zhao, Y. Zhou, and J. Chen, “Smart textiles for personalized healthcare,” Nat. Electron., vol. 5, no. 3, pp. 142–156, Mar. 2022, doi: 10.1038/s41928-022-00723-z.

[4] J. Yin et al., “Smart textiles for self-powered biomonitoring,” Med-X, vol. 1, no. 1, p. 3, 2023, doi: 10.1007/s44258-023-00001-3.

[5] M. R. Islam, S. Afroj, J. Yin, K. S. Novoselov, J. Chen, and N. Karim, “Advances in printed electronic textiles,” Adv. Sci., vol. 11, no. 6, p. 2304140, 2024, doi: 10.1002/advs.202304140.

[6] X. Xiao, J. Yin, G. Chen, S. Shen, A. Nashalian, and J. Chen, “Bioinspired acoustic textiles with nanoscale vibrations for wearable biomonitoring,” Matter, vol. 5, pp. 1342–1345, 2022, doi: 10.1016/j.matt.2022.03.014.

[7] K. Meng et al., “Wearable pressure sensors for pulse wave monitoring,” Adv. Mater., vol. 34, p. 2109357, 2022, doi: 10.1002/adma.202109357.

Accepted Manuscript

[8] X. Xiao, J. Yin, and J. Chen, "Triboelectric Nanogenerator for Healthcare," in *Handbook of Triboelectric Nanogenerators*, Z. L. Wang, Y. Yang, J. Zhai, and J. Wang, Eds. Cham, Switzerland: Springer, 2023, doi: 10.1007/978-3-031-28111-2_18.

[9] X. Zhao et al., "Air-permeable textile bioelectronics for wearable energy harvesting and active sensing," Adv. Mater. Technol., vol. 8, no. 8, p. 2201703, 2023, doi: 10.1002/admt.202201703.

[10] Z. Peng et al., "Self-charging electrostatic face masks leveraging triboelectrification for prolonged air filtration," Nat. Commun., vol. 13, no. 1, p. 7835, 2022, doi: 10.1038/s41467-022-35521-w.

[11] G. Chen, X. Xiao, X. Zhao, T. Tat, M. Bick, and J. Chen, "Electronic textiles for wearable point-of-care systems," Chem. Rev., vol. 122, pp. 3259–3291, 2022, doi: 10.1021/acs.chemrev.1c00502.

[12] I. Ali et al., "Advances in smart photovoltaic textiles," ACS Nano, vol. 18, no. 5, pp. 3871–3915, 2024, doi: 10.1021/acsnano.3c10033.

[13] G. Chen, Y. Li, M. Bick, and J. Chen, "Smart textiles for electricity generation," Chem. Rev., vol. 120, pp. 3668–3720, 2020, doi: 10.1021/acs.chemrev.9b00821.

[14] J. Li et al., "Stretchable thermoelectric fibers with three-dimensional interconnected porous network for low-grade body heat energy harvesting," ACS Nano, vol. 17, no. 19, pp. 19232–19241, 2023, doi: 10.1021/acsnano.3c05797.

[15] X. Xiao et al., "Advances in solid-state fiber batteries for wearable bioelectronics," Curr. Opin. Solid State Mater. Sci., vol. 26, no. 6, p. 101042, Dec. 2022, doi: 10.1016/j.cossms.2022.101042.

[16] Grand View Research, "Wearable technology market (2025–2030)," Grand View Research, 2024. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/wearable-technology-market

[17] "E-Textile Market by type (Classic Electronics, Modern Electronics), by product (Passive, Active, Ultra-Smart), by application (Defense, sports & fitness, healthcare, household textiles, fashion & entertainment, Transport, Protection & Military, Architecture)," *Market Research*, Allied Market Research. [Online]. Available: https://www.marketresearch.com/Allied-Market-Research-v4029/Textile-Type-Classic-Electronics-Modern-32965209/.

[18] Q. Chen, S. Sun, T. Zhai, M. Yang, X. Zhao, and H. Xia, "Yolk–shell NiS_2 nanoparticle-embedded carbon fibers for flexible fiber-shaped sodium battery," Adv. Energy Mater., vol. 8, p. 1800054, 2018, doi: 10.1002/aenm.201800054.

[19] J. He et al., "Scalable production of high-performing woven lithium-ion fibre batteries," Nature, vol. 597, pp. 57–63, 2021, doi: 10.1038/s41586-021-03772-0.

[20] X. Shi et al., "Large-area display textiles integrated with functional systems," Nature, vol. 591, pp. 240–245, 2021, doi: 10.1038/s41586-021-03295-8.

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2.2 - Key advancements and trends

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Status

This section highlights the key technological advancements and emerging trends that are reshaping modern smart textiles. Rather than focusing on individual device categories, we summarize cross-cutting shifts in sensing, actuation, energy harvesting, storage, and large-area display technologies that collectively define the next generation of textile electronics. The interplay between technological innovation and practical application is spawning a new generation of textiles that are not only smart but also scalable, opening up prospects for future integration into the global textile market. As these technologies mature, they promise to redefine the interface between humans and technology, making smart textiles an integral part of our digital and connected world.

Trend 1. Multimodal and human-interactive sensing textiles

A key trend in smart textiles is the convergence of multimodal sensing capabilities that support real-time human–machine interaction and continuous physiological monitoring. One representative example is a wearable sign-to-speech translation system that uses stretchable yarn-based sensor arrays to convert dynamic hand gestures into digital information, enabling natural communication through textile-integrated sensing interfaces (**Figure 4**a) [1]. This illustrates the shift from single-parameter sensing to interactive and user-adaptive textile systems capable of capturing complex body motions. In parallel, soft functional fibers have been developed that can be directly woven into textiles to monitor diverse physiological signals. When integrated into a face mask, these fibers detect variations in breathing patterns, while a knitted glove incorporating the same fibers can sense thermal changes and recognize distinct hand gestures (**Figure 4**b-c) [2]. Such multimodal fiber-based sensing platforms highlight a broader trend toward unobtrusive, garment-embedded electronics that expand the sensing bandwidth without compromising comfort or wearability.

Trend 2. Soft therapy textiles for personalized rehabilitation

Another emerging trend is the integration of soft therapeutic functions into textile platforms to provide personalized rehabilitation outside traditional clinical settings. The magnetoelastic effect, traditionally limited to rigid metal alloys used in civil engineering, has been innovatively applied to soft magnetic fibers, creating new possibilities for soft-matter electronics [3]. In response to the significant impact of arm injuries, which affect daily activities and sports and comprise nearly half of all upper extremity traumas in the U.S., a novel textile magnetoelastic patch has been developed to revolutionize arm injury treatment (**Figure 4**d) [4]. This innovative device, leveraging magnetoelastic technology, converts biomechanical signals from muscle movements into electrical signals, offering real-time, quantitative feedback on muscular workload and activity tolerance. Its lightweight, skin-conformal, waterproof, and pressure-sensitive properties make it an ideal solution for continuous monitoring and personalized treatment during rehabilitation, helping to manage patient workload and prevent overexertion. This demonstrates a broader shift from rigid, clinic-based rehabilitation tools toward soft, textile-integrated therapeutic systems capable of long-term, individualized treatment.

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Trend 3. Hybrid and self-powered textile energy harvesting

Energy harvesting in smart textiles is moving toward hybrid architectures that combine multiple ambient energy sources to achieve continuous, maintenance-free power generation. One example is a micro-cable textile that integrates photovoltaic units with triboelectric nanogenerators, enabling simultaneous harvesting of solar and biomechanical energy within a thin, flexible fabric [5]. This textile combines solar cells and triboelectric nanogenerators into a fabric just 320 μm thick, making it suitable for integration into various everyday applications like clothing and curtains (**Figure 4**e). Demonstrating remarkable utility, this hybrid power textile can charge devices quickly under normal environmental conditions and has proven capable of powering electronic watches, charging cell phones, and driving water-splitting reactions. This hybrid strategy reflects a growing trend toward multi-source energy systems that can operate effectively in diverse daily-wear environments.

Soft magnetoelastic fibers represent another major advancement, enabling high-efficiency biomechanical energy harvesting in wearable formats without the need for external magnetic fields [6], [7] (**Figure 4**f). These fibers, which align mechanically with human tissue and require no external magnetic fields, have been used to develop a textile magnetoelastic This generator effectively harnesses biomechanical energy to power devices, even under significant perspiration, due to its intrinsic humidity resistance (**Figure 4**g). Integrated into smart textiles, it offers vast potential for energy generation, health monitoring, and data-driven diagnostics, paving the way for advancements in wearable technologies across medical, robotics, and sensory perception fields (**Figure 4**h) [8], [9], [10].

Trend 4. Scalable fiber-based energy storage

A transformative trend in smart textiles is the emergence of scalable fiber-based energy storage systems that can be woven directly into garments while maintaining mechanical flexibility and durability. Fiber lithium-ion batteries have emerged as a key innovation in this area, offering a flexible power solution ideally suited for wearable electronics due to their ability to be seamlessly integrated into textiles (**Figure 4**i). Although historically challenging to produce in long lengths due to increased internal resistance that impacts electrochemical performance, recent breakthroughs have demonstrated that the internal resistance in these fibers decreases and then stabilizes as they lengthen, leading to the development of an industrial process capable of producing meters-long, high-performing fiber batteries [11]. These batteries exhibit an energy density of 85.69 watt-hours per kilogram and impressive durability, maintaining significant capacity even after extensive mechanical stress. Their integration into textiles has been practically demonstrated, with applications such as wirelessly charging cellphones and powering smart garments (**Figure 4**k), marking a significant advancement in the integration of robust, high-performance power sources into next-generation smart textiles.

Advances in polymer gel electrolytes have further enhanced interface stability in fiber batteries, allowing the formation of continuous, flexible energy storage networks suitable for large-area textile applications (**Figure 4**k) [12]. In addition, ultrathin zinc-ion fiber batteries offer safe and deformable alternatives for wearable electronics, maintaining reliable performance under stretching and bending [13] . These novel electrolytes facilitate enhanced ion transport and offer mechanical properties suited for wearable applications—stretchability, high ion conductivity, and self-healing

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capabilities—enabling the ZIB fibers to perform reliably under various conditions (**Figure 4**l). Collectively, these innovations highlight a trend toward robust, textile-integrable fiber batteries that provide distributed and high-efficiency energy storage for future smart garments.

Trend 5. Display textiles and integrated computing fibers

The integration of display technology into textiles marks a significant advancement in the field of electronic textiles, setting the stage for the next generation of wearable technology. This innovative approach has led to the development of a 6-meter-long, 25-centimeter-wide display textile composed of over half a million electroluminescent units, each spaced approximately 800 micrometers apart [14]. These units are created by weaving conductive weft and luminescent warp fibers, forming micro-scale electroluminescent points at their intersections. Notably, the brightness variation among these units is less than 8 percent, and their performance remains consistent under physical deformations such as bending, stretching, or pressing (**Figure 4**m). The durability of the display textile is further underscored by its ability to withstand repeated machine washings, maintaining flexibility and breathability, which are essential for everyday wear. Demonstrated as a communication tool within an integrated system that includes a display, keyboard, and power supply, this textile underscores its potential utility in the internet of things (**Figure 4**). This pioneering work not only enhances the functionality of textiles with robust, functional displays but also aligns with ongoing efforts to seamlessly blend electronic devices with fabric materials, promising transformative impacts on how electronic devices are worn and interacted with in daily life.

Complementing these advances, interactive computing fibers have been developed that integrate sensing, actuation, display feedback, and signal modulation within a single soft fiber [15]. These fibers operate without traditional chips or rigid circuit components, relying instead on body-coupled interactions and textile-scale energy coupling (**Figure 4**o-p). Such systems demonstrate a shift toward chipless, fabric-embedded computing, enabling future garments to function as fully integrated electronic systems.

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Figure 4. Advancements in electronic textile from evolving fields of sensing, therapy, energy and display. (a) Photograph of skin-attached yarn-based stretchable sensor arrays with wireless PCB for sign-to-speech translation. Reproduced with permission from [1]. Copyright 2020 Nature Publishing Group. **(b)** Sensing face mask with an electronic fiber in the middle layer for breath conditions monitoring. **(c)** Sensing glove with an electronic fiber on the fingertip area for thermal sensing. Reproduced with permission from [2]. Copyright 2023 Nature Publishing Group. **(d)** Magnetoelastic textile patch detecting muscle mechanical motions for personalized physiotherapy. Reproduced with permission from [4]. Copyright 2023 Elsevier. **(e)** Photograph of the hybrid power textile harvesting power from sunlight and biomechanics. Reproduced with permission from [5]. Copyright 2016 Nature Publishing Group. **(f-g)** Textile-based magnetoelastic generator (MEG) for harvesting biomechanical energy under wet conditions and powering wearable electronic. Reproduced with permission from [6]. Copyright 2021 Nature Publishing Group. **(h)** Textile-based MEG for powering thermometer. Reproduced with permission from [7]. Copyright 2021 Elsevier. **(i-j)** Fiber lithium-ion battery photograph and its application for powering coils to transmission to charge phones. Reproduced with permission from [12]. Copyright 2021 Nature Publishing Group. **(k)** The stability of fiber lithium-ion battery during cut off test. Reproduced with permission from [11]. Copyright 2024 Nature Publishing Group. **(l)** Integration of ultrathin rechargeable Zinc ion fiber battery for electronic textiles. Reproduced with permission from [13]. Copyright 2021 American Association for the Advancement of Science. **(m-n)** Electroluminescence performance of the display textile and its integration with keyboard as communication platform. Reproduced with permission from [14]. Copyright 2021 Nature Publishing Group. **(o-p)** Photographs of interactive fiber being wirelessly powered by contacting with bio-tissues and coupling the surrounding electromagnetic energy. Reproduced with permission from [15]. Copyright 2021 American Association for the Advancement of Science.

Concluding Remarks

The projection of widely adopted 5G technologies and IoT accelerates the data communication and clinical-level data analysis among smart textiles for personalized healthcare. As these devices become more integrated with users' lives, they offer the promise of proactive health management, enhanced communication, and a deeper interaction with the surrounding digital world. Further advances could lead to even greater personalization of healthcare, more efficient energy usage, and innovations in digital connectivity that could redefine human-computer interaction. In this review, we have comprehensively summarized the textile diagnostic devices, textile therapeutic devices, and communication technologies regarding the working mechanisms, representative materials, and clinical scenarios. Despite the tremendous research progress, many bottlenecks need to be

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addressed prior to the widespread use of smart textiles. This field remains critically important due to its vast potential to impact health monitoring, personal safety, and efficiency in everyday tasks.

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References

[1] Z. Zhou et al., “Sign-to-speech translation using machine-learning-assisted stretchable sensor arrays,” Nat. Electron., vol. 3, no. 9, pp. 571–578, 2020, doi: 10.1038/s41928-020-0428-6.

[2] S. Zhang et al., “Biomimetic spinning of soft functional fibres via spontaneous phase separation,” Nat. Electron., vol. 6, pp. 1–11, 2023, doi: 10.1038/s41928-023-00960-w.

[3] Y. Zhou et al., “Giant magnetoelastic effect in soft systems for bioelectronics,” Nat. Mater., vol. 20, pp. 1670–1676, 2021, doi: 10.1038/s41563-021-01093-1.

[4] J. Xu et al., “A textile magnetoelastic patch for self-powered personalized muscle physiotherapy,” Matter, vol. 6, no. 7, pp. 2235–2247, 2023, doi: 10.1016/j.matt.2023.06.008.

[5] J. Chen et al., “Micro-cable structured textile for simultaneously harvesting solar and mechanical energy,” Nat. Energy, vol. 1, p. 16138, 2016, doi: 10.1038/nenergy.2016.138.

[6] X. Zhao et al., “Soft fibers with magnetoelasticity for wearable electronics,” Nat. Commun., vol. 12, no. 1, p. 6755, 2021, doi: 10.1038/s41467-021-27066-1.

[7] G. Chen et al., “Discovering giant magnetoelasticity in soft matter for electronic textiles,” Matter, vol. 4, no. 11, pp. 3725–3740, 2021, doi: 10.1016/j.matt.2021.09.012.

[8] X. Zhao et al., “A soft magnetoelastic generator for wind-energy harvesting,” Adv. Mater., vol. 34, no. 38, p. 2204238, 2022, doi: 10.1002/adma.202204238.

[9] J. Xu et al., “Spherical magnetoelastic generator for multidirectional vibration energy harvesting,” ACS Nano, vol. 17, no. 4, pp. 3865–3872, 2023, doi: 10.1021/acsnano.2c12142.

[10] I. W. Ock, J. Yin, S. Wang, X. Zhao, J. M. Baik, and J. Chen, “Advances in blue energy fuels: Harvesting energy from ocean for self-powered electrolysis,” Adv. Energy Mater., vol. 14, p. 2400563, 2024, doi: 10.1002/aenm.202400563.

[11] C. Lu et al., “High-performance fibre battery with polymer gel electrolyte,” Nature, vol. 629, no. 8010, pp. 86–91, 2024, doi: 10.1038/s41586-024-07343-x.

[12] J. He et al., “Scalable production of high-performing woven lithium-ion fibre batteries,” Nature, vol. 597, pp. 57–63, 2021, doi: 10.1038/s41586-021-03772-0.

[13] X. Xiao et al., “An ultrathin rechargeable solid-state zinc ion fiber battery for electronic textiles,” Sci. Adv., vol. 7, p. eabl3742, 2021, doi: 10.1126/sciadv.abl3742.

Accepted Manuscript

[14] X. Shi et al., “Large-area display textiles integrated with functional systems,” Nature, vol. 591, pp. 240–245, 2021, doi: 10.1038/s41586-021-03295-8.
[15] W. Yang et al., “Single body-coupled fiber enables chipless textile electronics,” Science, vol. 384, no. 6691, pp. 74–81, 2024, doi: 10.1126/science.adk3755.

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2.3 - Market analysis in wearable technology and smart textiles

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Status

The wearable technology and smart textiles market has experienced substantial growth, driven by advancements in sensor technology, increasing consumer health awareness, and the integration of digital health monitoring systems. This market encompasses a wide range of products, from smartwatches and fitness trackers to smart clothing and health monitoring patches, each catering to specific health monitoring needs. Understanding the market dynamics and identifying the major players is crucial for stakeholders aiming to navigate this rapidly evolving landscape. This paper provides a cost analysis and examines the adoption rates of wearable devices across different regions, highlighting significant differences in price and regional adoption influenced by economic, technological, and cultural factors.

From a translational perspective, market demand acts as the primary mechanism by which technological advances in wearable devices and smart textiles are converted into deployable healthcare solutions. While preceding sections focus on sensing and system-level innovations, market analysis provides insight into which technologies are adopted at scale, sustained by clinical demand, affordability, and integration into healthcare workflows. In this context, adoption trends reveal how wearable technologies progress from consumer wellness tools toward clinically meaningful monitoring, diagnostics, and long-term patient management.

The global wearable technology market is experiencing rapid growth. According to Market Research Future, the market was valued at approximately USD 53.1 billion in 2023 and is anticipated to reach USD 69.67 billion by 2024, with a compound annual growth rate (CAGR) of 26.83% from 2024 to 2032 [1]. Similarly, the smart textiles market is expected to expand significantly. MarketsandMarkets projects that the market will grow from USD 1.6 billion in 2019 to USD 5.3 billion by 2024, with an expected CAGR of 26.2% [2].

For health professionals, the commercial success of wearable technologies increasingly reflects their ability to support continuous, non-invasive, and remote physiological monitoring. Clinically relevant wearables now enable longitudinal tracking of cardiovascular, metabolic, and activity-

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related biomarkers, facilitating early detection, chronic disease management, and remote patient monitoring. Importantly, market growth since 2025 has favored platforms that emphasize data reliability, clinical validation, and interoperability with digital health systems, signaling a shift from lifestyle-focused devices toward healthcare-oriented solutions.

From a market perspective, wearable technologies are commonly segmented into fitness and wellness devices, consumer health wearables, and clinically oriented monitoring systems, each exhibiting distinct adoption drivers, price sensitivity, and regulatory requirements.

Cost analysis of wearables

The cost of wearable health monitoring devices varies significantly, reflecting their technological complexity and the range of functionalities they offer (**Figure 5a**). Understanding these cost dynamics is crucial for evaluating their accessibility and potential for widespread adoption.

- Smartwatches ($300): Smartwatches, such as the Apple Vatch Series 8 and Samsung Galaxy Vatch 4, offer comprehensive health monitoring features, including heart rate and ECG capabilities, which justify their average cost [3,4].
- Chest Straps ($150): Chest straps like the Polar H10 Heart Rate Monitor and Garmin HRM-Dual provide accurate cardiac data, making them cost-effective solutions for precise health monitoring [5,6].
- Smart Clothing ($200): Smart clothing, including products like Hexoskin Smart Shirts and OMSignal BioMan+ shirts, integrates sensors for continuous monitoring of vital signs, representing the mid-range cost of smart textiles [7,8].
- Patches ($100): Vearable patches such as the iRhythm Zio Patch and Abbott FreeStyle Libre offer non-invasive, continuous monitoring essential for managing chronic conditions [9,10].
- Earbuds ($250): Advanced health-monitoring earbuds, such as the Jabra Elite Sport, incorporate heart rate sensors and other features, reflecting their higher price point [11].

These cost tiers correspond to different clinical and translational use cases, ranging from population-level wellness screening to prescription-grade monitoring for chronic disease management and post-acute care.

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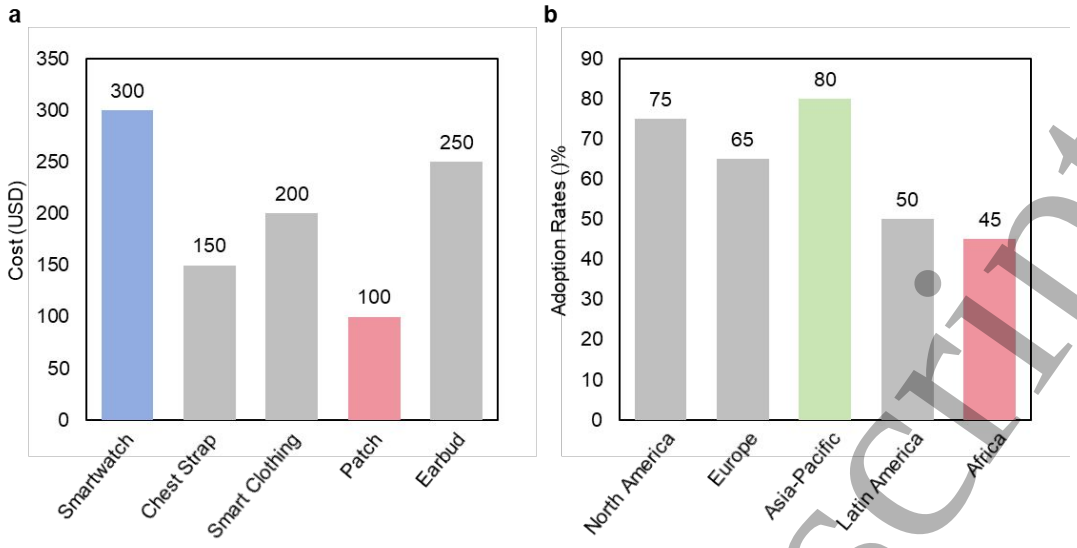


Figure 5. Cost analysis and adoption rates of wearable health monitoring devices. **(a)** the cost analysis of various wearable health monitoring devices highlights significant differences in price based on the type and complexity of the device. **(b)** the adoption rates of wearable devices across different regions show notable variations.

Wearable device adoption rates in different regions

The adoption rates of wearable devices vary globally due to economic, technological, and cultural factors (**Figure 5b**). These variations provide insights into the global landscape of wearable health technology:

- North America (75%): North America leads in wearable device adoption with a 75% penetration rate, driven by technological advancements, high consumer spending power, and the convenience of comprehensive health tracking features [12].
- Europe (65%): Europe follows with a 65% adoption rate, bolstered by strong healthcare initiatives and consumer interest in fitness technology [13].
- Asia-Pacific (80%): The Asia-Pacific region exhibits the highest adoption rate at 80%, fueled by increasing awareness and significant investments in healthcare technology [14].
- Latin America (50%): Latin America s adoption rate is 50%, influenced by growing middle-class populations and increasing health awareness [15].
- Africa (45%): Africa has the lowest adoption rate at 45%, primarily due to eco- nomic constraints. However, there is growing interest in mobile health technologies due to their affordability and scalability [16].

The variations in adoption rates underscore the importance of tailoring health technology strategies to specific regional contexts. In North America and Europe, where adoption rates are already high, the focus should be on integrating advanced functionalities and improving user experience. In contrast, in regions like Latin America and Africa, efforts should enhance affordability and accessibility to bridge the healthcare gap.

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While consumer fitness wearables currently dominate unit volume globally, clinical-grade wearables—particularly patches and smart garments—represent the fastest-growing segment in terms of healthcare integration and reimbursement-driven deployment.

Figure 5 reveals that regions with higher adoption rates often correlate with the availability of affordable wearable options. For instance, the Asia-Pacific region leads in adoption rates, likely due to cost-effective wearable solutions catering to diverse consumers. Conversely, regions with lower adoption rates, such as Africa, may benefit from increased accessibility to lower-cost wearable devices, potentially spurring adoption and improving health outcomes.

Moreover, sustainable practices in the production and disposal of wearable devices should be prioritized to mitigate environmental impacts as the market expands. Addressing these areas will enhance the global adoption of wearable health technologies, driving improvements in both health monitoring and overall public health.

Conclusion

The wearable technology and smart textiles market is rapidly evolving, driven by advancements in sensor technology and increasing consumer health awareness. Significant regional variations in cost and adoption rates highlight the need for tailored strategies to meet diverse needs. Future efforts should focus on affordability, advanced technology integration, and sustainability. By addressing these areas, wearable health technologies can achieve broader global adoption, enhancing health monitoring and contributing to public health improvements.

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References

[1] Market Research Future, “Wearable technology market research report—Global forecast till 2032,” Market Research Future, Jan. 2023. [Online]. Available: https://www.marketresearchfuture.com/reports/wearable-technology-market-2336. Accessed: May 7, 2024.

[2] MarketsandMarkets, “Smart textiles market by type, application, and geography—Global forecast to 2024,” MarketsandMarkets, Jul. 2023. [Online]. Available: https://www.marketsandmarkets.com/Market-Reports/smart-textiles-market-13764132.html. Accessed: May 7, 2024.

[3] Apple Inc., “Apple Watch Series 8 technical specifications,” Apple Inc., 2023. [Online]. Available: https://support.apple.com/en-us/111848. Accessed: May 7, 2024.

Accepted Manuscript

[4] Samsung Electronics, "Samsung Galaxy Watch 4 technical specifications," Samsung Electronics, 2023. [Online]. Available: https://www.samsung.com/uk/watches/galaxy-watch/galaxy-watch4-pink-gold-bt-sm-r860nzdaeua/. Accessed: May 7, 2024.

[5] Polar Electro, "Polar H10 heart rate sensor technical specifications," Polar Electro, 2023. [Online]. Available: https://support.polar.com/e_manuals/h10-heart-rate-sensor/polar-h10-user-manual-english/technical-specifications.htm. Accessed: May 7, 2024.

[6] Garmin Ltd., "Garmin HRM-Dual heart rate monitor," Garmin Ltd., 2023. [Online]. Available: https://www.garmin.ae/p/010-12883-00?srsltid=AfmBOoop1RAj0kmmuVodWdKOEhg9nvVw4B_yWKUkiza72FeqD66yWv53. Accessed: May 7, 2024.

[7] Hexoskin, "Hexoskin smart shirt product information," Hexoskin, 2023. [Online]. Available: https://hexoskin.com/?srsltid=AfmBOop6YkNg_VyIwIZWSjTnnC4WbSsr4jGBUDuaZV_ABHN38O0JvvTq. Accessed: May 7, 2024.

[8] OMSignal, "OMSignal BioMan+ shirt overview," OMSignal, 2023. [Online]. Available: https://smartclothinglab.com/brands/omsignal/. Accessed: May 7, 2024.

[9] iRhythm Technologies, "Zio XT patch technical specifications," iRhythm Technologies, 2023. [Online]. Available: https://www.irhythmtech.com/us/en/solutions-services/irhythm-service/zio-xt. Accessed: May 7, 2024.

[10] Abbott Laboratories, "FreeStyle Libre continuous glucose monitoring system," Abbott Laboratories, 2023. [Online]. Available: https://www.freestyle.abbott/en-ca/home.html. Accessed: May 7, 2024.

[11] Jabra, "Jabra Elite Sport earbuds features," Jabra, 2023. [Online]. Available: https://www.jabra.com/en-sg/supportpages/jabra-elite-sport#/#100-98700000-40. Accessed: May 7, 2024.

[12] Deloitte, "2021 global health care outlook: Accelerating industry change," Deloitte Insights, 2021. [Online]. Available: https://www2.deloitte.com/us/en/insights/industry/health-care/global-health-care-outlook.html. Accessed: May 7, 2024.

[13] Statista, "Global wearable devices market share by region," Statista, 2021. [Online]. Available: https://www.statista.com/statistics/878144/worldwide-smart-wristwear-shipments-forecast/. Accessed: May 7, 2024.

[14] IDC, "Asia-Pacific wearable device market analysis," IDC, 2021. [Online]. Available: https://www.idc.com/promo/wearablevendor/. Accessed: May 7, 2024.

[15] HealthTech Magazine, "Wearable technology adoption in Latin America," HealthTech Magazine, Apr. 2021. [Online]. Available: https://www.healthtechmagazines.com/digital-health/. Accessed: May 7, 2024.

[16] World Health Organization, "Mobile health technologies and adoption rates in Africa," World Health Organization, 2021. [Online]. Available: https://www.afro.who.int/publications/mhealth-new-horizons-health-through-mobile-technologie. Accessed: May 7, 2024.

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Section 3: Applications in Healthcare

3.1 - Wearables for health monitoring and diagnostics

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Status

Healthcare systems are facing increasing challenges due to factors including aging populations and rising rates of chronic illness. These challenges are further exacerbated in rural areas, where geographical isolation creates additional barriers to provision of healthcare services. Wearable devices have the potential to enable remote and at-home health monitoring. Such monitoring could enable early detection of health conditions, support early intervention, and improved outcomes. This in turn would reduce pressure on healthcare systems and provide greater access to care irrespective of location.

Much progress has been made towards health monitoring with wearables, as shown in **Figure 6**. In cardiorespiratory health monitoring research, photoplethysmogram (PPG) sensors are commonly leveraged to capture heart activity due to their widespread deployment in wrist-based wearables[1]. Additionally, single-lead electrocardiogram (ECG) sensors are increasingly implemented in wearables to capture electrical activity of the heart, showing good agreement with medical-grade 12-lead ECGs [2]. Recent research has utilised artificial intelligence (AI) to extract complex health parameters including respiratory rate [3] and blood pressure [4,5] from PPG or ECG data, or both.

Beyond research, there have also been advancements in commercialisation of PPG-based approaches, such as the recent FDA clearance of the Apple Watch's "Hypertension Notification Feature" [6]. However, this clearance applies only to use in untreated adults, and does not serve as a diagnostic - users are instructed to confirm with cuff-based BP measurements and consult with a doctor, with validation results indicating that over 50% of untreated hypertensives will not receive an alert [7,8]. Although these commercial advancements show promise, recent studies indicate that there remains insufficient evidence that any cuffless blood pressure device are adequate for clinical use [7].

Beyond vital sign monitoring, studies have also applied AI to PPG or ECG data for detection of health issues including COVID-19 [9], sleep apnoea [10], depression pre-screening [11], and loss-of-pulse detection [12]. Beyond PPG and ECG, several studies have explored alternative cardiorespiratory sensors based on approaches including detecting chest movement [13], cardiorespiratory sounds [14], or ultrasonic heart motion analysis [15], however these are not yet used clinically.

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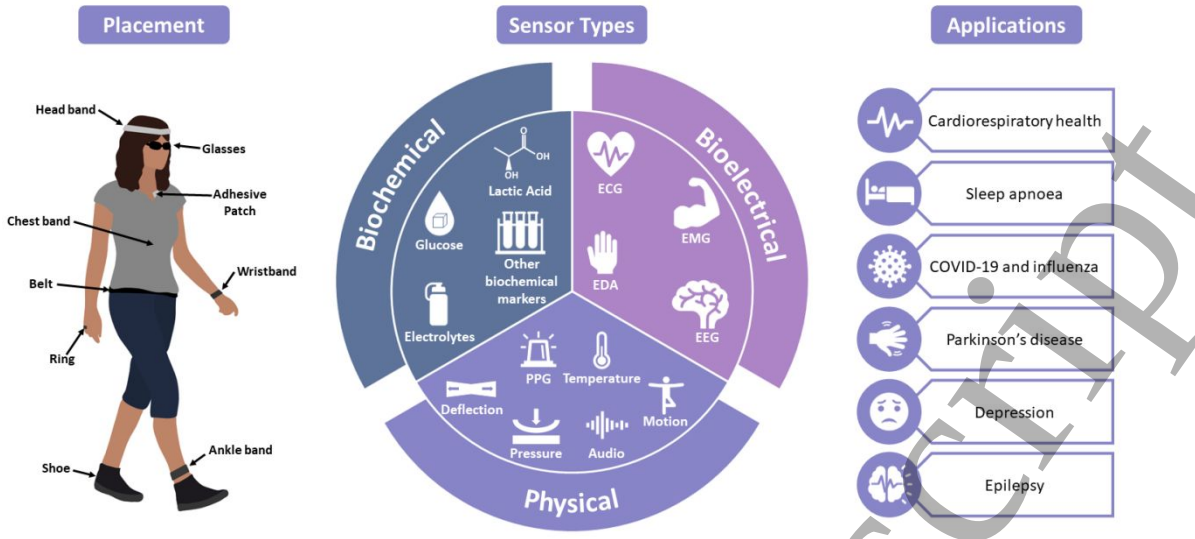


Figure 6. An overview of wearable devices for health monitoring and diagnosis, including device placement options, key sensor types, and selected diagnostic and monitoring applications.

Wearable sensors, often supported by AI, are also being developed to monitor physiological parameters relevant to specific conditions. Wearable sweat sensors have shown promise for monitoring chemical biomarkers, from glucose [16] to electrolyte levels [17]. These in turn can assist in diagnosis and management of various chronic illnesses. Wearable movement sensors such as accelerometers can be used to support detection and monitoring of conditions that affect gait, such as Parkinson's disease [18], as well as acute medical events, including falls [19] and seizures [20]. Sensors that are established in clinical practice, such as electroencephalography (EEG) and electromyography (EMG) for assessing neurological and neuromuscular activity respectively, are increasingly available in wearable formats. This further supports at-home monitoring and earlier diagnosis of conditions.

The outcomes of wearables research are increasingly being realised in commercially available fitness devices, with several such devices incorporating limited monitoring of parameters including heart rate, heart arrythmias, and falls. However, much work remains to be done towards medical-grade monitoring with wearables before these can be used in clinical monitoring and diagnosis for remote care settings.

Current and Future Challenges

Data quality is a key challenge in wearable sensing. Movement introduces motion artifacts to data obtained from many sensing modalities, complicating the accurate extraction of health parameters for monitoring and diagnostic purposes [21]. Further inaccuracies can be introduced through factors including device placement and environmental conditions. While methods for quantifying signal quality have been explored in the literature [22], these primarily assist in discarding noisy segments of data. This can result in gaps in the data, which is undesirable in health monitoring applications.

Some sensing modalities have been shown to have unequal performance across different demographic groups. A notable example is PPG, with some evidence suggesting that factors including skin tone, body mass index, and age may influence quality of obtained signals [23]. This can lead to greater inaccuracies for some demographic groups; however, the research is not yet

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conclusive. Further work is needed towards evaluating the performance of candidate wearable sensing methods across diverse and representative populations. Methods to mitigate any identified sensor inaccuracies are also needed, as is further exploration of alternative sensing modalities, to provide more equitable healthcare.

Artificial intelligence excels at finding patterns in complex data. As such, AI enables monitoring of complex health parameters based on wearable sensor data, as well as subsequent diagnostics. These benefits make AI a critical technology for healthcare wearables, though challenges remain, as illustrated in **Figure 7**. Advanced AI approaches require significant computational resources and power; as wearables have limited resources and battery life, they are largely unable to implement AI directly. This limitation is commonly addressed by sharing sensor data to higher-powered cloud services for AI assessment, with the resulting health parameter measurement or diagnosis returned to the wearable or another connected device, such as a smartphone. This introduces new issues, including the need for internet connectivity and privacy risks associated with processing sensitive health data in a remote location.

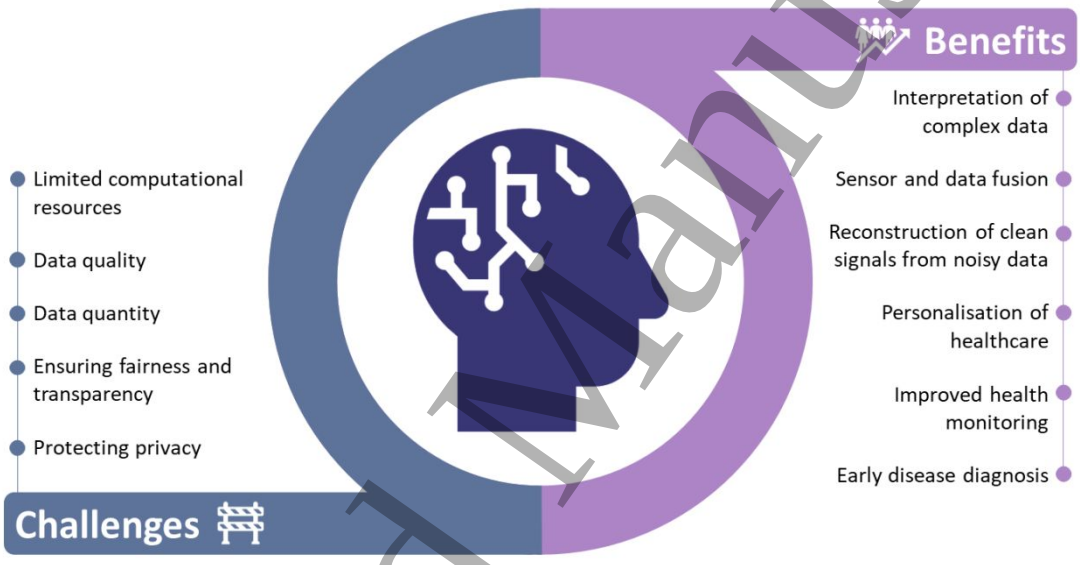


Figure 7. Challenges and benefits of artificial intelligence for wearable health monitoring and diagnostics

Another challenge associated with AI is the need for large quantities of representative data to learn from. This challenge is amplified in the healthcare context due to privacy and ethical concerns surrounding the sensitive data being collected. The challenge of collecting large data see many studies using small databases for research, increasing the risk of introducing unfair biases due to poor sample size. AI models are also susceptible to perpetuating other forms biases in data, which can arise from sources including human data labellers and inequities in healthcare access [24]. These challenges can result in AI models that underperform when deployed, or that exhibit unfairness towards individuals or groups.

Advances in Science and Technology to Meet Challenges

Signal quality is essential for reliable health monitoring and diagnostics. With wearable sensor data affected by a wide range of factors from environmental conditions to motion, there is a strong need to develop novel methods for improving signal quality. A promising approach is reconstructing clean time-series sensor data from noisy data. Emerging methods that warrant further research include

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advanced AI models such as autoencoders and decomposition methods such as variational mode decomposition.

Sensor fusion can also mitigate the impacts of poor signal quality. By fusing data from multiple sensing modalities, dependency of an algorithm on any one sensor can be reduced. For example, fusing data from both PPG and pressure sensors for monitoring cardiorespiratory health can improve robustness, as these sensors are affected by different sources of noise. Similarly, monitoring for conditions which affect a key sensor and fusing this with sensor data can enable compensation. An example is fusion of accelerometer motion with cardiovascular sensor data to compensate for motion effects. Fusion with other types of data, including self-reported symptoms and clinical tests, can also support improved diagnosis. The domain of data fusion is rich with research opportunity, from fusion of multimodal data types to development of enhanced fusion methods using AI or other advanced algorithms.

AI is critical in the future of wearables, however there are advancements needed to effectively meet the unique challenges in healthcare wearables, as was illustrated in **Figure 7.** For AI to be used in healthcare, it must first be responsible. A key factor towards that is improving the fairness of AI to ensure it provides equitable healthcare to all. Much work remains to be done towards quantifying AI fairness. Transparency is also critical to improve patient and clinician trust, and thus opportunity remains in the use of explainable AI for improving interpretability of decisions made by wearable devices.

In terms of technical aspects, AI requires large amounts of data to learn. Federated learning, which involves training local AI models at private institutions before combining these models for further use, is emerging as a key approach to enable AI development on a greater quantity of data without compromising participant privacy within healthcare contexts [25]. The computational cost of AI models also remains a problem for wearable devices. There is a need to develop AI models that operate directly on the wearable or a directly connected device such as a smartphone, reducing the need to share data with online cloud computing services.

Concluding Remarks

The field of wearables for health monitoring and diagnosis has advanced significantly in recent years. Recent studies have shown promising results towards monitoring a wide range of physiological parameters and subsequently using these to support diagnoses, with works spanning general health through to specific chronic conditions. While this has laid the foundations for a future with greater access to healthcare through wearables, much of the research to date has not been adopted in clinical practice. This is primarily due to the challenges that remain with data quality and algorithmic robustness. Artificial intelligence has shown great promise towards addressing many of the current challenges, provided it is developed responsibly through prioritising fairness, transparency, privacy, and robustness. Sensor and data fusion using AI or other methods is also increasingly critical towards improved health monitoring and diagnostics, particularly integrating wearable data with other clinical measurements. Overall, there remains much need and opportunity for future research in this broad and active field of research.

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References

[1] P. H. Charlton, J. Allen, R. Bailón, S. Baker, J. A. Behar, F. Chen, et al., "The 2023 wearable photoplethysmography roadmap," Physiol. Meas., 2023. [Online]. Available: https://iopscience.iop.org/article/10.1088/1361-6579/acead2

[2] S. Sufyan, I. Minahil, S. Humza, H. Sara, B. Amna, K. Salman, et al., "Diagnostic accuracy of Apple Watch electrocardiogram for atrial fibrillation," JACC Adv., vol. 4, no. 2, p. 101538, Feb. 2025, doi: 10.1016/j.jacadv.2024.101538.

[3] Y. Lin, X. Song, Y. Zhao, C. Zhang, and X. Ding, "Continuous respiratory rate monitoring through temporal fusion of ECG and PPG signals," PLoS One, vol. 20, no. 6, p. e0325307, Jun. 2025, doi: 10.1371/journal.pone.0325307.

[4] Z. Tian, A. Liu, G. Zhu, and X. Chen, "A paralleled CNN and transformer network for PPG-based cuff-less blood pressure estimation," Biomed. Signal Process. Control, vol. 99, p. 106741, 2025, doi: 10.1016/j.bspc.2024.106741.

[5] S. Baker, W. Xiang, and I. Atkinson, "A computationally efficient CNN–LSTM neural network for estimation of blood pressure from features of electrocardiogram and photoplethysmogram waveforms," Knowl.-Based Syst., vol. 250, p. 109151, Aug. 2022, doi: 10.1016/j.knosys.2022.109151.

[6] Apple Inc., "Apple debuts Apple Watch Series 11, featuring groundbreaking health insights," Sep. 9, 2025. [Online]. Available: https://www.apple.com/newsroom/2025/09/apple-debuts-apple-watch-series-11-featuring-groundbreaking-health-insights/

[7] G. S. Stergiou, A. Menti, D. Mariglis, and A. Kollias, "The quest for accurate wearable blood pressure monitors," Hypertens. Res., 2025, doi: 10.1038/s41440-025-02410-w.

[8] Apple Inc., "Hypertension notification feature on Apple Watch," 2025. [Online]. Available: https://www.apple.com/health/pdf/Hypertension_Notifications_Validation_Paper_September_2025.pdf

[9] C. Aliani, E. Rossi, M. Luchini, I. Calamai, R. Deodati, R. Spina, et al., "Automatic COVID-19 severity assessment from HRV," Sci. Rep., vol. 13, no. 1, p. 1713, 2023, doi: 10.1038/s41598-023-28681-2.

[10] T. Choksatchawathi, G. Sawadwuthikul, P. Thuwajit, T. Kaewlee, T. Mateepithaktham, S. Saisaard, et al., "ApSense: Data-driven algorithm in PPG-based sleep apnea sensing," IEEE Internet Things J., vol. 11, no. 20, pp. 33915–33926, 2024.

[11] S. Karimi, M. Nateghi, G. I. Cestero, L. Chitadze, Deepanshi, Y. Yang, et al., "Prescreening depression using wearable electrocardiogram and photoplethysmogram data from a psycholinguistic experiment," Physiol. Meas., vol. 46, no. 8, p. 085004, 2025, doi: 10.1088/1361-6579/adf6fe.

[12] K. Shah, A. Wang, Y. Chen, J. Munjal, S. Chhabra, A. Stange, et al., "Automated loss of pulse detection on a consumer smartwatch," Nature, vol. 642, no. 8066, pp. 174–181, 2025, doi: 10.1038/s41586-025-08810-9.

[13] M. Janusz, M. Roudjane, D. Mantovani, Y. Messaddeq, and B. Gosselin, "Detecting respiratory rate using flexible multimaterial fiber electrodes designed for a wearable garment," IEEE Sens. J., vol. 22, no. 13, pp. 13552–13561, 2022.

[14] K.-J. Butkow, T. Dang, A. Ferlini, D. Ma, Y. Liu, and C. Mascolo, "An evaluation of heart rate monitoring with in-ear microphones under motion," Pervasive Mobile Comput., vol. 100, p. 101913, 2024, doi: 10.1016/j.pmcj.2024.101913.

[15] A. Shahshahani, Z. Zilic, and S. Bhadra, "An ultrasound-based biomedical system for continuous cardiopulmonary monitoring: A single sensor for multiple information," IEEE Trans. Biomed. Eng., vol. 67, no. 1, pp. 268–276, 2020.

Accepted Manuscript

[16] Y. Chen, Y. Sun, Y. Li, Z. Wen, X. Peng, Y. He, et al., "A wearable non-enzymatic sensor for continuous monitoring of glucose in human sweat," Talanta, vol. 278, p. 126499, 2024, doi: 10.1016/j.talanta.2024.126499.

[17] S. Wang, M. Rovira, S. Demuru, C. Lafaye, J. Kim, B. P. Kunnel, et al., "Multisensing wearables for real-time monitoring of sweat electrolyte biomarkers during exercise and analysis on their correlation with core body temperature," IEEE Trans. Biomed. Circuits Syst., vol. 17, no. 4, pp. 808–817, 2023.

[18] Y. Yang, L. Chen, J. Pang, X. Huang, L. Meng, and D. Ming, "Validation of a spatiotemporal gait model using inertial measurement units for early-stage Parkinson's disease detection during turns," IEEE Trans. Biomed. Eng., vol. 69, no. 12, pp. 3591–3600, 2022.

[19] S. Campanella, A. Alnasef, L. Falaschetti, A. Belli, P. Pierleoni, and L. Palma, "A novel embedded deep learning wearable sensor for fall detection," IEEE Sens. J., vol. 24, no. 9, pp. 15219–15229, 2024.

[20] J. Zhang, L. Swinnen, C. Chatzichristos, V. Broux, R. Proost, K. Jansen, et al., "Multimodal wearable EEG, EMG and accelerometry measurements improve the accuracy of tonic-clonic seizure detection," Physiol. Meas., vol. 45, no. 6, p. 065005, 2024, doi: 10.1088/1361-6579/ad4e94.

[21] D. Seok, S. Lee, M. Kim, J. Cho, and C. Kim, "Motion artifact removal techniques for wearable EEG and PPG sensor systems," Front. Electron., vol. 2, p. 685513, 2021.

[22] S. T. P. Raghu, D. T. MacIsaac, and A. D. C. Chan, "Automated biomedical signal quality assessment of electromyograms: Current challenges and future prospects," IEEE Instrum. Meas. Mag., vol. 25, no. 1, pp. 12–19, 2022.

[23] J. Fine, K. L. Branan, A. J. Rodriguez, T. Boonya-ananta, Ajmal, J. C. Ramella-Roman, et al., "Sources of inaccuracy in photoplethysmography for continuous cardiovascular monitoring," Biosensors, vol. 11, no. 4, 2021.

[24] L. H. Nazer, R. Zatarah, S. Waldrip, J. X. C. Ke, M. Moukheiber, A. K. Khanna, et al., "Bias in artificial intelligence algorithms and recommendations for mitigation," PLOS Digit. Health, vol. 2, no. 6, p. e0000278, 2023.

[25] D. C. Nguyen, Q.-V. Pham, P. N. Pathirana, M. Ding, A. Seneviratne, Z. Lin, et al., "Federated learning for smart healthcare: A survey," ACM Comput. Surv., vol. 55, no. 3, pp. 1–37, 2022.

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3.2 - Predictive Modelling and Personalized Healthcare

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Status

Wearable health monitors have evolved significantly, transforming from activity trackers to advanced physiological monitors [1]. This evolution was driven by a heightened interest in continuous health data, particularly for sports and lifestyle devices, relying primarily on accelerometers to derive activity and step counts [2]. These devices could contribute to addressing global healthcare challenges in light of increasing (cost) pressure with an ageing population [5] and the rise of non-communicable diseases [6]. Here the WHO's strategies—Promotion, Prevention, Curation, Rehabilitation, and Palliative Care—underscore the need for enhanced rehabilitation [7], particularly for secondary health conditions [8]. This is crucial, as the need for rehabilitation is projected to rise. A recent analysis showed that 2.4 billion individuals globally had conditions that would benefit from rehabilitation [4], such as strokes, spinal cord injuries, and cardiovascular diseases.

In this work, we discuss the state of the art in current technologies and medical (shown in **Figure 8**). We consider wearable health monitoring a pivotal tool in transitioning from reactive to preventive healthcare, aiding in chronic disease management and rehabilitation with novel biomarker tracking. However, translation from the lifestyle to clinical domain is slow, with few wearables in medical care usage [3]. Here, we foresee three strong needs and use cases for wearables in the coming decade:

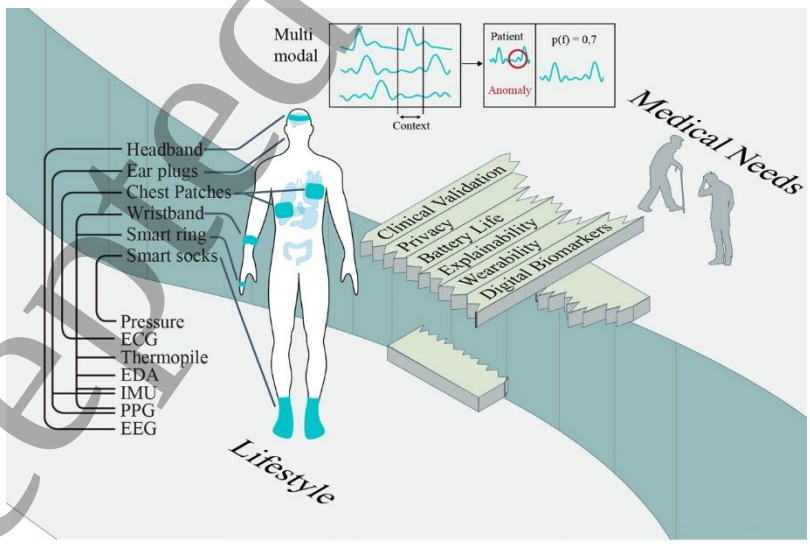


Figure 8. Bridging the Gap: Challenges for Wearable Technology in Rehabilitation and Chronic Disease Management — From accessibility and clinical validation to privacy, battery life, and acceptability, overcoming these hurdles is crucial to connecting innovative wearables with effective healthcare solutions for chronic disease management and rehabilitation.

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Objective monitoring of patient status. The rehabilitation process traverses different practitioners and data sources; here the handover varies in quality, making incomplete symptom recalls and long waits between visits are a common issue. Wearables will enable continuous monitoring and transmitting patient status to multiple healthcare professionals. This constant stream of data will allow early identification of changes in a patient's condition that might go unnoticed. As a result, hospital (re)admissions could be reduced by 20-30% [8], leading to significant cost savings in healthcare systems, where one re-hospitalization can cost over 20k USD [9].

Improving rehabilitation adherence. Patients returning home often neglect recommended rehabilitation, leading to poorer outcomes. Wearables will provide patients and healthcare professionals with real-time feedback improving adherence by continuous feedback on quality and quantity in rehabilitation efforts, which will be immediately visible. Additionally, enabling real-time gamification of therapy which has shown to increase patients' adherence [10].

Predictive modelling for preventive care. Wearable sensor data allows insight into health status evolution. This provides a basis for developing predictive models, *digital twins*, that aim to allocate targeted preventive interventions to avoid secondary health conditions [11].

Current and Future Challenges

Three major axes require significant research and development efforts for adopting wearable technology in preventive care, where uninterrupted data collection is essential:

Customization of wearables. Tailoring them to monitor specific health conditions or populations while maintaining affordability and scalability for a broader market remains challenging**.** Moreover, the device design must translate to the expectations of long-term use in rehabilitation and chronic disease management. Current devices struggle with comfort due to their size, weight, and material properties, leading to extended times required for donning and doffing [12][13]. Equally, the *social acceptability* of wearable devices varies widely, and the stigma associated with their use can deter some individuals from using them. Finally, *battery life* is critical for continuous use; high-frequency data collection increases power consumption [14].

Data management and interpretation. The need for *interoperability* across different service platforms and the absence of standardized data protocols significantly hinder the widespread adoption of wearable devices in healthcare. Devices must seamlessly integrate with existing healthcare systems, including electronic health records (EHRs).

Equally, future remote health status monitoring depends on the ability to contextualize sensor data into useful information [15]. i.e., physiological signals such as blood pressure have different implications when walking slowly versus leisurely jogging. Furthermore, the *interpretability* of artificial intelligence (AI) models used to analyse such information is crucial for valid medical decision support. Healthcare providers need to understand and trust these models to make informed decisions [16].

Subsequent problems arise from the lack of a *consistent legal framework* addressing data privacy, security, and ethical concerns for the processing of information from different hospitals and countries.

Clinical validation. The *accuracy and reliability* of sensors must adhere to clinical-grade standards [17] and for novel methods, proper metrics should be standardized. Specific population studies and clinical validation should provide validation for translational research into monitoring and treatment. Rigorous *clinical testing* of the effectiveness of each sensor integration and contextualization are crucial for new digital biomarkers tailored to specific populations [17].

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Advances in Science and Technology to Meet the Challenges

In an ideal scenario, as we propose in **Figure 9**, seamless data collection with multimodal sensing with a special focus on contextualisation would enable remote monitoring and rehabilitation, supported by data aggregated foundational models of the condition tailored to the individual, notwithstanding, several advancements must be overcome to achieve it:

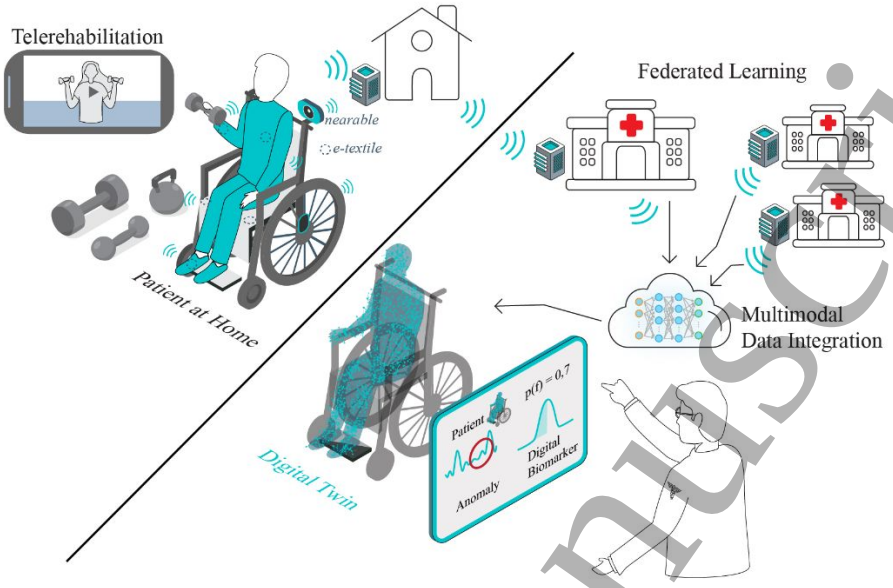


Figure 9. The future of wearables in medicine starts with data management and unobtrusive sensing aimed at the population in need. The physicians receive access to continuous, objective data that wholistically describes a patient's health status. This is possible through multimodal sensor integration and facilitates more informed decision making and forward simulations using digital twin models.

Device design. The embodiment in fabrics and in-skin design should be addressed together for improved durability, new battery chemistries, onboard energy harvesting, and ultra-low-power electronics. These advances extend usable time span and make devices suitable for long-term monitoring, which should ideally last over a week with *zero-interaction* and provide continuous observations [19]. Coming from innovations in biochemical non-invasive protein and chemical detection from sweat and other body fluids [18], to contextualized behavioural information of the patient through embedded multimodal sensors. Here, nearable, airable, and contactless sensors offer great potential by reducing patient interaction with the technology, increasing compliance for using systems that do not need to be worn or recharged, being connected to the power source as in the case of sensors embedded in patients' homes, e.g., pressure mattresses, radars, and lidars [19].

Data management and interpretability. Improved frameworks and legal basis for extensive data-sharing methods that implement data protection, such as *federated learning* [20] should be addressed in edge or cloud computing to enhance the effectiveness in real-world settings. This investment in translational work is crucial for maintaining data privacy while allowing researchers and healthcare providers to access and analyse rich datasets that will lead to the development of new biomarkers and personalized healthcare interventions. Research in *explainable AI* algorithms will ensure that the model outcomes are accurate and interpretable by healthcare providers, enhancing the system's trustworthiness, particularly in preventive care, where early detection and intervention are critical. Furthermore, advancements in compact AI models that can operate on-device will be vital to enabling real-time health monitoring without continuous data transmission, thereby improving data security and reducing the risk of breaches.

Clinical validation. There is a long-lasting need for translational research in wearable technology [20], where extensive clinical trials and population studies should be addressed with each sensor.

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Awareness and interaction of medical personnel with scientific and technical personnel can stimulate the pathway towards *validation* of new technologies with specific patient populations, testing their reliability and accuracy in determining and monitoring biomarkers of chronic diseases, preventing secondary diseases, and improving the rehabilitation process.

Concluding Remarks

Personalized medicine will be significantly enhanced by continuously monitoring a person's health status, particularly for chronic conditions and long-term rehabilitation, where there is a growing demand in the healthcare sector. By addressing all challenges in sensor design, data management, interpretable AI models and contextualized information, multimodal wearable health monitors could shift medicine from reactive treatment to preventive care. We strongly believe in the need for a multidisciplinary approach with a strong focus on translation from medicine, materials science, engineering, and data science to healthcare with a laser focus on clinical needs and validity to ensure subsequent integration into healthcare systems both technically and economically.

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References

[1] J. V. Vaghasiya, C. C. Mayorga-Martinez, and M. Pumera, "Wearable sensors for telehealth based on emerging materials and nanoarchitectonics," npj Flex. Electron., vol. 7, no. 1, p. 26, Jun. 2023, doi: 10.1038/s41528-023-00261-4.

[2] J. Takacs, C. L. Pollock, J. R. Guenther, M. Bahar, C. Napier, and M. A. Hunt, "Validation of the Fitbit One activity monitor device during treadmill walking," J. Sci. Med. Sport, vol. 17, no. 5, pp. 496–500, Sep. 2014, doi: 10.1016/j.jsams.2013.10.241.

[3] M. H. Iqbal, A. Aydin, O. Brunckhorst, P. Dasgupta, and K. Ahmed, "A review of wearable technology in medicine," J. R. Soc. Med., vol. 109, no. 10, pp. 372–380, Oct. 2016, doi: 10.1177/0141076816663560.

[4] A. Cieza, K. Causey, K. Kamenov, S. W. Hanson, S. Chatterji, and T. Vos, "Global estimates of the need for rehabilitation based on the Global Burden of Disease study 2019," Lancet, vol. 396, no. 10267, pp. 2006–2017, Dec. 2020, doi: 10.1016/S0140-6736(20)32340-0.

[5] C. Chen, S. Ding, and J. Wang, "Digital health for aging populations," Nat. Med., vol. 29, no. 7, pp. 1623–1630, Jul. 2023, doi: 10.1038/s41591-023-02391-8.

[6] L. A. N. Gordon, "Assessment of smart watches for management of non-communicable diseases in the ageing population: A systematic review," Geriatrics, vol. 3, no. 3, p. 56, Aug. 2018, doi: 10.3390/geriatrics3030056.

[7] H. Timm, J. Thuesen, and D. Clark, "Rehabilitation and palliative care: histories, dialectics and challenges," Wellcome Open Res., vol. 6, p. 171, Jul. 2021, doi: 10.12688/wellcomeopenres.16979.1.

[8] G. Mattison et al., "The influence of wearables on health care outcomes in chronic disease: Systematic review," J. Med. Internet Res., vol. 24, no. 7, p. e36690, Jul. 2022, doi: 10.2196/36690.

[9] A. Lorio, C. Garcia-Rodriguez, and A. Seifi, "Two decades of stroke in the United States: A healthcare economic perspective," Neuroepidemiology, vol. 58, no. 2, pp. 143–150, 2024, doi: 10.1159/000536011.

Accepted Manuscript

[10] L. Mayrhuber et al., "Movement reminders to encourage arm use during daily life in stroke patients," in Proc. IEEE Int. Conf. Rehabil. Robot. (ICORR), Singapore, Sep. 2023, pp. 1–6, doi: 10.1109/ICORR58425.2023.10304727.

[11] C. Tang, W. Yi, E. Occhipinti, Y. Dai, S. Gao, and L. G. Occhipinti, "A roadmap for the development of human body digital twins," Nat. Rev. Electr. Eng., vol. 1, no. 3, pp. 199–207, Feb. 2024, doi: 10.1038/s44287-024-00025-w.

[12] K. Bayoumy et al., "Smart wearable devices in cardiovascular care: Where we are and how to move forward," Nat. Rev. Cardiol., vol. 18, no. 8, pp. 581–599, Aug. 2021, doi: 10.1038/s41569-021-00522-7.

[13] S. Canali, V. Schiaffonati, and A. Aliverti, "Challenges and recommendations for wearable devices in digital health: Data quality, interoperability, health equity, fairness," PLOS Digit. Health, vol. 1, no. 10, p. e0000104, Oct. 2022, doi: 10.1371/journal.pdig.0000104.

[14] L. Wang, Y. Zhang, and P. G. Bruce, "Batteries for wearables," Natl. Sci. Rev., vol. 10, no. 1, p. nwac062, Jan. 2023, doi: 10.1093/nsr/nwac062.

[15] P. Daniore, V. Nittas, C. Haag, J. Bernard, R. Gonzenbach, and V. von Wyl, "From wearable sensor data to digital biomarker development: Ten lessons learned and a framework proposal," npj Digit. Med., vol. 7, no. 1, p. 161, Jun. 2024, doi: 10.1038/s41746-024-01151-3.

[16] R. Marcinkevičs and J. E. Vogt, "Interpretable and explainable machine learning: A methods-centric overview with concrete examples," WIREs Data Min. Knowl. Discov., vol. 13, no. 3, p. e1493, May 2023, doi: 10.1002/widm.1493.

[17] J. C. Goldsack et al., "Verification, analytical validation, and clinical validation (V3): The foundation of determining fit-for-purpose for biometric monitoring technologies (BioMeTs)," npj Digit. Med., vol. 3, no. 1, p. 55, Apr. 2020, doi: 10.1038/s41746-020-0260-4.

[18] C. Xu, S. A. Solomon, and W. Gao, "Artificial intelligence-powered electronic skin," Nat. Mach. Intell., vol. 5, no. 12, pp. 1344–1355, Dec. 2023, doi: 10.1038/s42256-023-00760-z.

[19] N. Schütz et al., "A systems approach towards remote health-monitoring in older adults: Introducing a zero-interaction digital exhaust," npj Digit. Med., vol. 5, no. 1, p. 116, Aug. 2022, doi: 10.1038/s41746-022-00657-y.

[20] A. Zhang, L. Xing, J. Zou, and J. C. Wu, "Shifting machine learning for healthcare from development to deployment and from models to data," Nat. Biomed. Eng., vol. 6, no. 12, pp. 1330–1345, Jul. 2022, doi: 10.1038/s41551-022-00898-y.

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3.3 - Respiration Monitoring via ECG and PPG in Wearable Devices

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Status

Although the term respiration refers to the gas exchange at cellular level, it is usually used as synonym of ventilation, which refers to the movement of air between the environment and the lungs. This is also the case of this Section.

Monitoring respiration is interesting in several applications. The first and most sensitive indicator of many pulmonary diseases is usually respiratory rate (RR) [1], being of interest in in the context of acute respiratory dysfunction [2], chronic obstructive pulmonary disease (COPD) [3], and dynamic lung compliance [4], among others. RR has been also used in other contexts, including epileptic seizure detection [5], and stress level assessment [6]. A common basis of those applications is that they try to detect events that change the amount of body-demanded ventilation through changes in RR. However, ventilation can change also because of changes in tidal volume (TV), which remains the amount of air displaced in a respiratory cycle. Thus, these applications may benefit from adding information about TV. Actually, the product of RR and TV is an important marker known as minute ventilation in the clinics. The ideal respiratory monitor would unobtrusively provide continuous information on TV, RR, and the degree of gas exchange [7].

There are several algorithms available in the literature for deriving RR (number of breaths per unit of time) from the electrocardiogram (ECG) and/or the pulse photoplethysmogram (PPG) signals [8]. These are usually based on beat (or pulse, in case of PPG) occurrence and/or morphology [9]. During sinus rhythm, beat occurrence is modulated by breathing through the respiratory sinus arrhythmia, which consists of an increase of the heart rate during inspiration followed by a decrease during expiration [10]. Besides beat occurrence, breathing also modulates beat morphology through movement of the heart with respect to the electrodes and changes of the impedance related to the changes of the volume of air in the lungs. In addition, breathing-related changes of intrathoracic pressure and of arterial stiffness modulate the PPG pulse morphology [11]. Moreover, it is well known that one of the mechanisms for venous return is the negative intrathoracic pressure during inspiration, that attracts blood to the thorax, and this effect can be observed in the PPG signal as a modulation of its baseline.

The number of papers focused on deriving TV from ECG and/or PPG signals is quite limited. Variations in QRS area were studied in [12], and peak-to-peak changes in the direction of vectorcardiogram loops were studied in [13]. Moreover, root-mean-square-based measurement of QRS amplitude were used in [14] to estimate TV from mechanically ventilated Yorkshire swine. In another study [15], TV was estimated from ECG signals based on both heart rate and ECG-derived respiration (EDR) based on morphology during an exercise stress test. In a recent study, morphology-based EDR techniques were used in [16] for tracking TV using ECG signals recorded by a wearable device.

Current and Future Challenges

When speaking about wearable devices, one of the challenges is always the quality of the data. The quality of the data that is acquired by a wearable device depends on the sensor electronics and on

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the activity that the subject is doing. Moreover, most applications where a wearable monitoring is especially interesting are not supervised by experts, e.g., daily life monitoring. This makes that a relevant variable impacting on the acquired signals quality, is how properly the device is being worn.

The amount of accurate data that a wearable device provides is usually referred as coverage, and it also depends on the parameters that are being measured. For example, the quality of an ECG/PPG signal may be enough for beat/pulse detection while being not enough for measuring some beat/pulse morphological features accurately. The assessment of the coverage of a specific device on a specific parameter is crucial for considering the use of a device in a specific application. Thus, coverage is expected to be higher for those methods based on beat/pulse occurrence than for those methods based on beat/pulse morphology. However, methods based on beat/pulse occurrence are limited to subjects in sinus rhythm, while methods based on beat/pulse morphology can be used also with patients suffering of some kinds of arrhythmia, such as atrial fibrillation [17].

Another challenge often present when using wearable devices is the limited computational resources. It is usually desired that the algorithms run in real time while the device is desired to be small and to have a high autonomy, limiting the computational resources to be embedded in the system.

These issues above mentioned must be taken into account when selecting an algorithm for obtaining respiratory information from a wearable device, as well as the accuracy of the methods in different situations. As mentioned before, the number of methods for deriving RR from ECG and/or PPG signals available in the literature is much higher than the number of methods for deriving TV from such signals. While RR-monitoring methods are based on the frequency of the oscillations of features derived from ECG/PPG signals known to be affected by respiration-related modulations, TVmonitoring methods are usually based on the amplitude of those oscillations [16]. This represents an additional challenge for TV estimation, since the amplitudes can also change due to postural changes, or different breathing manners (abdominal or thoracic dominance).

Advances in Science and Technology to Meet Challenges

The needs regarding quality of data are two: automatically detecting low-quality segments to be discarded as information derived from them is not trustable and minimizing the number and/or length of those low-quality segments so increasing the coverage. The requirement of use simplicity of a wearable device has an impact on the provided quality, as they are typically used without expert supervision. This should be taken into account when designing a wearable device for a specific application. Furthermore, signal quality requirements depend on the target information to be extracted. Thus, the signal quality definitions should be adapted for each application.

On the other hand, several approaches can be followed for minimizing the number and/or length of low-quality segments. Redundancy in the sensors can be used together with fusion algorithms to improve the quality of the acquired signals. These fusion algorithms may include signal processing algorithms such as Kalman filtering (and its variants) and/or more recent artificial intelligence (AI) algorithms. Besides redundancy, the devices can include different sensors that allow a subsequent multimodal analysis, e.g., recording accelerometery provides information about device motion and position.

Algorithms for deriving RR from ECG and/or PPG, particularly for morphology-based methods, must be adapted for each sensor. E.g., an algorithm for deriving RR from PPG signal that has been validated with signals from a transmission finger sensor in lab-controlled environments (as most algorithms in the literature) may need adaptations for a reflection wrist sensor used during daily life.

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Also, ECG-based wearable devices usually acquire less and different leads than conventional electrocardiographs, making not possible the direct extension of all the available EDR techniques that have been validated with conventional ECG signals. Moreover, more studies are needed for tracking TV from the ECG and/or PPG, including derived respiration techniques, TV-related features, and fusion algorithms.

Fusion algorithms can also be used for combining different algorithms for deriving respiratory information from the ECG/PPG signals, increasing the accuracy of the estimations. This is particularly interesting during daily life monitoring, given the inherent highly non-stationarity environment that it represents. Some fusion algorithms have been applied to ECG/PPG for combining RR-monitoring methods, such as [18]. However, these algorithms should be adapted to the specific application. All this signal processing approaches have some computational cost, while the computational resources of the wearable devices are limited. A possible solution for this is to use cloud computing, which is a common solution nowadays and it is still becoming more common. However, it is desirable to minimize the amount of information to process or to transmit to the cloud. Thus, studies on minimizing sampling rate for each application are needed. Compression algorithms are also interesting for this purpose and, again, they should be adapted for each application in order not to remove relevant information.

Concluding Remarks

While there is a relatively high number of algorithms for deriving respiratory rate from ECG and/or PPG signals available in the literature, most of these algorithms cannot be considered validated for their use with wearable devices, due to the different nature of the signals (different and lower number of ECG leads, reflection PPG instead of transmission PPG at different body locations…). Studies for adaptation and validation with wearable devices are needed. The state of the art about tidal volume tracking with ECG and/or PPG signals is more limited. More studies are needed in order to assess the performance of tidal volume tracking from wearable devices. Studies focused on monitoring respiratory information from wearable devices should be conducted for each specific application (used sensor, required information, activity level of patients…), including the selection, adaptation, and validation of the deriving respiration technique, and maximizing and assessing the coverage on the target information.

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References

[1] B. Krieger, D. Feinerman, A. Zaron, and F. Bizousky, “Continuous noninvasive monitoring of respiratory rate in critically ill patients,” Chest, vol. 90, no. 5, pp. 632–634, Nov. 1986, doi: 10.1378/chest.90.5.632.

[2] T. R. Gravelyn and J. G. Weg, “Respiratory rate as an indicator of acute respiratory dysfunction,” JAMA, vol. 244, no. 10, pp. 1123–1125, Sep. 1980.

Accepted Manuscript

[3] H. J. Davies, P. Bachtiger, I. Williams, P. L. Molyneaux, N. S. Peters, and D. P. Mandic, "Wearable in-ear PPG: Detailed respiratory variations enable classification of COPD," IEEE Trans. Biomed. Eng., vol. 69, no. 7, pp. 2390–2400, Jul. 2022, doi: 10.1109/TBME.2022.3145688.

[4] H. Yamazaki and K. Fujimoto, "A new noninvasive method for measurement of dynamic lung compliance from fluctuations on photoplethysmography in respiration," J. Appl. Physiol., vol. 130, no. 1, pp. 215–225, Jan. 2021, doi: 10.1152/japplphysiol.00295.2020.

[5] C. Varon, K. Jansen, L. Lagae, and S. Van Huffel, "Can ECG monitoring identify seizures?" J. Electrocardiol., vol. 48, no. 6, pp. 1069–1074, 2015, doi: 10.1016/j.jelectrocard.2015.08.020.

[6] A. Hernando et al., "Inclusion of respiratory frequency information in heart rate variability analysis for stress assessment," IEEE J. Biomed. Health Inform., vol. 20, no. 4, pp. 1016–1025, Jul. 2016, doi: 10.1109/JBHI.2016.2553578.

[7] M. Folke, L. Cernerud, M. Ekström, and B. Hök, "Critical review of non-invasive respiratory monitoring in medical care," Med. Biol. Eng. Comput., vol. 41, no. 4, pp. 377–383, Jul. 2003, doi: 10.1007/BF02348078.

[8] P. H. Charlton et al., "Breathing rate estimation from the electrocardiogram and photoplethysmogram: A review," IEEE Rev. Biomed. Eng., vol. 11, pp. 2–20, 2018, doi: 10.1109/RBME.2017.2763681.

[9] P. H. Charlton et al., "The 2023 wearable photoplethysmography roadmap," Physiol. Meas., vol. 44, no. 11, p. 111001, Nov. 2023, doi: 10.1088/1361-6579/acead2.

[10] J. A. Hirsch and B. Bishop, "Respiratory sinus arrhythmia in humans: How breathing pattern modulates heart rate," Am. J. Physiol., vol. 241, no. 4, pp. H620–H629, Oct. 1981, doi: 10.1152/ajpheart.1981.241.4.H620.

[11] J. Lázaro, E. Gil, R. Bailón, A. Mincholé, and P. Laguna, "Deriving respiration from photoplethysmographic pulse width," Med. Biol. Eng. Comput., vol. 51, no. 1–2, pp. 233–242, Feb. 2013, doi: 10.1007/s11517-012-0954-0.

[12] G. Moody, R. Mark, A. Zoccola, and S. Mantero, "Derivation of respiratory signals from multi-lead ECGs," in Proc. Comput. Cardiol., 1985, pp. 113–116.

[13] M. Noshiro et al., "Indirect measurement of tidal volume by multi-lead electrocardiograms: Effect of filtering, deep breath, lead and posture," Front. Med. Biol. Eng., vol. 7, no. 3, pp. 207–219, 1996.

[14] O. Sayadi, E. H. Weiss, F. M. Merchant, D. Puppala, and A. A. Armoundas, "An optimized method for estimating the tidal volume from intracardiac or body surface electrocardiographic signals: Implications for estimating minute ventilation," Am. J. Physiol. Heart Circ. Physiol., vol. 307, no. 3, pp. H426–H436, Aug. 2014, doi: 10.1152/ajpheart.00038.2014.

[15] J. Milagro et al., "Electrocardiogram-derived tidal volume during treadmill stress test," IEEE Trans. Biomed. Eng., vol. 67, no. 1, pp. 193–202, Jan. 2020, doi: 10.1109/TBME.2019.2911351.

[16] J. Lázaro et al., "Tracking tidal volume from Holter and wearable armband electrocardiogram monitoring," IEEE J. Biomed. Health Inform., vol. 28, no. 6, pp. 3457–3465, Jun. 2024, doi: 10.1109/JBHI.2024.3383232.

[17] S. Kontaxis et al., "ECG-derived respiratory rate in atrial fibrillation," IEEE Trans. Biomed. Eng., vol. 67, no. 3, pp. 905–914, Mar. 2020, doi: 10.1109/TBME.2019.2923587.

[18] S. Khreis, D. Ge, H. A. Rahman, and G. Carrault, "Breathing rate estimation using Kalman smoother with electrocardiogram and photoplethysmogram," IEEE Trans. Biomed. Eng., vol. 67, no. 3, pp. 893–904, Mar. 2020, doi: 10.1109/TBME.2019.2923448.

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3.4 - Applications in Advancing Stroke Rehabilitation with Functional Electrical Stimulation and Wearable Technologies

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Status

Stroke is one of the leading causes of long-term adult disability worldwide, leaving nearly two-thirds of survivors with limited walking ability [1]. As a result, gait rehabilitation has become a primary goal in post-stroke care. Post-stroke hemiplegic gait, characterized by complex sensorimotor dysfunctions and compensatory motions [2], presents significant challenges to recovery. Therefore, developing innovative strategies to enhance walking ability is a critical priority in stroke rehabilitation research.

Conventional manual physical and occupational therapies, such as Bobath therapy, have been shown to effectively improve walking function in acute and subacute patients [3]. However, these manual training approaches, while effective, are resource-intensive, requiring significant time and personnel. To address these challenges, the field has embraced innovative technologies, such as robot-assisted training [3], transcranial current stimulation [4], and trans-spinal current stimulation [5]. While these therapies hold promise, they often necessitate specialized, costly equipment and expert administration. Balancing effectiveness with accessibility remains a crucial consideration in stroke rehabilitation.

Functional electrical stimulation (FES), also known as neuromuscular electrical stimulation (NMES), has been used for lower-limb interventions in stroke survivors for decades [6]. FES transmits control signals from an external device to stimulate the neuromuscular system, assisting or restoring motor functions. In clinical therapy, it has served as a therapeutic intervention for restoring neurological functions in post-stroke rehabilitation [7]. Despite its long-standing use, FES remains underutilized, primarily due to the limitations of single- or few-channel systems. Current personalization in clinical practice typically relies on therapist expertise to manually adjust stimulation parameters based on patient response and simple functional assessments conducted during limited therapy sessions. Enhancing the personalization of FES applications could significantly improve their effectiveness in rehabilitation.

To personalize any FES intervention, the sensorimotor functional status of the stroke survivor must first be reliably assessed. Current assessment methods are evolving towards a combination of traditional lab-confined techniques and continuous, ubiquitous recording through wearables [8]. The gold standard marker-based motion capture systems (e.g., VICON) and video-based motion capture

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technology, primarily used for indoor investigations due to spatial limitations, are now complemented by wearable electromyographic (EMG) sensors. These advancements provide comprehensive assessments of gait patterns and muscle activity in both controlled laboratory and unconstrained real-world settings [9]. Researchers have leveraged EMG data to optimize multi-channel FES parameters, enabling fine-tuning of stimulation protocols to more closely approximate natural motor control patterns. After FES parameter optimization, ongoing kinematic and EMG measurements assess rehabilitation progress. This integration of high-fidelity lab-based measurements with continuous, real-world data represents a significant advancement in stroke rehabilitation assessment, offering a more comprehensive understanding of intervention efficacy over time.

Current and Future Challenges

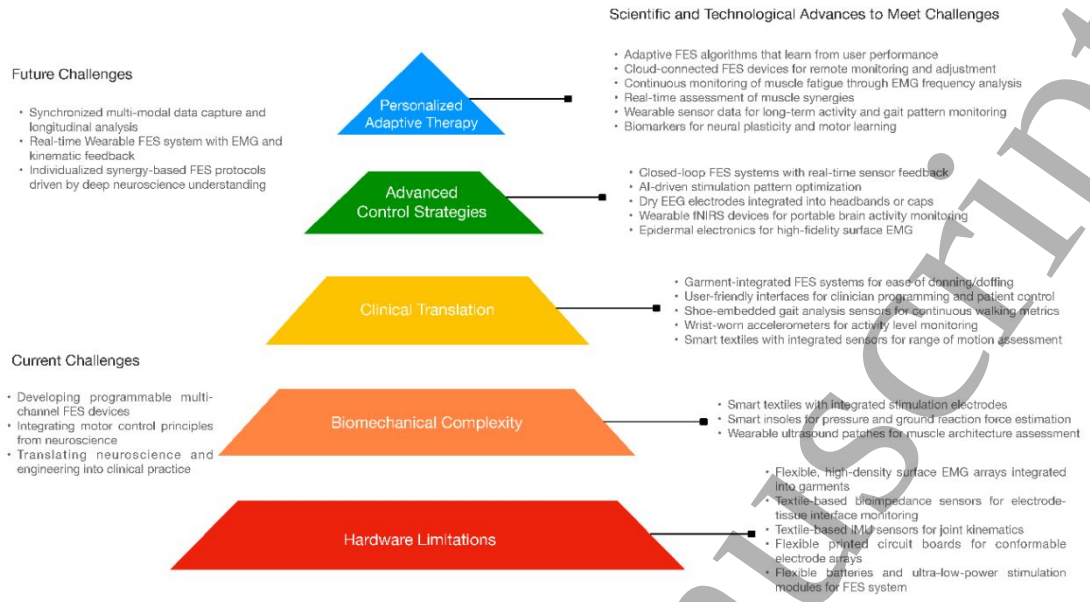
FES in stroke rehabilitation has evolved with the advent of wearable technologies. Single-channel stimulation of the tibialis anterior muscle, a sixty-year-old technique for preventing foot-drag, remains a common clinical practice despite its limitations in achieving natural gait patterns. While single-channel stimulation is functional, the resulting gait often appears unnatural, sparking debate over optimal FES application. In contrast, recent research has explored distributed wireless FES with real-time sensor feedback [19], but its performance is limited by its reliance on simplistic closed-loop proportional control systems that focus solely on engineering aspects, overlooking the underlying complexities of neuromuscular control. Key challenges include quantifying the effects of multi-channel FES on motor recovery and developing personalized approaches to optimize crucial parameters such as intervention timing, dosage, and control strategy based on individual patient characteristics and stroke specifics [10]. These challenges reflect a broader progression in FES development—from hardware and sensing constraints toward advanced control strategies and ultimately personalized, adaptive therapy enabled by wearable technologies, as summarized in **Figure 10**.

Addressing these challenges requires a neuroscientifically grounded approach for personalizing FES protocols based on the subject's functional and neuromotor control. As such, our current understanding of how the central nervous system activates groups of muscles synergistically (i.e., muscle synergies) during complex, multi-joint tasks [13] may provide insights into designing individually tailored FES waveforms. Efforts have been made to characterize lower-limb muscle synergies in neurologically intact individuals across different age groups [14, 15], as well as in subjects with various movement disorders, including stroke [16], Parkinson's disease [17], and spinal muscular atrophy [18]. It has been proposed that normative muscle synergies can serve as building blocks for FES waveform construction [8]. These scientific findings could enable more personalized interventions, potentially improving stroke rehabilitation strategies.

In parallel, FES technologies should advance to support coordinated stimulation of muscle groups during multi-joint tasks more effectively [8]. For example, FES garments under research aim to integrate comfortably with everyday clothing [11], allowing adaptability in diverse, time-varying, real-world environments for long-term use. Nonetheless, achieving a portable and comfortable FES system requires size reduction, which severely restricts battery capacity [12]. These hardware challenges demand innovative wearable solutions such as flexible batteries, smart textiles, and ultra-

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low-power stimulation circuits. In addition, advancements in software control algorithms will be crucial for optimizing stimulation parameters in response to changing user conditions and



environmental terrains. Together, these developments will enable the translation of FES from laboratory settings to community rehabilitation.

Advances in Science and Technology to Meet Challenges

Recent FES advancements aim to mimic natural motor patterns using multi-channel systems and advanced electrode arrays that provide precise spatial and temporal stimulation. Cheung *et al.* proposed coordinated stimulation of muscle groups for multi-joint tasks [8], consistent with modular neuromotor control theories. Furthermore, initial results from upper-limb rehabilitation in subacute stroke patients show promise for this neuroscientific approach [6].

Extending this approach to lower-limb rehabilitation, especially for chronic stroke patients, presents unique challenges due to complex biomechanics, weight-bearing considerations, and the need for intricate balance control during post-stroke gait. Biomechanical modelling is essential for enhancing the effectiveness of FES strategies. Additionally, wearable sensor systems enable continuous gait analysis and detailed muscle activation mapping in real-world environments. This shift from episodic to continuous assessment also requires a transition in control theory from open-loop, low-dimensional systems to adaptive strategies for closed-loop, high-dimensional, time-varying systems. High-density electrode arrays and advanced stimulation protocols facilitate more precise muscle

Figure 10. FES Advancements through wearable technologies from hardware to personalized therapy

activation patterns, while closed-loop control systems integrate real-time kinematic, kinetic, and EMG data for continuous parameter adjustment. Concurrently, machine learning algorithms, including reinforcement learning, can be explored to optimize stimulation patterns based on individual patient responses over extended periods [20]. The integration of control theory, machine learning, and wearable technology creates a robust feedback loop, allowing FES interventions to be refined after each step and optimizing rehabilitation strategies across multiple sessions. This

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advancement in personalized neurorehabilitation for lower-limb function enables interventions to evolve alongside patient progress, ultimately improving rehabilitation outcomes.

Importantly, FES rehabilitation is not only about refining stimulation patterns, but also about decoding and validating the neural basis of recovery. Advanced neuroimaging techniques are necessary to provide insights into the neural plasticity mechanisms at work as gait improves through FES intervention. Concurrently, smart textiles will enable the continuous, long-term collection of extensive bio-signal and kinematic data from stroke survivors, transforming everyday activities into ongoing rehabilitation that extends beyond indoor settings. This wealth of data can be leveraged to construct detailed computational models of individual patients' motor control and learning processes. Integrating these rich datasets with advanced machine learning techniques allows for mapping neural reorganization and behavioural recovery trajectories. This approach enables the development of predictive models that can anticipate patient outcomes and guide personalized FES strategies. Ultimately, this neuroscience-informed framework promises to create a more adaptive and effective rehabilitation approach, dynamically tailored to each patient's unique pattern of neural recovery and behavioural progression.

Concluding Remarks

FES has been underutilized due to the limitations of single- or few-channel systems. To harness its full benefits, FES is evolving into multi-channel systems that embody the principles of biological motor control and learning. Among various FES approaches, muscle synergy-based methods represent a promising direction by capturing modular motor control in multi-joint tasks. The efficacy of FES relies on accurate assessments, which are indispensable quantitative measures for improving rehabilitation outcomes. Consequently, closed-loop wearable FES systems that integrate real-time wearable EMG and kinematic feedback are expected to enhance recovery of lower-limb motor function. In addition, these systems may incorporate other neural measurements, such as wearable EEG, to further engage the neural plasticity of the human central nervous system. Looking ahead, future research may explore how these advanced FES paradigms can not only transcend rehabilitation but also improve motor capabilities in the aging population and reveal new insights into motor learning.

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References

[1] H. S. Jørgensen, H. Nakayama, H. O. Raaschou, and T. S. Olsen, “Recovery of walking function in stroke patients: The Copenhagen Stroke Study,” Arch. Phys. Med. Rehabil., vol. 76, no. 1, pp. 27–32, 1995.

[2] T. Krasovsky and M. F. Levin, “Toward a better understanding of coordination in healthy and poststroke gait,” Neurorehabil. Neural Repair, vol. 24, no. 3, pp. 213–224, 2010.

Accepted Manuscript

[3] J.-E. Cho, J. S. Yoo, K. E. Kim, S. T. Cho, W. S. Jang, K. H. Cho, W.-H. Lee, et al., "Systematic review of appropriate robotic intervention for gait function in subacute stroke patients," Biomed. Res. Int., vol. 2018, Art. no. 4085298, 2018.

[4] G. Schlaug, V. Renga, and D. Nair, "Transcranial direct current stimulation in stroke recovery," Arch. Neurol., vol. 65, no. 12, pp. 1571–1576, 2008.

[5] M. A. Nitsche and W. Paulus, "Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation," J. Physiol., vol. 527, no. 3, pp. 633–639, 2000.

[6] R. Merletti, F. Zelaschi, D. Latella, M. Galli, S. Angeli, and M. B. Sessa, "A control study of muscle force recovery in hemiparetic patients during treatment with functional electrical stimulation," Scand. J. Rehabil. Med., vol. 10, no. 3, pp. 147–154, 1978.

[7] T. Yan, C. W. Hui-Chan, and L. S. Li, "Functional electrical stimulation improves motor recovery of the lower extremity and walking ability of subjects with first acute stroke: A randomized placebo-controlled trial," Stroke, vol. 36, no. 1, pp. 80–85, 2005.

[8] V. C. Cheung, C. M. Niu, S. Li, Q. Xie, and N. Lan, "A novel FES strategy for post-stroke rehabilitation based on the natural organization of neuromuscular control," IEEE Rev. Biomed. Eng., vol. 12, pp. 154–167, 2019.

[9] A. Mathis, P. Mamidanna, K. M. Cury, et al., "DeepLabCut: Markerless pose estimation of user-defined body parts with deep learning," Nat. Neurosci., vol. 21, no. 9, pp. 1281–1289, 2018.

[10] G. Alon, A. F. Levitt, and P. A. McCarthy, "Functional electrical stimulation enhancement of upper extremity functional recovery during stroke rehabilitation: A pilot study," Neurorehabil. Neural Repair, vol. 21, no. 3, pp. 207–215, 2007.

[11] B. Moineau, C. Marquez-Chin, M. Alizadeh-Meghrazi, et al., "Garments for functional electrical stimulation: Design and proofs of concept," J. Rehabil. Assist. Technol. Eng., vol. 6, p. 2055668319854340, 2019.

[12] M. M. Rodgers, G. Alon, V. M. Pai, et al., "Wearable technologies for active living and rehabilitation: Current research challenges and future opportunities," J. Rehabil. Assist. Technol. Eng., vol. 6, p. 2055668319839607, 2019.

[13] A. d'Avella, A. Portone, L. Fernandez, and F. Lacquaniti, "Control of fast-reaching movements by muscle synergy combinations," J. Neurosci., vol. 26, no. 30, pp. 7791–7810, 2006.

[14] X. Guo, B. He, K. Y. S. Lau, et al., "Age-related modifications of muscle synergies and their temporal activations for overground walking," IEEE Trans. Neural Syst. Rehabil. Eng., vol. 30, pp. 2700–2709, 2022.

[15] R. J. Baggen, J. H. van Dieën, E. Van Roie, S. M. Verschueren, G. Giarmatzis, C. Delecluse, and N. Dominici, "Age-related differences in muscle synergy organization during step ascent at different heights and directions," Appl. Sci., vol. 10, no. 6, p. 1987, 2020.

[16] V. C. Cheung, L. Piron, M. Agostini, et al., "Stability of muscle synergies for voluntary actions after cortical stroke in humans," Proc. Natl. Acad. Sci. U.S.A., vol. 106, no. 46, pp. 19563–19568, 2009.

[17] M. Ghislieri, M. Lanotte, M. Knaflitz, et al., "Muscle synergies in Parkinson's disease before and after deep brain stimulation of the bilateral subthalamic nucleus," Sci. Rep., vol. 13, no. 1, p. 6997, 2023.

[18] V. C. Cheung, S. C. W. Ha, J. H. Zhang-Lea, et al., "Motor patterns of patients with spinal muscular atrophy suggestive of sensory and corticospinal contributions to the development of locomotor muscle synergies," J. Neurophysiol., vol. 131, no. 2, pp. 338–359, 2024.

Accepted Manuscript

[19] D. Andreu, B. Sijobert, M. Toussaint, et al., "Wireless electrical stimulators and sensors network for closed-loop control in rehabilitation," Front. Neurosci., vol. 14, p. 117, 2020.
[20] A. Coronato, M. Naeem, G. De Pietro, et al., "Reinforcement learning for intelligent healthcare applications: A survey," Artif. Intell. Med., vol. 109, p. 101964, 2020.

3.5 - Innovations in Textile-Based Wearable Diagnostics for Personalized Healthcare

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Status

The field of wearable health monitors and diagnostic tools has seen significant growth in recent years, marking a transformative period in healthcare technology [1]. This surge is particularly notable in the cancer detection and monitoring critical health parameters [2].

Traditional screening methods are being refined for better efficiency and accessibility [3]. Simultaneously, there is a shift towards developing novel, non-invasive wearable devices [4]. These new technologies aim to supplement them, not replace the existing methods, making preliminary health screenings more accessible to diverse populations [5].

Wearable health monitors are evolving from standalone devices to integrated, textile-based systems. These systems can track a wide range of health parameters, including heart rate, blood glucose levels, pulse, and respiratory rate [6], [7]. Integration these capabilities into comfortable, wearable formats allows for seamless daily health monitoring. This evolution reflects broader advances in device integration strategies, ranging from on-skin and non-planar electronics to fully textile-integrated and structurally embedded systems, as illustrated in **Figure 11**.

A key advantage of these wearable technologies is their ability to provide continuous monitoring. This facilitates early detection of anomalies in vital signs and enables timely intervention by healthcare providers [8]. In addition, the Internet connectivity of these devices opens new possibilities for telemedicine and remote patient monitoring, applicable in various settings from home care to intensive care units [9].

The potential impact of these technologies extends beyond monitoring. They are poised to play an important role in advancing personalised medicine and preventive healthcare. For example, wearable sensors could autonomously regulate drug delivery based on real-time physiological data [10]. In preventive care, these devices could detect early diseases indicators, such as glucose levels fluctuations in diabetic patients, preventing potential complications [11]. Representative examples of fully integrated, non-invasive wearable diagnostic systems—such as electrochemical biosensors

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for biofluid analysis—demonstrate the feasibility of continuous biochemical monitoring in wearable formats (**Figure 12**).

Wearable health monitors and diagnostic tools are poised to revolutionise healthcare. These devices have the potential to transform how we manage our health and prevent diseases, offering exciting possibilities from early disease detection to personalised treatment plans.

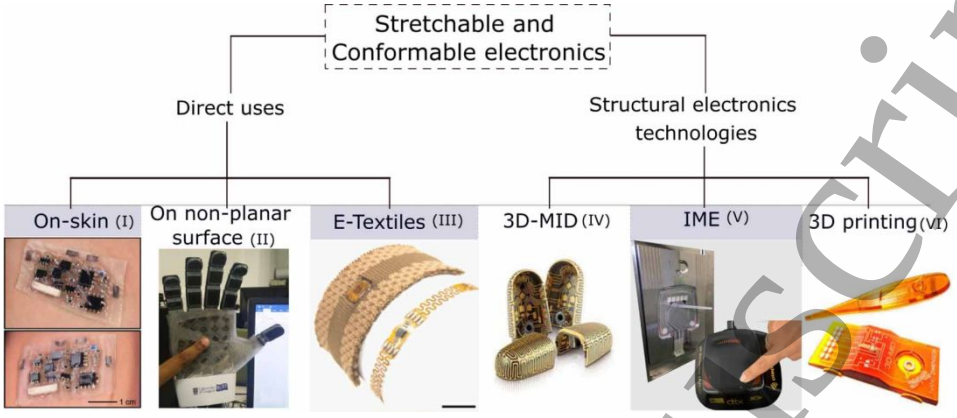


Figure 11. Device integration. (I) On-skin electronics (e-skin device). **(II)** Nanowire FET pressure sensing array on a robotic hand. Flexible and stretchable electronics embedded on textile for vital signs monitoring (e-textile). Laser direct structuring of 3D-Molded interconnect devices (3D-MID). **(V)** In-mold electronics (IME) demonstrator developed in the framework of the Molded Electronics project by DTx, Celoplás, Bosch, PIEP, Minho University, Simoldes and INL consortium. **(VI)** 3D printed embedded electronic devices created by Nanodimension® LDM™ technology. Figure 11 Adapted from [11].

Current and Future Challenges

The promising field of wearable health monitors and diagnostic tools presents several critical challenges that must be addressed to fully harness their full potential in healthcare. A primary issue is the limited diagnostic performance of current technologies. For example, numerous studies on wearable cancer detection devices rely on small patient cohorts or artificial models, which may not accurately represent the diverse tissue compositions and tumor characteristics found in real-world populations [12]. This lack of comprehensive clinical data impedes the development of reliable diagnostic algorithms.

The psychological impact of continuous health monitoring on users remains largely unexplored. There is particular concern regarding the stress induced by false positives, which could lead to unnecessary anxiety and medical interventions [3]. From a technical perspective, the durability and washability of wearable monitors present pose substantial challenges, particularly for textile-based devices [13].

Noise interference is another significant challenge, as these monitors are susceptible to mechanical and environmental disturbances that can compromise reading accuracy [14]. Ensuring comfort and flexibility for long-term wear necessitates advancements in materials science and design engineering. Power supply remains a critical issue, requiring innovative solutions such as long-lasting batteries or energy-harvesting technologies [15].

Ensuring the accuracy of collected data and developing reliable interpretation methods are ongoing challenges. As these devices generate vast amounts of health data, creating robust algorithms for analysis and interpretation is crucial for effective clinical decision-making.

Finally, validation against gold standards presents significant challenges, particularly when these standards are either unavailable or unreliable. For example, the gold standard for measuring

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respiration—manual counting—is highly subjective and less reliable due to its dependence on the healthcare professional's accuracy. Discrepancies between the algorithms of two wearables measuring the same physiological parameter further complicate validation, as they may yield different outcomes that are difficult to compare. In addition, the lack of a clearly defined acceptable variability from the gold standard complicates the assessment of wearables' accuracy for clinical use.

Addressing these challenges will necessitate interdisciplinary collaboration among engineers, clinicians, data scientists, and human factors experts. Overcoming these hurdles is essential to unlocking the full potential of wearable health monitors and diagnostic tools, thereby revolutionising healthcare delivery and improving patient outcomes.

Advances in Science and Technology to Meet Challenges

Recent advancements in science and technology are addressing many of the challenges faced by wearable health monitors and diagnostic tools. Significant progress has been made in sensor technology, with improvements in spatial resolution and sensitivity such as enabling the detection of tumors as small as 5 to 9mm in diameter [16]. This enhanced capability represents a substantial advancement in early disease detection.

In the realm of data processing, evolving machine learning algorithms are revolutionising the interpretation of complex biosignals (e.g. biopotential). These algorithms are becoming increasingly proficient at distinguishing between benign and malignant growths, thereby enhancing diagnostic accuracy [17]. Furthermore, researchers are exploring multi-modal sensing approaches, such as combining thermal imaging with bioimpedance measurements, to reduce false positives and enhance overall diagnostic precision [18].

To address the challenges of comfort and durability, innovative manufacturing techniques are being developed. These include laminating sensors onto textiles, employing encapsulation techniques, and utilising water-resistant materials. The integration of flexible electronics and conductive threads into garments is also showing promise in creating more comfortable and washable wearable devices [19], [20].

Energy supply concerns are being tackled through advancements in power management and energy harvesting. For instance, researchers have developed a stretchable, wearable hybrid supercapacitor-biofuel cell system that can scavenge biochemical energy from sweat [21]. This technology offers a potential solution for sustainable power in wearable electronics.

In the field of smart textiles, materials combining coaxial fibres and piezoelectric polymers are demonstrating enhanced comfort and functionality. These materials offer flexibility, breathability, and mechanical stability, making them suitable for long-term wear in healthcare applications. Importantly, some of these materials maintain or even improve their voltage generation capabilities after washing, addressing the crucial issue of durability [3].

As we move towards more personalised medicine, researchers are working on textiles capable of not only monitoring but also adjusting treatments in real-time based on a patient's physiological data [22]. This development represents a significant step towards truly adaptive and personalized healthcare solutions.

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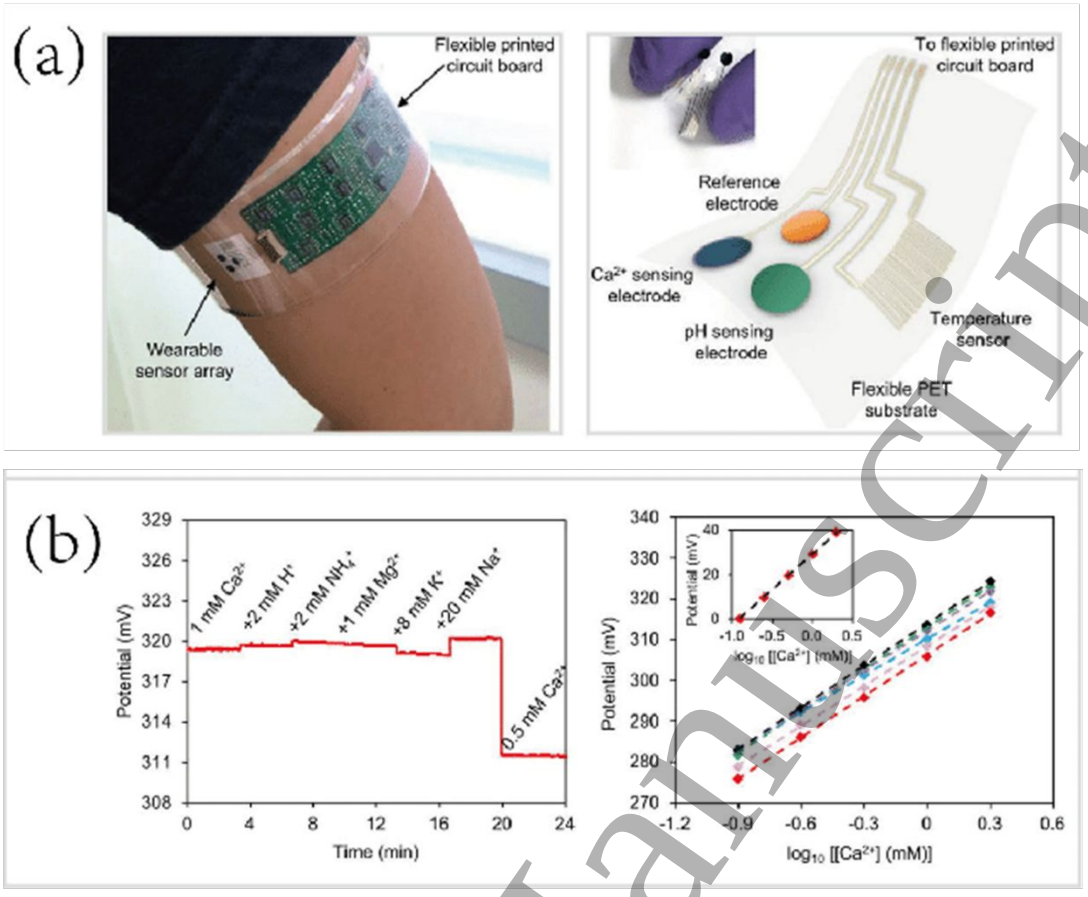


Figure 12. A fully integrated electrochemical biosensor for non-invasive in situ analysis of biofluids. (a) An image and a schematic illustration of a fully integrated potentiometric biosensor, consisting of Ca 2+, pH, and temperature sensors patterned on PET substrate **(b)** Performance test results of Ca 2+ sensors: ion-selectivity and reproducibility (n = 6). Copyright 2016, American Chemical Society [23].

Concluding Remarks

Wearable health monitors and diagnostic tools are poised to revolutionize healthcare. These devices offer the potential for continuous health tracking, early disease detection, and the development of personalized treatment plans. However, to fully leverage their capabilities, it is essential to address the technical, medical, and ethical challenges associated with their clinical implementation.

Beyond the technological advancements, it is crucial to consider the human factors involved in adopting these devices. User acceptance, data privacy, and the potential for health anxiety are critical considerations that warrant further research. Additionally, integrating wearable health monitors with existing healthcare infrastructure presents both opportunities and challenges that must be navigated.

Looking ahead, the continued evolution of wearable health technologies will likely lead to more sophisticated, multi-functional devices capable of providing comprehensive health insights. Realizing this potential will require ongoing interdisciplinary collaboration among engineers, clinicians, data scientists, and ethicists. By overcoming current challenges and capitalizing on emerging opportunities, wearable health devices could play a pivotal role in advancing personalized and preventive healthcare.

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References

[1] T. O. Tobore, "On the need for the development of a cancer early detection, diagnostic, prognosis, and treatment response system," Future Sci. OA, vol. 6, no. 2, p. FSO439, Feb. 2020, doi: 10.2144/fsoa-2019-0028.

[2] S. Hussain et al., "Modern diagnostic imaging technique applications and risk factors in the medical field: A review," Biomed. Res. Int., vol. 2022, p. 5164970, 2022, doi: 10.1155/2022/5164970.

[3] T. A. Karthikeyan, M. Nesasudha, S. Saranya, and B. Sharmila, "A review on fabrication and simulation methods of flexible wearable antenna for industrial tumor detection systems," J. Ind. Inf. Integr., vol. 41, p. 100673, Sep. 2024, doi: 10.1016/j.jii.2024.100673.

[4] Z. Alizadeh, C. Rohani, M. Rassouli, M. Ilkhani, and M. Hazrati, "Bridging the gap and developing a home-based palliative care model for cancer patients," Asia-Pac. J. Oncol. Nurs., p. 100583, Sep. 2024, doi: 10.1016/j.apjon.2024.100583.

[5] K. Guk et al., "Evolution of wearable devices with real-time disease monitoring for personalized healthcare," Nanomaterials, vol. 9, no. 6, p. 813, Jun. 2019, doi: 10.3390/nano9060813.

[6] A. Prabha, J. Yadav, A. Rani, and V. Singh, "Intelligent estimation of blood glucose level using wristband PPG signal and physiological parameters," Biomed. Signal Process. Control, vol. 78, p. 103876, Sep. 2022, doi: 10.1016/j.bspc.2022.103876.

[7] N. Hayward et al., "A capaciflector provides continuous and accurate respiratory rate monitoring for patients at rest and during exercise," J. Clin. Monit. Comput., vol. 36, no. 5, pp. 1535–1546, Oct. 2022, doi: 10.1007/s10877-021-00798-7.

[8] D. Dias and J. P. S. Cunha, "Wearable health devices—Vital sign monitoring, systems and technologies," Sensors, vol. 18, no. 8, p. 2414, Aug. 2018, doi: 10.3390/s18082414.

[9] M. J. Field and J. Grigsby, "Telemedicine and remote patient monitoring," JAMA, vol. 288, no. 4, pp. 423–425, Jul. 2002, doi: 10.1001/jama.288.4.423.

[10] J. Manikkath and J. A. Subramony, "Toward closed-loop drug delivery: Integrating wearable technologies with transdermal drug delivery systems," Adv. Drug Deliv. Rev., vol. 179, p. 113997, Dec. 2021, doi: 10.1016/j.addr.2021.113997.

[11] K. Dziergowska, M. B. Łabowska, M. Gąsior-Głogowska, B. Kmiecik, and J. Detyna, "Modern noninvasive methods for monitoring glucose levels in patients: A review," Bio-Algorithms Med.-Syst., vol. 15, no. 4, Dec. 2019, doi: 10.1515/bams-2019-0052.

Accepted Manuscript

[12] M. Särestöniemi, D. Singh, R. Dessai, C. Heredia, S. Myllymäki, and T. Myllylä, "Realistic 3D phantoms for validation of microwave sensing in health monitoring applications," Sensors, vol. 24, no. 6, p. 1975, Jan. 2024, doi: 10.3390/s24061975.

[13] M. L. R. Liman, M. T. Islam, and M. M. Hossain, "Mapping the progress in flexible electrodes for wearable electronic textiles: Materials, durability, and applications," Adv. Electron. Mater., vol. 8, no. 1, p. 2100578, Jan. 2022, doi: 10.1002/aelm.202100578.

[14] R. Ramadhan and I. A. Akbar, "Exploration of factors influencing noise detection on health wearable devices during hand motion artifacts," in Proc. Int. Semin. Intell. Technol. Appl. (ISITIA), Jul. 2024, pp. 349–354, doi: 10.1109/ISITIA63062.2024.10668366.

[15] M. Dargusch, W.-D. Liu, and Z.-G. Chen, "Thermoelectric generators: Alternative power supply for wearable electrocardiographic systems," Adv. Sci., vol. 7, no. 18, p. 2001362, 2020, doi: 10.1002/advs.202001362.

[16] M. Ghamati, M. Taherzadeh, F. Nabki, and M. Popović, "Integrated fast UWB time-domain microwave breast screening," IEEE Trans. Instrum. Meas., vol. 72, pp. 1–12, 2023, doi: 10.1109/TIM.2023.3328068.

[17] S. Kadian, P. Kumari, S. Shukla, and R. Narayan, "Recent advancements in machine learning-enabled portable and wearable biosensors," Talanta Open, vol. 8, p. 100267, Dec. 2023, doi: 10.1016/j.talo.2023.100267.

[18] M.-V. Moreno and E. Herrera, "Evaluation on phantoms of the feasibility of a smart bra to detect breast cancer in young adults," Sensors, vol. 19, no. 24, p. 5491, Jan. 2019, doi: 10.3390/s19245491.

[19] J. Stanley, P. Kunovski, J. A. Hunt, and Y. Wei, "Stretchable electronic strips for electronic textiles enabled by 3D helical structure," Sci. Rep., vol. 14, no. 1, p. 11065, May 2024, doi: 10.1038/s41598-024-61406-7.

[20] M.-N. Nashed, D. A. Hardy, T. Hughes-Riley, and T. Dias, "A novel method for embedding semiconductor dies within textile yarn to create electronic textiles," Fibers, vol. 7, no. 2, p. 12, Feb. 2019, doi: 10.3390/fib7020012.

[21] J. Lv et al., "Sweat-based wearable energy harvesting–storage hybrid textile devices," Energy Environ. Sci., vol. 11, no. 12, pp. 3431–3442, 2018, doi: 10.1039/C8EE02792G.

[22] Y. ElSaboni, J. A. Hunt, J. Stanley, C. Moffatt, and Y. Wei, "Development of a textile-based protein sensor for monitoring the healing progress of a wound," Sci. Rep., vol. 12, no. 1, p. 8780, May 2022, doi: 10.1038/s41598-022-11982-3.

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Section 4: Applications in Fitness and Lifestyle

4.1 - Wearable fitness trackers and performance monitors

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Status

Fitness trackers have become integral companions in our quest to monitor health, transforming how we keep information on our well-being. The first example of a fitness tracker was designed in 1780 when Swiss watchmaker Abraham-Louis Perrelet crafted an early version of the pedometer [1]. Fast forward to the 1960s, Dr. Yoshiro Hatano, concerned about the health of the Japanese population, created a novel version of a wearable pedometer aiming to address rising obesity rates [2].
Modern fitness trackers are far more advanced than their predecessors. Designed to monitor various aspects of health and activity, these devices provide valuable insights into body movement activities and help improve the user's overall fitness. They can take various forms, from wristbands to rings and even insoles, and fit comfortably on different body parts (see **Figure 13**).

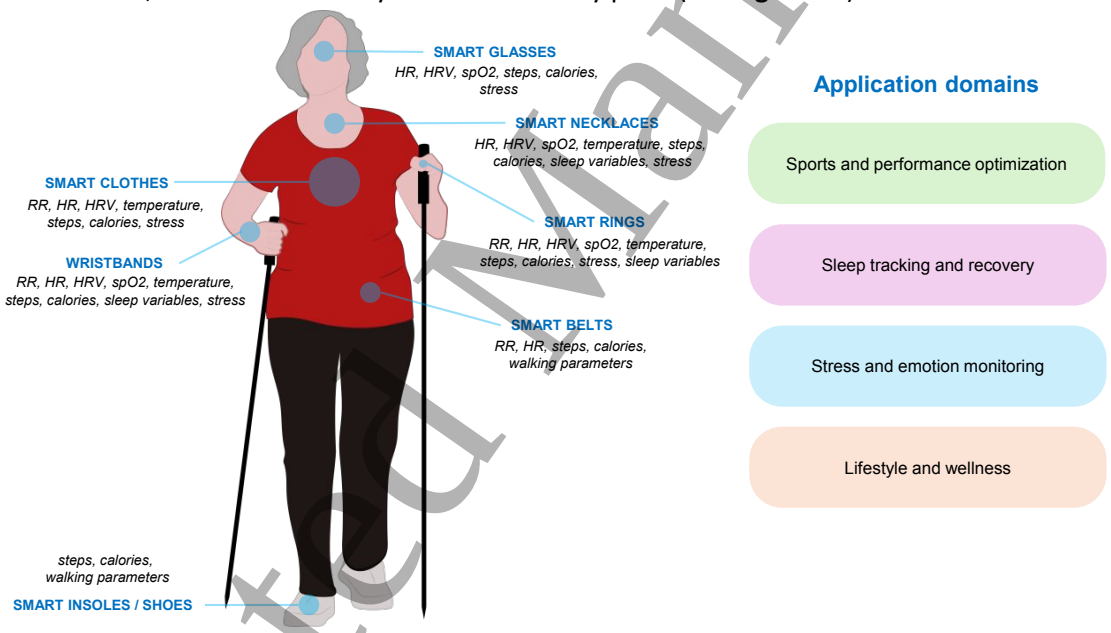


Figure 13. Measurable or estimated parameters on the human body and their detection methods, categorized by body region and the physiological systems to which the signals pertain and main application domains.

Modern trackers integrate multiple sensing modalities (e.g., accelerometers, optical sensors, occasionally electrodes and temperature sensors) and advanced signal processing, providing continuous measurements of physical activity, heart rate (HR), heart rate variability (HRV), sleep, and “readiness” or “recovery” [3], [4], [5], [6], [7], [8], [9]. As a result, these systems are no longer used only to track basic activity levels but to support broader goals related to health, performance, and well-being.

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From an application perspective, four main domains can be identified: (i) sports and performance optimization, (ii) sleep tracking and recovery, (iii) stress and emotion monitoring, and (iv) lifestyle and wellness. In the following, we summarize representative use cases and quantitative outcomes in each domain, emphasizing how technological capabilities translate into measurable benefits for users.

In sports and performance optimization, wearable fitness trackers are primarily used to guide exercise prescription and prevent overtraining. Key physiological metrics in sport performance include heart rate (HR), heart rate variability (HRV), energy expenditure, and maximal oxygen uptake (VO_2max). Commercial wearables like Apple Watch, Fitbit, Garmin, Whoop, and others claim to track these. At rest and light exercise, wrist wearables generally track HR well (mean absolute error often <2 bpm; MAPE <10%) [10]. A validation in young and older adults found that Garmin wrist band had MAPE in the range 3.8%-4.7% and a Xiaomi band 6.0-7.7%, with high concordance (0.80–0.92) against a Polar ECG chest strap [11]. During moderate treadmill running, devices like Apple Watch Series 3 and Fitbit Ionic showed excellent agreement with ECG (Lin's concordance 0.93–0.96), with trivial bias (Apple Watch mean bias +0.5 bpm) and tight limits of agreement (±5 bpm) [11], [12].
Energy expenditure estimates typically rely on proprietary algorithms (often combining HR, motion, and user profile data) and frequently exhibit larger errors than HR estimates. Systematic reviews indicate that no current brand consistently stays within ±3% of true energy expenditure for most activities [13]. Fitness trackers tend to underestimate calories at lower intensities and overestimate at higher intensities; typical errors on exercise energy expenditure are on the order of 20%-30% or more [10].

Some watches (e.g., Garmin, Apple) estimate VO_2max from user data and exercise metrics. Validation studies show moderate agreement but notable errors. A 2024 lab study of Apple Watch Series 7 found the watch's VO_2max estimates were significantly lower than laboratory VO_2max (mean 41.4 mL/kg/min vs 45.9 mL/kg/min, 10% underestimation), with estimates tending to overestimate VO_2max for low-fit individuals and underestimate for very fit individuals, a pattern also noted for other brands [14].

In sleep tracking and recovery, consumer wearables typically combine accelerometer signals with HR/HRV features to estimate sleep–wake patterns, sleep duration, and, in some cases, sleep stages. Gold standard sleep measurement is laboratory polysomnography (PSG). Validations, therefore, compare wearables to PSG (often also against clinical-grade actigraphy for context). Recent studies have tested popular devices for sleep staging and duration. A 2021 evaluation of seven consumer sleep trackers (including Apple Watch, Oura Ring, Fitbit, Garmin, and others) showed that they detect overall sleep versus wake fairly well, with approximately 86%–94% agreement with PSG for classifying epochs as "sleep" or "wake" [11].

Regarding the sleep stage classification, accuracy drops markedly. Deep and REM sleep in particular are. One device (Garmin) misclassified 61% of true deep sleep (N3) as lighter stages, and REM is commonly misclassified as light sleep or wake by many wearables [11]. The Oura Ring showed the highest agreement with PSG on sleep stage proportions in some studies (owing to using HRV and other signals in addition to motion) [15].
Fitness wearables often provide a "recovery" or "readiness" score each morning, which is largely based on nocturnal HRV, resting HR, and sleep quality. For this reason, the devices are typically tested for HRV estimation accuracy against an ECG device. The majority of wearables' HRV correlates well with ECG, with Apple Watch underestimating HRV (RMSSD) by an average of 9.6 ms, with absolute bias of 22.5 ms, and intraclass correlation of 0.67 [11]. Overall, most devices showed a tendency to underestimate absolute HRV (e.g., lower SDNN or rMSSD values than ECG) but with small biases, except at higher HRV ranges where some proportional bias appeared.

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Recent advances in AI-driven analytics and large language models (LLMs) are beginning to reshape how sleep-related signals from wearables are interpreted and translated into personalised guidance. A prominent example is the use of personal health large language models for sleep and fitness coaching capable of integrating multi-night wearable data, behavioural patterns, and contextual user information to deliver tailored recommendations and adaptive feedback loops [16] .

In the domain of stress and emotion monitoring, fitness trackers promise to monitor stress by sensing physiological proxies of emotional arousal. Key parameters here are heart rate variability (HRV) (lower HRV is associated with higher stress via autonomic activation) and sometimes electrodermal activity (EDA) or skin conductance (which rises with sweat gland activity during stress). A few devices incorporate these: e.g., Fitbit's Sense/Charge 5 have an EDA palm sensor, Garmin and Apple use HRV-derived "stress scores", etc. Gold standard stress measures can be psychological questionnaires, cortisol levels, or lab stress test protocols. In real-world settings the correlation between wearable metrics and perceived stress is weak. A large 2022 study tracked 657 workers over 8 weeks, with participants wearing a popular fitness tracker and reporting their stress levels multiple times a day [17]. Even the best-performing HRV measures (e.g., low-frequency/high-frequency power ratio) gave marginal predictive value for momentary stress levels. As for device-specific stress scores, Garmin's and others compute a stress index (often scaled 0–100) from HRV short-term fluctuations. Independent validation of these scores is sparse. One recent analysis found Garmin's stress score correlated with HRV from ECG in lab tests [18]. Emotion recognition beyond generic "stress" (e.g., detecting happiness, sadness) is outside the scope of most fitness trackers. Some research-grade wearables (e.g., Empatica E4) combine signals to classify stress vs calm with 80–90% accuracy in lab settings [19], but those results degrade in daily life.

Finally, in the lifestyle and wellness domain, wearable trackers are employed to promote physical activity, reduce sedentary behaviour, and support long-term adherence to healthy habits in both healthy individuals and people living with chronic conditions. This domain includes everyday health metrics such as daily step count, distance, floors climbed, resting heart rate, blood oxygen saturation (SpO_2), and even blood pressure in newer devices. Wearables are generally quite accurate in counting steps in typical free-living conditions. Multiple validation studies (2015–2020) found that numerous commercially available devices tend to be within 5% of actual steps for ambulatory adults under normal walking speeds [20]. Overall, daily step totals from modern trackers correlate very strongly with manual step counts or research-grade pedometers (often $r>0.95$). In clinical populations or older adults with irregular gait, errors can be larger, but devices like Fitbit and Actigraph still showed good agreement in many studies (within 5% in hospital settings for most patients). Thus, for general activity monitoring and step-count goals, commercial trackers are considered sufficiently valid [10].

Many recent wearables (Apple Watch Series 6/7+, Garmin, Fitbit Sense/Charge, Withings, etc.) include pulse oximetry sensors. Validation against medical-grade finger pulse oximeters shows mixed but promising results. In general, devices also show high accuracy in normoxia (within 2–3%), but reduced accuracy in hypoxia (sometimes missing readings or showing bigger deviations) [21]. Overall, wearable SpO_2 is suitable for wellness (spot-checking oxygen during sleep or altitude), and studies conclude devices like Apple Watch do not differ significantly from medical pulse-oximeters under stable conditions [22].

Blood pressure tracking is the new frontier for fitness trackers. Traditional cuffs are gold standard (auscultatory or oscillometric). A few wrist-worn devices have achieved validation: the Omron HeartGuide is FDA-approved and meets the ISO standard, with mean differences under 5 mmHg from a standard cuff in clinical testing. However, it requires the user to sit and press a button to inflate the strap. Newer approaches use pulse wave analysis via PPG sensors. For instance, Aktiia is a cuffless optical bracelet that earned CE certification in Europe. In a controlled trial, Aktiia met

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accuracy requirements in a seated resting position (comparable to standard cuff BP) [23]. However, studies have found that its readings can drift or become unreliable during daily activities and non-sitting postures [24].

Despite the growing popularity of fitness trackers, focusing on their primary goal is essential: helping users optimize their health, wellness, and even aspects of medical care. However, it is crucial to understand that these devices typically estimate health and wellness variables rather than providing medical-grade insights. Many users, especially those with specific health conditions, may have difficulty distinguishing between these two types of data (i.e., measured and estimated) and understanding the limitations of their fitness devices, especially related to some physiological variables (i.e., blood pressure). Regarding physical activity, even if counted steps may not be considered a direct medical use of fitness tracker technologies, monitoring health and wellness data can have indirect benefits. In one retrospective analysis of a six-month weight loss study using Fitbit monitors, participants who took more steps per day and engaged in at least 60 minutes of high-intensity exercise experienced significant weight loss. Interestingly, overweight and obese individuals in the study saw more significant improvements when they used these devices to track their daily steps and exercise intensity [25]. So, by enabling users to monitor their health goals, fitness trackers may contribute to improved overall well-being, potentially leading to positive health outcomes.

Current and Future Challenges

Despite the progress, wearable fitness trackers and performance monitors face several significant challenges that must be addressed to realize their full potential.

One of the primary issues is the accuracy and reliability of the data collected. Some variables retrieved from fitness trackers are measured as the number of steps, heart rate, spO2, and skin temperature. In this case, an established measurement method for that specific parameter requires a sensor designed for the task. For example, heart rate monitoring in wrist-worn fitness trackers typically relies on photoplethysmography (PPG) sensors, which are widely recognized for their ability to detect blood volume changes through light absorption [26]. Similarly, SpO2 levels are measured using pulse oximetry, which calculates blood oxygen saturation based on the differential absorption of red and infrared light by oxygenated and deoxygenated haemoglobin [27].

Conversely, other relevant physiological variables are still not robustly captured by consumer wearables. A notable example is respiratory rate (RR), which represents a fundamental vital sign with strong clinical significance[28]: changes in RR are among the earliest indicators of physiological deterioration, respiratory distress, and metabolic imbalance in clinical settings [29], and several studies have demonstrated that RR abnormalities can be predictive not only of impending clinical deterioration in patients, but also of excessive cardiorespiratory strain in occupational scenarios (e.g., workers exposed to high physical and thermal loads [30]) and of inadequate recovery or overreaching in athletes and physically active individuals [31]. Despite this importance, RR is rarely provided as a primary output in fitness trackers. This limits its interpretability and reduces its potential usefulness for detecting early signs of fatigue, cardiorespiratory stress, or changes in recovery status during real-world activities.

Other variables provided by fitness trackers are not measured but estimated. Estimations vary in complexity, ranging from well-established methods as the one used to calculate the maximal heart rate with Fox & Haskell, Tanaka, and Gellish formulas considering age-based calculation [32], to more complicated estimations as the one used to estimate blood pressure or sleep stages based on

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heart rate variability, movement, temperature and circadian features with machine learning algorithms and sensor fusion techniques [11]. To obtain a truly accurate measurement of sleep stages, it requires monitoring more detailed physiological signals, such as brain waves (EEG), eye movement (EOG), and muscle activity (EMG), which are captured through polysomnography (PSG) in sleep labs. Wearable devices worn on the wrist or finger offer estimates of sleep stages but cannot track these critical variables directly. Instead, they rely on surrogate markers like heart rate variability, movement, and sometimes skin temperature to infer sleep stages, which may introduce some inaccuracies, especially when distinguishing between REM and deep sleep [33].

The measurement scenario also has an essential impact on the accuracy of estimations and their interpretability, which is sometimes neglected by end-users. For example, PPG sensors used to calculate heart rate wristbands are exposed to rapid movements during high-intensity workouts, which can strongly affect the measurement and related estimations. Some wristbands that lack an accelerometer cannot reliably monitor heart rate during intense exercise; accelerometers play a critical role in stabilizing the heart rate signal by accounting for motion artifacts. Although this issue may seem less significant during static activities, its impact can result in inaccurate data during physical exercise. Similarly, PPG sensors are less accurate when measuring rapid changes in heart rate, such as those captured by a single-lead ECG at the onset of running or cycling. During these activities, a decrease in total peripheral resistance can mask variations in pulse pressure, which, in turn, impedes the sensor's ability to accurately detect the blood pulse [23]. Similarly, certified trackers for blood pressure estimation based on PPG measurement (i.e., Aktiia Bracelet) even demonstrated accurate according to the ISO81060-2 in the sitting position, may provide inaccurate values during daily activities and other positions [24].

Advances in Science and Technology to Meet Challenges

Addressing the challenges facing wearable fitness trackers and performance monitors will require significant advances in several areas of science and technology. First, improving sensor technology is crucial.

Thanks to the research in the miniaturization of sensors and novel sensing elements, we expect to achieve more and more measurements instead of estimates of vital parameters soon. One notable example could be blood pressure measurement through the oscillometric method with sensors and elements of the measurement chain integrated into a smartwatch and its strap, as recently presented in Omron HeartGuide.

Looking at the measurable parameters, tracking sweat in fitness trackers could gain importance because sweat provides valuable insights into several aspects of a person's health and fitness. Yet, for unclear reasons, sweat-related parameters have to be fully incorporated into commercial products available to end-users. Sweat rate and composition can help estimate hydration levels better than now. And this hydration may give new insights into users' performance since it correlates to the risk of heat-related illnesses and cognitive function. Moreover, the amount of sweat produced connects with exercise intensity and duration. By tracking sweat rate, fitness trackers can estimate more accurately than now the effort exerted during a workout, offering a more comprehensive measure of calorie expenditure and workout effectiveness. Emerging technologies aim to track biomarkers available in the sweat like cortisol, glucose, and other indicators that could provide early warnings of health conditions such as diabetes or chronic stress.

Finally, integrating wearable devices into broader healthcare ecosystems will require advances in interoperability and standardization. Devices must be able to communicate seamlessly with other

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health monitoring systems and electronic health records to provide a widespread view of a user's health. This will also require collaboration between device manufacturers, healthcare providers, and regulatory bodies to establish common standards and protocols.

Concluding Remarks

Fitness trackers have transformed how health is monitored and tracked, providing real-time data on physical activity and wellness. Despite significant technological advancements, these devices still face challenges with data accuracy and reliability. Many measurements rely on indirect measurement methods, which can introduce errors, particularly during intense physical activity. Despite this, it is uncommon for the manufacturing company to state data on measurement accuracy that might guide a more informed choice about the specific fitness tracker's use.

The future of fitness trackers will require more advanced, less intrusive, and more accurate sensors capable of providing detailed measurements of physiological variables like sweat, which can reveal important insights into hydration, stress, and metabolism.

Another critical challenge will be integrating these devices into broader healthcare systems, allowing seamless communication with electronic health records and other monitoring tools. Technology standardization and collaboration between manufacturers, healthcare providers, and regulatory bodies will be essential to fully harnessing these devices' potential.

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References

[1] D. V. Gaz, T. M. Rieck, and N. W. Peterson, "Activity tracking and improved health outcomes," in Fitness Medicine. London, U.K.: IntechOpen, 2016, doi: 10.5772/65240.

[2] M. Armstrong, A. Winnard, N. Chynkiamis, S. Boyle, C. Burtin, and I. Vogiatzis, "Use of pedometers as a tool to promote daily physical activity levels in patients with COPD: A systematic review and meta-analysis," Eur. Respir. Rev., vol. 28, no. 154, Dec. 2019, doi: 10.1183/16000617.0039-2019.

[3] H. W. Chow and C. C. Yang, "Accuracy of optical heart rate sensing technology in wearable fitness trackers for young and older adults: Validation and comparison study," JMIR mHealth uHealth, vol. 8, no. 4, p. e14707, Apr. 2020, doi: 10.2196/14707.

[4] F. El-Amrawy and M. I. Nounou, "Are currently available wearable devices for activity tracking and heart rate monitoring accurate, precise, and medically beneficial?" Healthc. Inform. Res., vol. 21, no. 4, pp. 315–320, Oct. 2015, doi: 10.4258/hir.2015.21.4.315.

[5] N. Alugubelli, H. Abuissa, and A. Roka, "Wearable devices for remote monitoring of heart rate and heart rate variability—What we know and what is coming," Sensors, vol. 22, no. 22, p. 8903, Nov. 2022, doi: 10.3390/s22228903.

Accepted Manuscript

[6] C. Song, P. Zeng, Z. Wang, H. Zhao, and H. Yu, "Wearable continuous body temperature measurement using multiple artificial neural networks," IEEE Trans. Ind. Informatics, vol. 14, no. 10, pp. 4395–4406, Oct. 2018, doi: 10.1109/TII.2018.2793905.

[7] A. H. Ibrahim, C. T. Beaumont, and K. Strohacker, "Exploring regular exercisers' experiences with readiness/recovery scores produced by wearable devices: A descriptive qualitative study," Appl. Psychophysiol. Biofeedback, vol. 49, no. 3, pp. 395–405, Apr. 2024, doi: 10.1007/s10484-024-09645-2.

[8] M. De Zambotti, S. Claudatos, S. Inkelis, I. M. Colrain, and F. C. Baker, "Evaluation of a consumer fitness-tracking device to assess sleep in adults," Chronobiol. Int., vol. 32, no. 7, pp. 1024–1028, Aug. 2015, doi: 10.3109/07420528.2015.1054395.

[9] E. D. Chinoy et al., "Performance of seven consumer sleep-tracking devices compared with polysomnography," Sleep, vol. 44, no. 5, pp. 1–16, May 2021, doi: 10.1093/sleep/zsaa291.

[10] A. Jamieson, T. J. A. Chico, S. Jones, N. Chaturvedi, A. D. Hughes, and M. Orini, "A guide to consumer-grade wearables in cardiovascular clinical care and population health for non-experts," npj Cardiovasc. Health, vol. 2, no. 1, p. 44, Sep. 2025, doi: 10.1038/s44325-025-00082-6.

[11] D. J. Miller, C. Sargent, and G. D. Roach, "Validation of six wearable devices for estimating sleep, heart rate, and heart rate variability in healthy adults," Sensors, vol. 22, no. 16, p. 6317, Aug. 2022, doi: 10.3390/s22166317.

[12] S. R. Pasadyn et al., "Accuracy of commercially available heart rate monitors in athletes: A prospective study," Cardiovasc. Diagn. Ther., vol. 9, no. 4, pp. 379–385, 2019, doi: 10.21037/CDT.2019.06.05.

[13] J. A. Bunn, J. W. Navalta, C. J. Fountaine, and J. D. Reece, "Current state of commercial wearable technology in physical activity monitoring (2015–2017)," 2018.

[14] P. Caserman, S. Yum, S. Göbel, A. Reif, and S. Matura, "Assessing the accuracy of smartwatch-based estimation of maximum oxygen uptake using the Apple Watch Series 7: Validation study," JMIR Biomed. Eng., vol. 9, no. 1, p. e59459, Jul. 2024, doi: 10.2196/59459.

[15] T. Svensson, K. Madhawa, H. N. T., U. I. Chung, and A. K. Svensson, "Validity and reliability of the Oura Ring Generation 3 with OSSA 2.0 compared to ambulatory polysomnography," Sleep Med., vol. 115, pp. 251–263, Mar. 2024, doi: 10.1016/j.sleep.2024.01.020.

[16] J. Khasentino et al., "A personal health large language model for sleep and fitness coaching," Nat. Med., vol. 31, no. 10, pp. 3394–3403, Aug. 2025, doi: 10.1038/s41591-025-03888-0.

[17] G. J. Martinez et al., "Alignment between heart rate variability from fitness trackers and perceived stress," JMIR Hum. Factors, vol. 9, no. 3, p. e33754, Aug. 2022, doi: 10.2196/33754.

[18] D. J. van der Mee, Z. Koyuncu, and I. L. J. Lemmers-Jansen, "Are you stressed or just excited? What the Garmin stress score can say about your mood," J. Affect. Disord. Rep., vol. 21, p. 100974, Jul. 2025, doi: 10.1016/j.jadr.2025.100974.

[19] S. Campanella, A. Altaleb, A. Belli, P. Pierleoni, and L. Palma, "A method for stress detection using Empatica E4 bracelet and machine-learning techniques," Sensors, vol. 23, no. 7, p. 3565, Mar. 2023, doi: 10.3390/s23073565.

[20] L. M. Feehan et al., "Accuracy of Fitbit devices: Systematic review and narrative syntheses of quantitative data," JMIR mHealth uHealth, vol. 6, no. 8, Aug. 2018, doi: 10.2196/10527.

[21] K. Rajakariar et al., "Accuracy of smartwatch pulse oximetry measurements in hospitalized patients with coronavirus disease 2019," Mayo Clin. Proc. Digit. Health, vol. 2, no. 1, pp. 152–158, Mar. 2024, doi: 10.1016/j.mcpdig.2024.02.001.

Accepted Manuscript

[22] P. Windisch, C. Schröder, R. Förster, N. Cihoric, and D. R. Zwahlen, “Accuracy of the Apple Watch oxygen saturation measurement in adults: A systematic review,” Cureus, vol. 15, no. 2, Feb. 2023, doi: 10.7759/cureus.35355.

[23] C. Massaroni, S. Silvestri, and E. Schena, “Comparison between heart rate estimated by single-lead ECG and optical-based wearable systems during outdoor running,” in Proc. IEEE Int. Workshop Metrol. Ind. 4.0 IoT, Jul. 2024, pp. 407–411, doi: 10.1109/metroind4.0iot61288.2024.10584238.

[24] D. Konstantinidis et al., “Wearable blood pressure measurement devices and new approaches in hypertension management: The digital era,” J. Hum. Hypertens., vol. 36, no. 11, pp. 945–951, Nov. 2022, doi: 10.1038/s41371-022-00675-z.

[25] J. L. Scheid, J. L. Reed, and S. L. West, “Commentary: Is wearable fitness technology a medically approved device? Yes and no,” Int. J. Environ. Res. Public Health, vol. 20, no. 13, Jul. 2023, doi: 10.3390/ijerph20136230.

[26] M. Ghamari, “A review on wearable photoplethysmography sensors and their potential future applications in health care,” Int. J. Biosens. Bioelectron., vol. 4, no. 4, p. 195, 2018, doi: 10.15406/ijbsbe.2018.04.00125.

[27] A. Jubran, “Pulse oximetry,” Crit. Care, vol. 19, no. 1, Jul. 2015, doi: 10.1186/s13054-015-0984-8.

[28] C. Massaroni, S. Silvestri, and E. Schena, “Contact-based methods for measuring respiratory rate,” Sensors, vol. 19, no. 4, p. 908, 2019, doi: 10.3390/s19040908.

[29] A. Nicolò, C. Massaroni, E. Schena, and M. Sacchetti, “The importance of respiratory rate monitoring: From healthcare to sport and exercise,” Sensors, vol. 20, no. 21, p. 6396, Nov. 2020, doi: 10.3390/s20216396.

[30] M. Pinnelli, S. Marsella, F. Tossut, E. Schena, R. Setola, and C. Massaroni, “Field testing multi-parametric wearable technologies for wildfire firefighting applications,” Sensors, vol. 25, no. 10, p. 3066, May 2025, doi: 10.3390/s25103066.

[31] C. Massaroni, D. Lo Presti, and E. Schena, “Wearable sensors for cardiorespiratory monitoring based on chest wall motion and their applications,” IEEE Sensors Rev., vol. 1, pp. 2–13, 2024, doi: 10.1109/SR.2024.3513953.

[32] P. T. Nikolaidis, T. Rosemann, and B. Knechtle, “Age-predicted maximal heart rate in recreational marathon runners: A cross-sectional study on Fox’s and Tanaka’s equations,” Front. Physiol., vol. 9, p. 226, Mar. 2018, doi: 10.3389/fphys.2018.00226.

[33] M. De Zambotti, N. Cellini, A. Goldstone, I. M. Colrain, and F. C. Baker, “Wearable sleep technology in clinical and research settings,” Med. Sci. Sports Exerc., vol. 51, no. 7, pp. 1538–1557, Jul. 2019, doi: 10.1249/MSS.0000000000001947.

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4.2 - Innovative applications of smart wearable and textile PPG technology in fitness and lifestyle

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Status

Photoplethysmography (PPG) has become a foundational non-invasive optical sensing technique within both clinical and consumer health technologies. Initially developed for the measurement of heart rate, arterial oxygen saturation, and vascular function in controlled medical environments, PPG has subsequently been adopted across a broad spectrum of fitness, sports performance, and lifestyle applications [1,2]. This transition has been driven by the increasing demand for continuous, real-time physiological monitoring, particularly in ambulatory and everyday settings.

The integration of PPG sensors into contemporary wearable devices, including wrist-worn monitors, ear-mounted sensors, and textile-embedded systems, has expanded the technology's utility beyond its original medical scope. Although many commercial systems rely on proprietary hardware designs and closed-loop algorithms, the intrinsic adaptability of PPG to dynamic, uncontrolled conditions remains a central advantage. This adaptability enables manufacturers to develop activity-specific signal-processing and validation frameworks for domains such as endurance running, cycling, resistance training, and high-intensity interval exercise [2,3].

Beyond the traditional parameters of heart rate and heart rate variability (HRV), PPG now supports a diverse range of advanced physiological and performance-related metrics. One key domain of application is aerobic performance assessment, where PPG-derived features are increasingly employed to estimate oxygen consumption (VO_2) and maximal oxygen uptake (VO_2max). These metrics are central indicators of aerobic capacity and endurance. Although current wearable devices do not yet achieve clinical-grade precision, many demonstrate population-level accuracy within 5–15% error, making them suitable for recreational performance assessment and longitudinal training analysis [3–5].

PPG also contributes significantly to energy-expenditure estimation. When PPG-derived heart rate data are combined with accelerometery, the accuracy of calorie-burn calculations improves substantially. Empirical studies indicate that incorporating cardiac signals such as PPG and ECG reduces estimation error by approximately 20–40% in comparison with accelerometery-only models, thereby enhancing the reliability of energy-balance assessments within fitness and lifestyle contexts [4]. This improvement is particularly relevant for weight-management applications and personalized training programs.

Another important area of application is the monitoring of cardiac effort and training load. Continuous PPG measurement enables real-time quantification of cardiovascular strain during

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exercise. Metrics such as heart-rate zone distribution, internal training load, and cardiovascular efficiency provide athletes with evidence-based guidance on optimizing workout intensity, structuring periodization, and managing recovery. These capabilities have made PPG a central tool in sports-performance platforms aimed at improving training precision [6,7].

PPG is equally valuable in consumer health monitoring, particularly in the domains of sleep analysis, autonomic regulation, and recovery assessment. Multi-hour nocturnal PPG recordings serve as the basis for estimating sleep stages, nighttime HRV, and indices of autonomic balance. Such metrics underpin the recovery and readiness scores that are widely used in both lifestyle and athletic applications to track overall physiological resilience and daily preparedness [8,9].

Novel applications further demonstrate the clinical potential of PPG. The technology is explored for preliminary detection of arrhythmias, hypertensive tendencies, and fluctuations in blood-oxygen saturation associated with sleep-disordered breathing. These developments align with current trends on remote physiological monitoring, where PPG serves as a scalable and cost-efficient complement to traditional clinical diagnostic pathways [5,10,11].

The grouping of these measurement capabilities within a single wearable platform highlights the versatility of PPG as both a consumer-facing and clinically adjacent sensing technology. As health-care systems continue to prioritize decentralized and continuous monitoring strategies, PPG is positioned as a central technology at the intersection of personal wellness, athletic performance optimization, and chronic-disease management. The aim of this subsection is therefore to provide a comprehensive overview of the evolution, application domains, and technological significance of PPG within modern smart wearables, enabling informed decision-making regarding its selection, deployment, and evaluation [3–11].

Current and Future Challenges

PPG technology has advanced significantly but still faces challenges, particularly in extracting accurate and reliable signals from peripheral areas like wrists, biceps, calves, and ankles. These regions, with low tissue microvascular density, are prone to motion artifacts and issues such as perspiration, which can compromise signal quality. Physical activity exacerbates these problems, leading to decreased accuracy and reliability of the captured data. [12,13].

Integrating different modules such as wireless transmission and accelerometers with optimized LED-photodiode configurations and PPG photodiodes is crucial for improving the accuracy of vascular signal detection. Accelerometers measure body movement, while strategic placement of LED-photodiodes enhances vascular signal capture. This integration helps address motion artifacts, particularly during intense activities like running or cycling. However, challenges persist, especially in developing algorithms to accurately differentiate between genuine cardiovascular signals and motion-induced noise. Current motion-compensation techniques are often imprecise, indicating a need for more advanced sensor fusion and adaptive machine learning algorithms that can effectively manage varying motion intensities and body locations. [14-17].

Advances in Science and Technology to Meet Challenges

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PPG technology still faces major challenges in fitness, health monitoring, and sports applications, particularly due to motion artifacts and low-tissue-density regions such as the wrist and ankle. Improving accuracy and reliability will require advances in both hardware and software, including better probe-tissue pressure control, pressure-sensitive designs, and noise-classification algorithms, all of which are active areas of industrial innovation [18–20]. A key development in this effort is the optimisation of analogue front-end (AFE) systems, which play a central role in early signal acquisition and conditioning. Well-designed AFEs enable more precise PPG signal extraction in difficult measurement conditions, and commercial solutions such as Osram's vital sign monitoring product line illustrate viable alternatives [19].

In parallel, wireless communication technologies are becoming essential to modern PPG devices. Standards such as Bluetooth Low Energy (BLE) support efficient data transfer for daily monitoring, while robust error-correction improves the reliability of transmitted signals. Long-distance PPG monitoring is also growing in importance, particularly in remote healthcare and fitness applications. To meet these demands, devices increasingly integrate advanced telecommunication protocols such as 4G and 5G, which deliver high bandwidth, low latency, and real-time transmission of large health datasets.

Concluding Remarks

Photoplethysmography (PPG) has become a key non-invasive optical technology for fitness and lifestyle monitoring, widely adopted in consumer-grade wearables. To unlock its full potential, improvements in sensor performance, motion artifact compensation, and integration with accelerometers with advanced LED-photodiode setups are needed. The miniaturization of wearables also demands more efficient data sampling and processing techniques. Future advancements will focus on developing robust motion and noise resistant sensing devices, AFE systems, secure broadband communication protocols, and enhanced data security through encryption. These innovations will ensure PPG's role as a cornerstone technology for preventative healthcare, fitness tracking, and remote care, improving signal reliability, motion compensation, and user trust.

References

1] J. Allen, "Photoplethysmography and its application in clinical physiological measurement," *Physiol. Meas.*, vol. 28, no. 3, pp. R1–R39, Feb. 2007, doi: 10.1088/0967-3334/28/3/R01.

[2] P. Rao, D. R. Seshadri, and J. J. Hsu, "Current and potential applications of wearables in sports cardiology," *Curr. Treat. Options Cardiovasc. Med.*, vol. 23, no. 10, Oct. 2021, doi: 10.1007/s11936-021-00942-1.

[3] D. J. Muggeridge *et al.*, "Measurement of heart rate using the Polar OH1 and Fitbit Charge 3 wearable devices in healthy adults during light, moderate, vigorous, and sprint-based exercise: Validation study," *JMIR mHealth uHealth*, vol. 9, no. 3, p. e25313, Mar. 2021, doi: 10.2196/25313.

[4] Z. Lu, J. Yang, K. Tao, X. Li, H. Xu, and J. Qiu, "Combined impact of heart rate sensor placements with respiratory rate and minute ventilation on oxygen uptake prediction," *Sensors*, vol. 24, no. 16, p. 5412, Aug. 2024, doi: 10.3390/s24165412.

[5] J. Romero *et al.*, "OptiBreathe: An earable-based PPG system for continuous respiration rate, breathing phase, and tidal volume monitoring," in *Proc. ACM Int. Conf. Wearable Implant. Body Sensor Netw.*, Feb. 2024, doi: 10.1145/3638550.3641136.

[6] X. Liu *et al.*, "A wearable PPG-based monitoring system for personalized free weight training," *IEEE Trans. Mobile Comput.*, vol. 24, no. 7, pp. 5824–5838, Jul. 2025, doi: 10.1109/TMC.2025.3540165.

[7] F. Scardulla, G. Cosoli, C. Gnoffo, L. Antognoli, F. Bongiorno, G. Diana, L. Scalise, L. D'Acquisto, and M. Arnesano, "Experimental analysis on the effect of contact pressure and activity level as influencing factors in PPG sensor performance," *Sensors*, vol. 25, no. 14, p. 4477, 2025, doi: 10.3390/s25144477.

Accepted Manuscript

[8] R. V. Sharan, H. Takeuchi, A. Kishi, J. Wang, T. Watanabe, and Y. Yamamoto, "Sleep staging using PPG-derived heart rate and accelerometer data from a smart ring with lightweight neural networks," *IEEE Trans. Instrum. Meas.*, vol. 74, pp. 1–14, 2025, doi: 10.1109/TIM.2025.3635330.

[9] C. Dong, J. P. van Dijk, R. M. Aarts, Y. Wang, and X. Long, "Detection of nocturnal epileptic seizures using a wearable armband: A deep learning approach combining accelerometry and photoplethysmography signals," *Comput. Methods Programs Biomed.*, vol. 273, p. 109087, Jan. 2026, doi: 10.1016/j.cmpb.2025.109087.

[10] J. Alam, M. F. Khan, M. A. Khan, R. Singh, M. Mundazeer, and P. Kumar, "A systematic approach focused on machine learning models for exploring the landscape of physiological measurement and estimation using photoplethysmography," *J. Cardiovasc. Transl. Res.*, vol. 17, no. 3, pp. 669–684, Nov. 2023, doi: 10.1007/s12265-023-10462-x.

[11] J. Khasentino *et al.*, "A personal health large language model for sleep and fitness coaching," *Nat. Med.*, vol. 31, pp. 1–10, 2025.

[12] Y. Zheng, C. Wu, P. Cai, Z. Zhong, H. Huang, and Y. Jiang, "Tiny-PPG: A lightweight deep neural network for real-time detection of motion artifacts in photoplethysmogram signals on edge devices," *Internet Things*, vol. 25, p. 101007, Apr. 2024, doi: 10.1016/j.iot.2023.101007.

[13] T. Kwon and S. W. Yoon, "Anomaly detection of motion artifact in photoplethysmography sensors using unsupervised learning," *IEEE Sensors J.*, vol. 24, no. 14, pp. 23163–23172, Jul. 2024, doi: 10.1109/JSEN.2024.3404558.

[14] I. T. Hettiarachchi, S. Hanoun, D. Nahavandi, and S. Nahavandi, "Validation of Polar OH1 optical heart rate sensor for moderate and high intensity physical activities," *PLOS ONE*, vol. 14, no. 5, p. e0217288, May 2019, doi: 10.1371/journal.pone.0217288.

[15] D. Seok, S. Lee, M. Kim, J. Cho, and C. Kim, "Motion artifact removal techniques for wearable EEG and PPG sensor systems," *Front. Electron.*, vol. 2, May 2021, doi: 10.3389/felec.2021.685513.

[16] C.-H. Goh, L. K. Tan, N. H. Lovell, S.-C. Ng, M. P. Tan, and E. Lim, "Robust PPG motion artifact detection using a 1-D convolutional neural network," *Comput. Methods Programs Biomed.*, vol. 196, p. 105596, Nov. 2020, doi: 10.1016/j.cmpb.2020.105596.

[17] S. Karolcik, D. K. Ming, S. Yacoub, A. H. Holmes, and P. Georgiou, "A multi-site, multi-wavelength PPG platform for continuous non-invasive health monitoring in hospital settings," *IEEE Trans. Biomed. Circuits Syst.*, vol. 17, no. 2, pp. 349–361, Apr. 2023, doi: 10.1109/TBCAS.2023.3254453.

[18] R. K. Pandey and P. C.-P. Chao, "An adaptive analog front end for a flexible PPG sensor patch with self-determined motion-related DC drift removal," in *Proc. IEEE Int. Symp. Circuits Syst. (ISCAS)*, May 2021, doi: 10.1109/ISCAS51556.2021.9401265.

[19] W. Cai, H. Wen, H. A. Beadle, C. Kjellqvist, M. Hedayati, and M. L. Scott, "Understanding and optimizing persistent memory allocation," in *Proc. ACM Int. Conf. Archit. Support Program. Lang. Oper. Syst.*, Jun. 2020, doi: 10.1145/3381898.3397212.

[20] V. Fleischhauer, J. Adrians, and S. Zaunseder, "Validation of skin perfusion monitoring by imaging photoplethysmography versus laser speckle imaging," *Curr. Dir. Biomed. Eng.*, vol. 9, no. 1, pp. 351–354, Sep. 2023, doi: 10.1515/cdbme-2023-1088.

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Section 5: Materials and Manufacturing for Wearables

5.1 - Conducting Polymers: Revolutionizing Flexible and Sustainable Wearable Sensors

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Status

With the rapid transition into a more digitized and connected world through the Internet of Things (IoT) and the increased focus on providing more personalized and continuous healthcare and fitness monitoring, the demand for reliable and in-obtrusive wearable sensors is increasing substantially to improve data collection, efficiency, and decision-making process in healthcare. While signal processing technologies have made strides, materials advancements have yet to be adopted. The 2000 Chemistry Nobel Prize awarded discovery of a new class of materials, namely conducting polymers (CPs), in 1977 by Shirakawa, Heeger, and MacDiarmid [1] revolutionized material science with numerous new commercial applications in electronics. CPs are made from conjugated polymer chains where an intricate coupling between the structural and charge dynamics through alternating single and double bonds creates a backbone that provides a robust and flexible structure accompanied by a system of delocalized π-electrons enhancing charge mobility and resulting in high electrical conductivity similar to that of metals [2]. Their tuneable electronic properties, literal flexibility and versatility in processing, has sparked systematic studies on their properties [2], processing [3], applications [4], as well as on the *de novo* synthesis of new materials to-the-purpose [5]. CPs can be specifically designed to adapt and conform to various surface types [6]. Films, hydrogels, fibrous matrices, and scaffold architectures are just some examples of their potential form factors, accommodating a wide range of devices in healthcare, fitness, and protective wear applications. Their easy-to-tune electrical properties via doping and de-doping of the polymer and their high sensitivity/ affinity for ionic molecules opens new avenues for biological sensing for example for detecting metabolites from sweat, [8] offering a non-invasive way of monitoring an individual's health. In addition, their cost-effectiveness and low environmental impact compared to their inorganic counterparts make them highly desirable in renewable energy and green electronics. As such, wearables have adopted CP materials in their "blueprints". One of CPs's key contributions to wearable electronics is their "seamless" interfacing resulting in improvements in signal stability between electrodes and human tissue (see **Figure 14**). This improves signal-to-noise ratio while minimizing artifacts, ensuring higher fidelity recordings which are crucial for real-time health monitoring. [7] CPs have also demonstrated applications in energy harvesting devices holding promise toward autonomous, self-powered sensors. [9] By integrating all these capabilities, CP-based wearable sensors are sought to contribute to the expansive IoT infrastructure that connects people, machines, and environments more efficiently and sustainably. [10]

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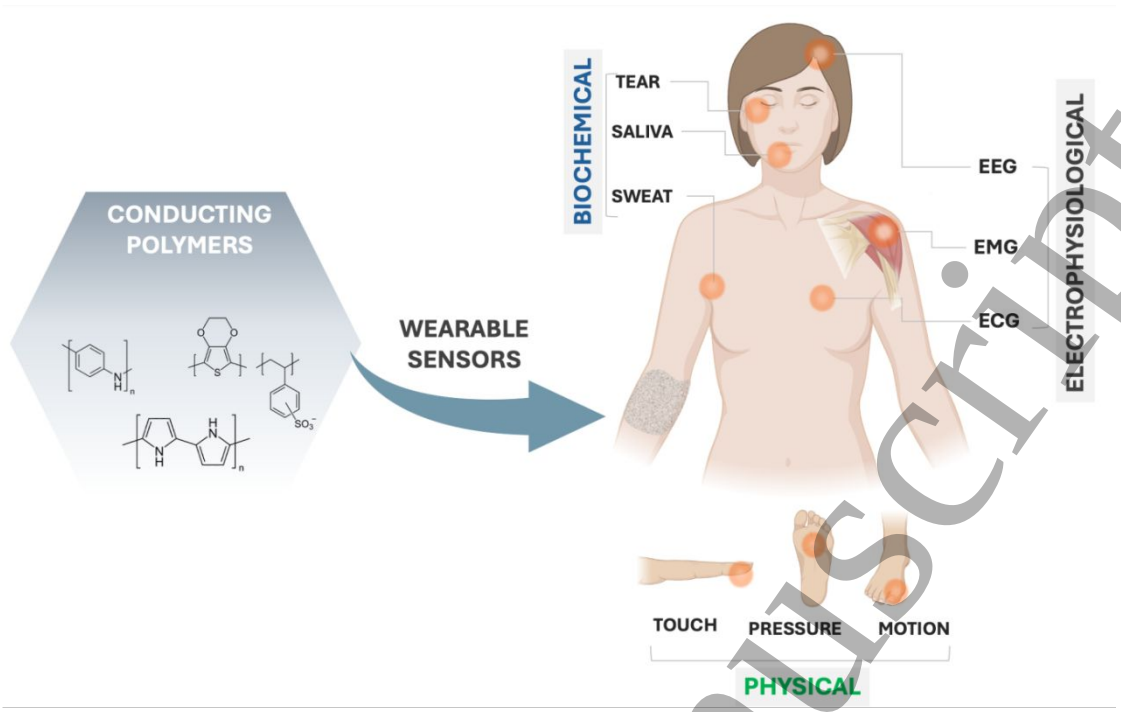


Figure 14. Schematic illustration depicting the integration of conducting polymers in human-electronics interface sensors and energy harvesting devices for wearable electronics applications.

Current and Future Challenges

Integrating CPs into wearable sensors technology is indeed promising, however it still faces several challenges. For example, the trade-off between electrical conductivity and mechanical properties is one of the most critical issues. Specifically, when CPs are engineered for better flexibility and conformability, their sensing or signal transmission capabilities tend to degrade due to the loss of their conducting nature. In addition, achieving long-term operational and performance stability in real-world environments remains a great challenge, as CP electronic materials can be sensitive to humidity, light, and temperature variations. Although CP-based sensors can be processed in a more sustainable fashion than traditional counterpart components, they lack biodegradability by nature, thus posing environmental risks, especially for short-lifecycle devices and high-volume production. Specifically, in biomedical applications, CP materials such as polyaniline, polypyrrole, and poly(3,4-ethylenedioxythiophene) polystyrene sulfonate derivatives have demonstrated promising biocompatibility characteristics. However, depending on the material and the involved human tissue, more tests are required to ensure safety and compliance. In addition, due to the synthetic complexity of conducting polymers, chemical modifications, and associated variations may reiterate further validation procedures. Nevertheless, as more knowledge is built on CPs, they may likely lead to FDA-approved applications. While scientists have made tremendous progress in the synthesis and engineering of CPs (i.e., side-chain engineering, co-polymerization), the plethora of promising candidate compounds presents a unique challenge itself. Each CP variation can yield different electrical, mechanical, or chemical properties, broadening the spectrum of potential applications. However, this diversity also makes it difficult to devote adequate research and resources to every candidate. The time and cost required for sufficient testing and optimization of each compound are substantial and become rather impractical. In addition, newly synthesized CPs are typically produced in small amounts, often resulting in batch-to-batch variations, which may delay or even discourage

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their transfer to real-world sensors. Future wearable devices are also expected to be autonomous and able to harvest energy from the user or through interactions with the environment while performing complex sensing tasks. Although there have been studies focused on self-powered CP-based devices [9], achieving the multifunctionality needed for wearable applications is still difficult. Moreover, the synergy between CPs and clothing materials should support dynamic interaction with the body's movements without compromising signal integrity. Finally, integrating CP-based wearables sensors into the broader IoT ecosystem requires overcoming issues related to data transmission and security.

Advances in Science and Technology to Meet Challenges

Advances in materials design and synthesis hold promise for next-generation wearables. Solution processing and in situ polymerization of polymers eases fabrication in various types of wearable devices, for example patch, strap, tattoo and hydrogel. Along these lines, better understanding the intricate balance between ionic permeability and electronic charge transport will allow informed design of materials with tuneable iono-electronic behaviour that could fit the intended application. [11] This, solves the one-material-fits-all bottleneck that currently obstructs the field of organic electronics. Previous breakthroughs in wearable electronics have largely been driven by strain engineering and nanocomposite techniques in order to infer the desired stretchability. Pathways to creating naturally stretchable CPs could lead to the use of simpler processing methods, such as printing and additive manufacturing, resulting in more resilient and conformable devices [12]. Overcoming the stability and durability aspect, advances in copolymerization of CPs have yielded homogenous, semicrystalline and redox-active thin films that are chemically and physically resistant, thus compatible with back-end-of-line conditions facilitating scaling up and integration with conventional electronics. Indeed, the presence of a semiconducting bulk allows modulation and control of the charges, promoting power-efficient switchable transistors for bio-signal amplification. Sweat analytes can be detected by harnessing the inherent amplification properties and ion affinity/permeability of CPs- based devices. Advances in this area include sweat ion detection [13] as well as metabolite detection combined with electricity generation through triboelectric effects during biomechanical motion.[14] For applications such as tactile sensing or stress-strain sensing, [15] the use of CP/polymer or CP/nanomaterial composites can enhance recorded signals, as well as their ability to take various form factors, including films, fibers, nanorods, sponges, foams, aerogels and textiles.[16] Furthermore, conformal and nanostructured CP alongside advances in their adhesiveness, stretchability and ionic permeability, can lead to improved electrophysiology recordings with higher signal-to-noise ratio compared to commercial gel electrodes, particularly during sweating [7] [17].

Concluding Remarks

The next generation of wearable systems requires flexible, breathable, and skin-friendly wireless sensors to enable body area networks and IoT. However, combining wearable comfort, environmental resistance, stability and portability remain a challenge and CPs still cannot fully replace traditional electronics. Advances in materials design synthesis and engineering need to meet flexible and wearable electronic needs, as well as standardised manufacturing at scale. With new knowledge and understanding on the structure-processing-function relationship, design criteria are emerging towards guided material development. Indeed, CPs strengthen continuously their position in the emerging era of communication and human-machine interfaces. In alignment with

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sustainability standards integrating CP-based sensors with energy harvesters will prove highly beneficial for the next generation of wearable electronics towards the ultimate goal of self-powered devices with multifunctional monitoring capabilities that can be seamlessly adapted to the human body.

Acknowledgments

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References

[1] H. Shirakawa, E. J. Louis, A. G. MacDiarmid, C. K. Chiang, and A. J. Heeger, "Synthesis of electrically conducting organic polymers: Halogen derivatives of polyacetylene, $(CH)_x$," J. Chem. Soc., Chem. Commun., no. 16, p. 578, 1977, doi: 10.1039/C39770000578.

[2] S. Fratini, M. Nikolka, A. Salleo, G. Schweicher, and H. Sirringhaus, "Charge transport in high-mobility conjugated polymers and molecular semiconductors," Nat. Mater., vol. 19, no. 5, pp. 491–502, May 2020, doi: 10.1038/s41563-020-0647-2.

[3] C. Pitsalidis et al., "Electrospray-processed soluble acenes toward the realization of high-performance field-effect transistors," ACS Appl. Mater. Interfaces, vol. 7, no. 12, pp. 6496–6504, Apr. 2015, doi: 10.1021/am508162m.

[4] J. Rivnay, S. Inal, A. Salleo, R. M. Owens, M. Berggren, and G. G. Malliaras, "Organic electrochemical transistors," Nat. Rev. Mater., vol. 3, no. 2, p. 17086, Jan. 2018, doi: 10.1038/natrevmats.2017.86.

[5] H. Bronstein, C. B. Nielsen, B. C. Schroeder, and I. McCulloch, "The role of chemical design in the performance of organic semiconductors," Nat. Rev. Chem., vol. 4, no. 2, pp. 66–77, Jan. 2020, doi: 10.1038/s41570-019-0152-9.

[6] R. M. Owens and G. G. Malliaras, "Organic electronics at the interface with biology," MRS Bull., vol. 35, no. 6, pp. 449–456, Jun. 2010, doi: 10.1557/mrs2010.583.

[7] N. B. Alsaafeen et al., "One-pot synthesis of a robust crosslinker-free thermo-reversible conducting hydrogel electrode for epidermal electronics," ACS Appl. Mater. Interfaces, Jan. 2024, doi: 10.1021/acsami.3c10663.

[8] O. Parlak, S. T. Keene, A. Marais, V. F. Curto, and A. Salleo, "Molecularly selective nanoporous membrane-based wearable organic electrochemical device for noninvasive cortisol sensing," Sci. Adv., vol. 4, no. 7, p. eaar2904, Jul. 2018, doi: 10.1126/sciadv.aar2904.

[9] D. Ohayon et al., "Biofuel-powered glucose detection in bodily fluids with an n-type conjugated polymer," Nat. Mater., vol. 19, no. 4, pp. 456–466, Apr. 2020, doi: 10.1038/s41563-019-0556-4.

[10] S. S. Arya, S. B. Dias, H. F. Jelinek, L. J. Hadjileontiadis, and A. M. Pappa, "The convergence of traditional and digital biomarkers through AI-assisted biosensing: A new era in translational diagnostics?" Biosens. Bioelectron., vol. 235, p. 115387, Apr. 2023, doi: 10.1016/j.bios.2023.115387.

[11] S. Samal, H. Roh, C. E. Cunin, G. G. Yang, and A. Gumyusenge, "Molecularly hybridized conduction in DPP-based donor–acceptor copolymers toward high-performance iono-electronics," Small, vol. 19, no. 3, p. 2207554, Jan. 2023, doi: 10.1002/smll.202207554.

Accepted Manuscript

[12] Y. Wang et al., "A highly stretchable, transparent, and conductive polymer," Sci. Adv., vol. 3, no. 3, p. e160207, Mar. 2017, doi: 10.1126/sciadv.160207.
[13] W. Gao et al., "Fully integrated wearable sensor arrays for multiplexed in situ perspiration analysis," Nature, vol. 529, no. 7587, pp. 509–514, Jan. 2016, doi: 10.1038/nature16521.
[14] S. M. Mugo, Dhanjai, and J. Alberkant, "Biomimetic lactate-imprinted smart polymers as capacitive sweat sensors," IEEE Sensors J., vol. 20, no. 11, pp. 5741–5749, Jun. 2020, doi: 10.1109/JSEN.2020.2974851.
[15] J. Castellanos-Ramos, R. Navas-González, H. Macicior, T. Sikora, E. Ochoteco, and F. Vidal-Verdú, "Tactile sensors based on conductive polymers," Microsyst. Technol., vol. 16, no. 5, pp. 765–776, May 2010, doi: 10.1007/s00542-009-0958-3.
[16] W. Zhang, L. You, X. Meng, B. Wang, and D. Lin, "Recent advances on conducting polymer-based nanogenerators for energy harvesting," Micromachines, vol. 12, no. 11, p. 1308, Oct. 2021, doi: 10.3390/mi12111308.
[17] K. Nagamine, S. Chihara, H. Kai, H. Kaji, and M. Nishizawa, "Totally shape-conformable electrode/hydrogel composite for on-skin electrophysiological measurements," Sens. Actuators B Chem., vol. 237, pp. 49–53, Dec. 2016, doi: 10.1016/j.snb.2016.06.076.

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5.2 - Advanced Materials and E-Textiles: Integrating Smart Functions into Everyday Fabrics

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Status

The integration of electronic textiles (e-textiles) with advanced materials marks a significant leap in smart textile development. These materials allow electronic components to be seamlessly embedded into smart garments or even allow the very fibres of a textile to act as electronic components. The progress in advanced materials transforms fabric from passive textiles into active, intelligent systems capable of responding to environmental stimuli and user's needs in real-time, opening new possibilities for wearable technology.

Novel materials in e-textile

1. Conductive materials

Conductive materials are fundamental to electronic devices. Currently, fiber materials with a conductivity greater than 10^{-6} $S{\cdot}m^{-1}$ are generally considered to be conductive fibers [1]. High flexibility, mechanical strength, and conductivity are essential for constructing fiber electrodes, circuit elements, connections, and full devices on textile. Materials used to provide conductivity to such fibers are mainly divided into three categories: metal-, carbon-, and polymer-based materials.

Novel conductive metal materials typically include metal (Cu, Ag, Au) nanoparticles, metal nanowires, nanomeshes, and liquid metals, with electrical conductivities exceeding 10^3 $S{\cdot}m^{-1}$ [2]. Conductive carbon materials generally have conductivities in the range 10^2~10^4 $S{\cdot}m^{-1}$ [2], including carbon nanotubes (CNTs), graphene, and carbon fiber. These materials have excellent tensile strength, conductivity, and specific surface area. Conductive polymers are intrinsically flexible due to their chemical structure. However, the conductivity of conductive polymer fiber is low, usually less than 10 $S{\cdot}m^{-1}$ [3]. Common conductive polymers include polyaniline (PANI), poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT: PSS), and polypyrrole (PPy).

Notably, translating the bulk properties of these materials onto textile is not straightforward. They are usually used as fiber components, e.g. fillings and coatings, which drastically affect material performance. Preservation of the advantageous properties of advanced materials during the textile processes remains a challenge in e-textiles.

2. Semiconductor material

Semiconductor materials are a key component enabling electronic functionality, creating the flexible, lightweight, and durable electronic components needed for e-textiles. Key materials include organic semiconductors like PANI, PPy, and PEDOT [4], known for their flexibility and conductivity, making them suitable also for sensors. Carbon-based semiconductors such as graphene and carbon nanotubes provide exceptional conductivity and strength, enabling touch-sensitive interfaces and flexible displays [5]. Innovations in silicon-based semiconductors have led to the development of ultra-thin, flexible chips that can be embedded in textiles for advanced applications like health monitoring. Metal oxides such as zinc oxide (ZnO) and titanium dioxide (TiO_2) are used for their piezoelectric properties, enabling self-powered strain sensing.

Majority of semiconductor-based devices is based on junctions of semiconductors with other semiconductors or other materials. Notable challenge in production of textile devices is formation and conservation of such junctions, which are often affected by wear, washing, humidity, and fouling.

Fiber manufacturing techniques

Figure 15 illustrates the primary main preparation methods for existing fiber electronics, including thermal drawing, wet spinning, coaxial coating, and one-dimensional (1D) braiding techniques.

a. **Thermal drawing technique** (**Figure 15a**) is applied to produce multi-material fiber electronics. It starts with designing a preform rod with a customized structure and materials, which is then

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heated and drawn through a heating ring. This technique offers several advantages, including precise control over the fiber's internal structure, the ability to integrate various materials and electronic components within the fiber, and the capability for continuous manufacturing [6].

b. **Wet spinning technique** (**Figure 15b**) utilizes wet chemical phase separation to precipitate functional materials dissolved in organic solvents within a coagulation bath. This approach is suitable for polymer materials that are challenging to melt but can be dissolved in organic solvents, e.g. polyvinyl alcohol and polyacrylonitrile [7]. Control of viscosity and surface tension allows for the uniform dispersion of functional materials in the solution, making the method particularly advantageous for creating ultra-thin coatings and electrolyte-based fiber electronics.

c. **Coaxial coating technique** (**Figure 15c**) involves passing the fiber through a viscous functional liquid, where surface tension controls the assembly of functional materials onto the fiber surface, achieving a layer-by-layer structure if several coatings are used. The resulting fiber can thus obtain several coaxial coatings, which can be deposited from a variety of solutions: polymer, composite, small molecules [8], making this a common technique for preparing fiber electronics.

d. **One-dimensional braiding technique** (**Figure 15d**) employs mechanical devices to interlace multiple yarns into one using a guiding device, with the weaving head controlling the surface texture, density, and size of the yarn. This technique is characterized by high efficiency, precision, and automation, allowing for the mixing and weaving of various functional fibers [9].

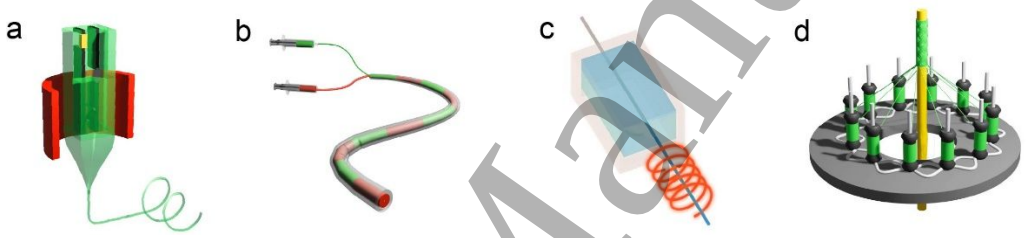


Figure 15. Electronic fiber manufacturing techniques. (a) Thermal drawing; **(b)** Wet spinning; **(c)** Coaxial coating; **(d)** One-dimensional braiding.

Textile integration technology

The intricate structures of e-textiles are essential to their functionality and versatility. The four primary techniques—weaving, knitting, embroidery, and nonwoven fabric production—each offer unique advantages for e-textiles.

a. Weaving

Woven textiles (**Figure 16a**) are produced through a weaving technique that interlaces vertical warp and horizontal weft yarns to create textiles. By varying the interlacing of these yarns, different woven structures with different properties can be achieved, e.g. plain, twill, satin. Weaving is essential for integrating smart fibers, allowing for the creation of size-controlled and breathable e-textiles [10]. While this method produces strong, durable textiles with stable structures and complex patterns, they are also more costly and less stretchable, with longer production times [11].

b. Knitting

Knitted textiles (**Figure 16b**) offer higher elasticity, softness, and breathability for smart textiles due to their structure consisting of intermeshed loops: courses and wales. Notably, knitting allows for production of elastic fabric, even when its individual threads are not expandible by themselves, especially in case of loose knit structures. Despite numerous advantages, it may have limitations in designing complex structures and may result in lower strength and potential deformation [12].

c. Embroidery

Embroidery of textiles (**Figure 16c**) offer a high degree of design freedom, allowing for patterns to be implemented on existing textile surfaces. For instance, conductive fibers can be embroidered onto the textile to create textile circuits, thereby integrating electronic functionalities [13]. Digital

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embroidery also offers high precision and reproducibility but comes with higher costs and complex maintenance. One of the challenges in embroidery is its effect on the underlying textile. Often non-stretchable threads are used to embroider functional patterns, which precludes the whole piece from stretching and affects its softness, whereas embroidery using stretchable fiber is separate engineering challenge.

d. Nonwoven

Nonwoven textiles (**Figure 16d**) are made by assembling micro/nano fibers into a mesh through mechanical, chemical, or thermal bonding, avoiding traditional weaving. The properties of these textiles can be fine-tuned through employment of different precursor materials and techniques, for example polyethylene melt-blown non-woven textiles can be used for ultra microfiltration [14], whereas electrospun biopolymer-based nonwovens are used for wound healing [15]. Overall, nonwoven textiles provide a vast range for property engineering, while facing some challenges in upscaling and use in clothing.

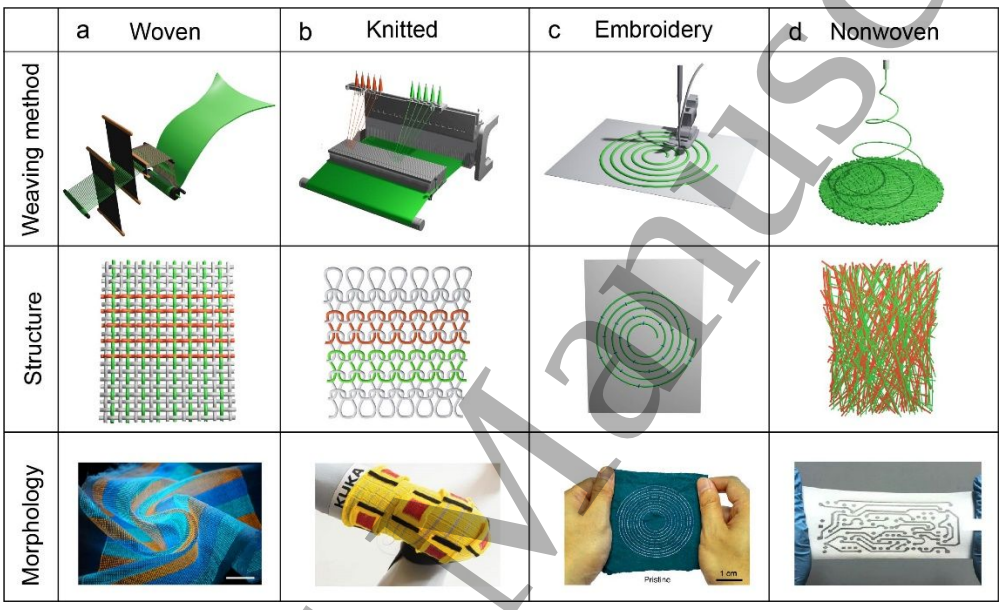


Figure 16. Structure and properties of e-textiles. (a) Woven. Digital photo adapted under the terms of the Creative Commons CC BY license from ref [10]; **(b)** Knitted. Digital photo adapted under the terms of the Creative Commons CC BY license from ref [12]; **(c)** Embroidery. Digital photo adapted under the terms of the Creative Commons CC BY license from ref [13]; **(d)** Nonwoven. Adapted with permission from ref [16]. Copyright 2021 Springer Nature.

Challenges and outlook

Manufacturing electronic fibers involves several key challenges, primarily related to material stability and function heritability. These fibers must retain their electrical properties under varying environmental conditions, as instability can compromise their long-term reliability and performance [17]. The small diameter and high curvature of electronic fibers further complicate their use, requiring precise control to ensure uniform coating and the integrity of functional layers, homogeneity of fillers, and uniformity of fiber twisting. Additionally, achieving continuous manufacturing is essential for scaling production, which demands an optimized balance between efficiency and consistent product quality.

Integrating electronic fibers into standard textile weaving technique is crucial for enhancing the functionality and practicality of e-textiles. However, this process faces challenges due to the immature morphology and weak mechanical properties of electronic fibers, which can negatively impact the performance and comfort of the textiles. Such integration requires modifying existing weaving equipment and methods to accommodate the unique properties of electronic fibers. Furthermore, it is crucial to ensure that incorporating electronic components does not compromise the fabric's flexibility and wearability.

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Developments in advanced materials for e-textiles are poised to significantly enhance the functionality of smart fabrics, opening new horizons for wearable electronics. The concepts of textile-based electronic devices and whole smart fabrics have been proven with great success; however, they face some challenges that preclude them from finding everyday use:

- Rarely do the advanced materials that provide the advantageous properties are tested for prolonged use in fabric form-factor. For example, wear and tear surely can damage intricate fine structures of fibre-based semiconductor junctions, ruining the textile transistors and diodes.
- Everyday use of fabric is also much less forgiving than majority of bench tests. Salinity of sweat and surfactants of wash machines are aggressive factors capable of destabilizing functional coatings, chemical equilibria, removing essential doping. While advancing the functional materials for e-textile is exciting, development of protective coatings, fixers, and sizings, is definitively on a roadmap towards everyday use.
- With big fraction of advanced e-textile function being provided by new materials (including nanosized objects, new small- and macro- molecules, and fine chemical arrangements, such as metal-organic-frameworks and MXenes) production scalability and sustainability of the processes is still a big milestone. Transition from bleeding-edge research onto the warp beam of the loom would require cheap and sustainable methods.

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References

[1] X. Xu, S. Xie, Y. Zhang, and H. Peng, “The rise of fiber electronics,” Angew. Chem. Int. Ed., vol. 58, pp. 13643–13653, Sep. 2019.

[2] X. Song, J. Ji, N. Zhou, M. Chen, R. Qu, H. Li, L. Zhang, S. Ma, Z. Ma, and Y. Wei, “Stretchable conductive fibers: Design, properties and applications,” Prog. Mater. Sci., vol. 144, p. 101288, Aug. 2024.

[3] L. Wei, S. Wang, M. Shan, Y. Li, Y. Wang, F. Wang, L. Wang, and J. Man, “Conductive fibers for biomedical applications,” Bioact. Mater., vol. 22, pp. 343–364, Apr. 2023.

[4] N. Coppedè, M. Giannetto, M. Villani, V. Lucchini, E. Battista, M. Careri, and A. Zappettini, “Ion-selective textile organic electrochemical transistor for wearable sweat monitoring,” Org. Electron., vol. 78, p. 105579, Mar. 2020.

[5] J. S. Heo, K. W. Lee, J. H. Lee, S. B. Shin, J. W. Jo, Y. H. Kim, M. G. Kim, and S. K. Park, “Highly sensitive textile pressure sensors enabled by suspended-type all–carbon nanotube fiber transistor architecture,” Micromachines, vol. 12, p. 1103, Dec. 2020.

[6] G. Loke, W. Yan, T. Khudiyev, G. Noel, and Y. Fink, “Recent progress and perspectives of thermally drawn multimaterial fiber electronics,” Adv. Mater., vol. 32, no. 1, p. e1904911, Jan. 2020.

[7] M. Liao, C. Wang, Y. Hong, Y. Zhang, X. Cheng, H. Sun, X. Huang, L. Ye, J. Wu, X. Shi, X. Kang, X. Zhou, J. Wang, P. Li, X. Sun, P. Chen, B. Wang, Y. Wang, Y. Xia, Y. Cheng, and H. Peng, “Industrial-scale production of fibre batteries by a solution-extrusion method,” Nat. Nanotechnol., vol. 17, pp. 372–377, 2022.

[8] W. Yang, S. Lin, W. Gong, R. Lin, C. Jiang, X. Yang, Y. Hu, J. Wang, X. Xiao, K. Li, Y. Li, Q. Zhang, J. S. Ho, Y. Liu, C. Hou, and H. Wang, “Single body-coupled fiber enables chipless textile electronics,” Science, vol. 384, pp. 74–81, Apr. 2024.

[9] D. Zhang, W. Yang, W. Gong, W. Ma, C. Hou, Y. Li, Q. Zhang, and H. Wang, “Abrasion-resistant and waterproof stretchable triboelectric yarns based on Fermat spirals,” Adv. Mater., vol. 33, p. e2100782, May 2021.

[10] X. Shi, Y. Zuo, P. Zhai, J. Shen, Y. Yang, Z. Gao, M. Liao, J. Wu, J. Wang, X. Xu, Q. Tong, B. Zhang, B. Wang, X. Sun, L. Zhang, Q. Pei, D. Jin, Q. Chen, and H. Peng, “Large-area display textiles integrated with functional systems,” Nature, vol. 591, no. 7849, pp. 240–245, Mar. 2021.

Accepted Manuscript

[11] V. Sanchez, C. Walsh, and R. Wood, "Textile technology for soft robotic and autonomous garments," Adv. Funct. Mater., vol. 31, p. 2008278, Dec. 2020.
[12] Y. Luo, K. Wu, T. Palacios, and W. Matusik, "KnitUI: Fabricating interactive and sensing textiles with machine knitting," in Proc. CHI Conf. Hum. Factors Comput. Syst., 2021.
[13] R. Lin, H. Kim, S. Achavananthadith, Z. Xiong, J. Lee, Y. L. Kong, and J. S. Ho, "Digitally embroidered liquid-metal electronic textiles for wearable wireless systems," Nat. Commun., vol. 13, no. 1, p. 2190, Apr. 2022.
[14] A. Banerji, K. Jin, M. K. Mahanthappa, F. S. Bates, and C. J. Ellison, "Porous fibers templated by melt-blowing cocontinuous immiscible polymer blends," ACS Macro Lett., vol. 10, no. 10, pp. 1196–1203, Sep. 2021.
[15] C. Cui, S. Sun, S. Wu, S. Chen, J. Ma, and F. Zhou, "Electrospun chitosan nanofibers for wound healing application," Eng. Regen., vol. 2, pp. 82–90, Aug. 2021.
[16] Z. Ma, Q. Huang, Q. Xu, Q. Zhuang, X. Zhao, Y. Yang, H. Qiu, Z. Yang, C. Wang, Y. Chai, and Z. Zheng, "Permeable superelastic liquid-metal fibre mat enables biocompatible and monolithic stretchable electronics," Nat. Mater., vol. 20, pp. 859–868, Feb. 2021.
[17] K. Zeng, X. Shi, C. Tang, T. Liu, and H. Peng, "Design, fabrication and assembly considerations for electronic systems made of fibre devices," Nat. Rev. Mater., vol. 8, no. 8, pp. 552–561, Aug. 2023.

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5.3 - Liquid Metals in E-Textiles: Combining Flexibility, Stretchability, and Conductivity

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Status

Liquid metals are interesting materials for electronic textiles (E-textiles) because they combine the electrical and thermal properties of a metal, yet the softness and fluidity of a liquid[1]. Combined, these properties enable metallically conductive fibers that are soft and highly stretchable; for example, we have injected liquid metals into hollow, elastic fibers to produce wires that maintain metallic conductivity to the point of failure of the encasing polymer (800% strain, **Figure 17a**).[2] The ability to conduct electricity is useful for interconnects[2], capacitive sensors of strain / touch / torsion (**Figure 17b**)[3], soft electromagnets[4], [5], and electrodes for energy harvesting [6]. They can also be used to create antibacterial coatings (by galvanic replacement to deposit Cu)[7], autonomously-healing circuits that maintain electrical conductivity when cut (**Figure 18a**)[8], and radiation shielding.

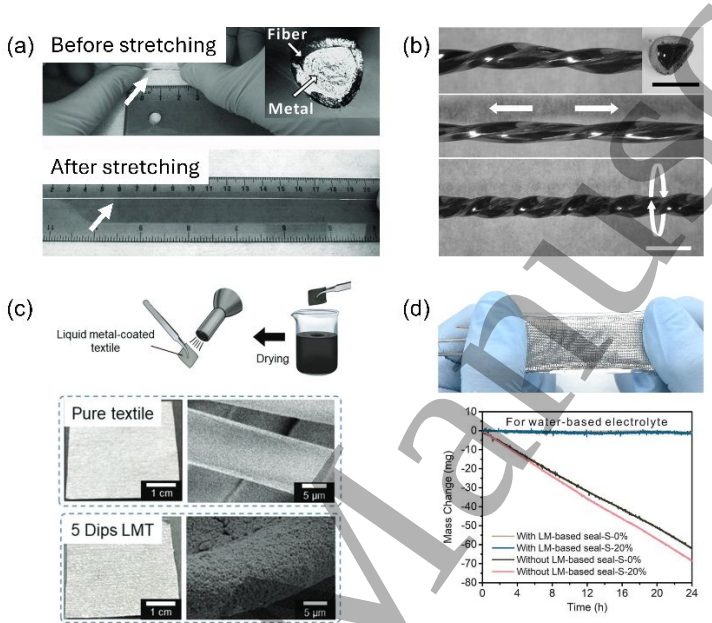


Figure 17. Liquid metal for e-textiles. (a) An ultrastretchable conductive fiber (white arrows) when relaxed (top) and stretched (bottom). The inset is the cross-section of the fiber. **(b)** Two intertwined fibers relaxed (top), stretched (middle), and twisted (bottom). The scale bar is 2.5 mm. Liquid metal fills the core of the fiber (inset; scale bar: 1mm). Changes in the capacitance between the two fibers (or between the fibers and a finger) can sense twisting, strain, and touch. **(c)** Uncoated, pure textile (top) and textile where liquid metal particles are coated via dip coating (bottom). **(d)** Stretchable liquid metal barrier packaging (top). The barrier can prevent water molecules from passing through it (bottom), whereas elastomer films without the liquid metal are highly permeable to vapor.

Here, we define liquid metal as gallium or gallium-based alloys that have melting points below body temperature[9]. These materials are notable because they have water like viscosity, yet unlike water, they have essentially zero vapor and therefore will not evaporate. Although liquid metals have high surface tension, they can be manipulated into non-spherical shapes due to the rapid formation of a thin (~3 nm) native oxide on the surface of the metal[10]. It is possible to break liquid metal into particles that are stabilized (*i.e.* do not merge together) due to the rapid formation of the oxide[11]. This oxide layer also improves the adhesion of the metal and metal particles to fibers used in textiles, which allows for the metal to be coated on the outside of fibers. This can be done by dip coating fabrics into suspensions of liquid metal particles (**Figure 17c**)[8] or by smearing liquid metal across a surface[12]. Such coatings typically allow the textile to maintain breathability due to pores in the coating, although it is also possible to create stretchable hermetic seals by using a conformal coating of metal (**Figure 18d**)[13]. The liquid metal can be injected into hollow fibers either during formation of the fibers via co-extrusion[14] or after forming hollow fibers by injecting

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into a hollow core.[2] The tension of the metal can also be lowered to near-zero using electrochemical oxidation, which can facilitate fiber formation[15] and manipulation (e.g. Lorentz force)[16].

Current and Future Challenges

1. A grand challenge with all conductive fibers, including those that contain liquid metal, is how to make robust electrical connections? For larger fibers, this can be done manually by inserting a wire into the end of the fiber, but there need to be more scalable and easier ways to make such connections, including connections to other electronic components.
2. With liquid metal, there are always practical questions about leakage even though liquid metal is not considered to be toxic. In our experience, liquid metal does not leak out of fibers easily because the oxide layer forms so quickly. However, it remains a possibility that liquid could leak out in principle (especially when compared to other solid conductors).
3. How to make and integrate the fibers? We mentioned several ways to incorporate liquid metal into fibers, but how does one integrate it into a fabric to add function?
4. Because of the surface roughness, it is difficult to adhere liquid metal directly to textiles (with the exception of small particle, **Figure 17c**). Are there better ways to promote direct wetting to textiles (**Figure 18c**)[18]?

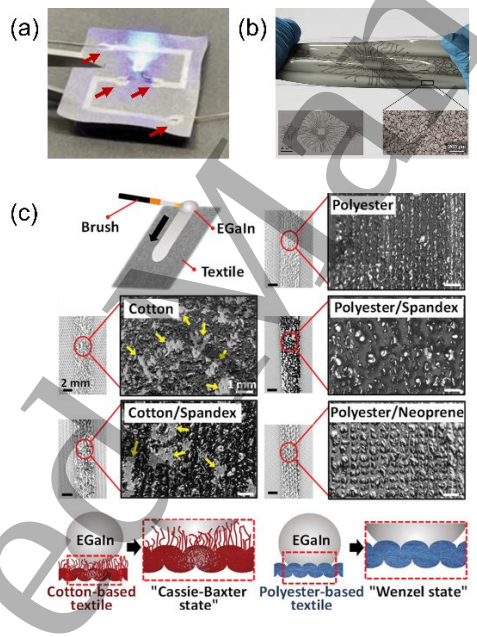


Figure 18. Current and future challenges of liquid metal for e-textiles. (a) An additional conductive paste (red arrows) was used to attach electrical connections to the liquid metal-coated textiles, but this approach is not scalable or robust enough for practical applications. **(b)** Liquid metal droplets encapsulated in a polydimethylsiloxane network prevents leakage. **(c)** Direct painting method of liquid metal on multiple textiles. Rough textiles are difficult to 'wet' with liquid metal.

Advances in Science and Technology to Meet Challenges

Approaches need to be explored and developed to more easily integrate and connect fibers that contain liquid metal. Fibers containing liquid metal need to be robust to be used for weaving methods and to prevent liquid metal from leaking [19]. Future studies can focus on understanding the mechanics of these systems, the wetting behaviour of liquid metals, and the durability, particularly when it comes to washing cycles and normal wear.

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Concluding Remarks

Liquid metals have several truly unique properties that are useful for e-textiles including conductivity and stretchability. Although there are many unique things that liquid metal can do for E-textiles (e.g. self-healing[8], antibacterial coatings [7]), there remain challenges in how to integrate and connect such materials into robust and functional E-textiles.

Acknowledgements

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References

[1] M. D. Dickey, "Stretchable and soft electronics using liquid metals," Adv. Mater., vol. 29, no. 27, p. 1606425, 2017, doi: 10.1002/adma.201606425.
[2] S. Zhu et al., "Ultrastretchable fibers with metallic conductivity using a liquid metal alloy core," Adv. Funct. Mater., vol. 23, no. 18, pp. 2308–2314, May 2013, doi: 10.1002/adfm.201202405.
[3] C. B. Cooper et al., "Stretchable capacitive sensors of torsion, strain, and touch using double helix liquid metal fibers," Adv. Funct. Mater., vol. 27, no. 20, p. 1605630, May 2017, doi: 10.1002/adfm.201605630.
[4] Y. Xu et al., "A soft magnetoelectric finger for robots' multidirectional tactile perception in nonvisual recognition environments," npj Flex. Electron., vol. 8, no. 1, pp. 1–11, Jan. 2024, doi: 10.1038/s41528-023-00289-6.
[5] R. Lin et al., "Digitally embroidered liquid metal electronic textiles for wearable wireless systems," Nat. Commun., vol. 13, no. 1, p. 2190, Apr. 2022, doi: 10.1038/s41467-022-29859-4.
[6] Y.-C. Lai et al., "Elastic multifunctional liquid–metal fibers for harvesting mechanical and electromagnetic energy and as self-powered sensors," Adv. Energy Mater., vol. 11, no. 18, p. 2100411, 2021, doi: 10.1002/aenm.202100411.
[7] K. Y. Kwon et al., "A liquid metal–mediated metallic coating for antimicrobial and antiviral fabrics," Adv. Mater., vol. 33, no. 45, p. 2104298, 2021, doi: 10.1002/adma.202104298.
[8] J. Yang et al., "Liquid metal–coated textiles with autonomous electrical healing and antibacterial properties," Adv. Mater. Technol., vol. 8, no. 14, p. 2202183, 2023, doi: 10.1002/admt.202202183.
[9] S.-Y. Tang, C. Tabor, K. Kalantar-Zadeh, and M. D. Dickey, "Gallium liquid metal: The devil's elixir," Annu. Rev. Mater. Res., vol. 51, pp. 381–408, 2021, doi: 10.1146/annurev-matsci-080819-125403.
[10] M. D. Dickey, R. C. Chiechi, R. J. Larsen, E. A. Weiss, D. A. Weitz, and G. M. Whitesides, "Eutectic gallium–indium (EGaIn): A liquid metal alloy for the formation of stable structures in microchannels at room temperature," Adv. Funct. Mater., vol. 18, no. 7, pp. 1097–1104, Apr. 2008, doi: 10.1002/adfm.200701216.
[11] Y. Lin, J. Genzer, and M. D. Dickey, "Attributes, fabrication, and applications of gallium-based liquid metal particles," Adv. Sci., vol. 7, no. 12, p. 2000192, 2020, doi: 10.1002/advs.202000192.
[12] Z. Ma et al., "Permeable superelastic liquid-metal fibre mat enables biocompatible and monolithic stretchable electronics," Nat. Mater., vol. 20, pp. 859–868, Feb. 2021, doi: 10.1038/s41563-020-00902-3.
[13] Q. Shen et al., "Liquid metal–based soft, hermetic, and wireless-communicable seals for stretchable systems," Science, vol. 379, no. 6631, pp. 488–493, Feb. 2023, doi: 10.1126/science.ade7341.
[14] M. A. H. Khondoker, A. Ostashek, and D. Sameoto, "Direct 3D printing of stretchable circuits via liquid metal co-extrusion within thermoplastic filaments," Adv. Eng. Mater., vol. 21, no. 7, p. 1900060, 2019, doi: 10.1002/adem.201900060.

Accepted Manuscript

[15] M. Song et al., "Overcoming Rayleigh–Plateau instabilities: Stabilizing and destabilizing liquid-metal streams via electrochemical oxidation," Proc. Natl. Acad. Sci. U.S.A., vol. 117, no. 31, pp. 19023–19030, Jul. 2020, doi: 10.1073/pnas.2006122117.
[16] Y. He, J. Tang, K. Kalantar-Zadeh, M. D. Dickey, and X. Wang, "Noncontact rotation, levitation, and acceleration of flowing liquid metal wires," Proc. Natl. Acad. Sci. U.S.A., vol. 119, no. 6, p. e2117535119, Feb. 2022, doi: 10.1073/pnas.2117535119.
[17] E. J. Markvicka, M. D. Bartlett, X. Huang, and C. Majidi, "An autonomously electrically self-healing liquid metal–elastomer composite for robust soft-matter robotics and electronics," Nat. Mater., vol. 17, no. 7, pp. 618–624, Jul. 2018, doi: 10.1038/s41563-018-0084-7.
[18] M.-Y. Choi, J.-H. Kim, S.-K. Kim, H.-J. Koo, and J.-H. So, "Textile-based stretchable supercapacitors with liquid metal current collectors," Adv. Funct. Mater., p. 2310318, 2023, doi: 10.1002/adfm.202310318.
[19] Y. Xu et al., "Porous liquid metal–elastomer composites with high leakage resistance and antimicrobial property for skin-interfaced bioelectronics," Sci. Adv., vol. 9, no. 1, p. eadf0575, Jan. 2023, doi: 10.1126/sciadv.adf0575.

5.4 - Prospects and Opportunities in Smart-Textile Sensors based on MXene Nanocomposites

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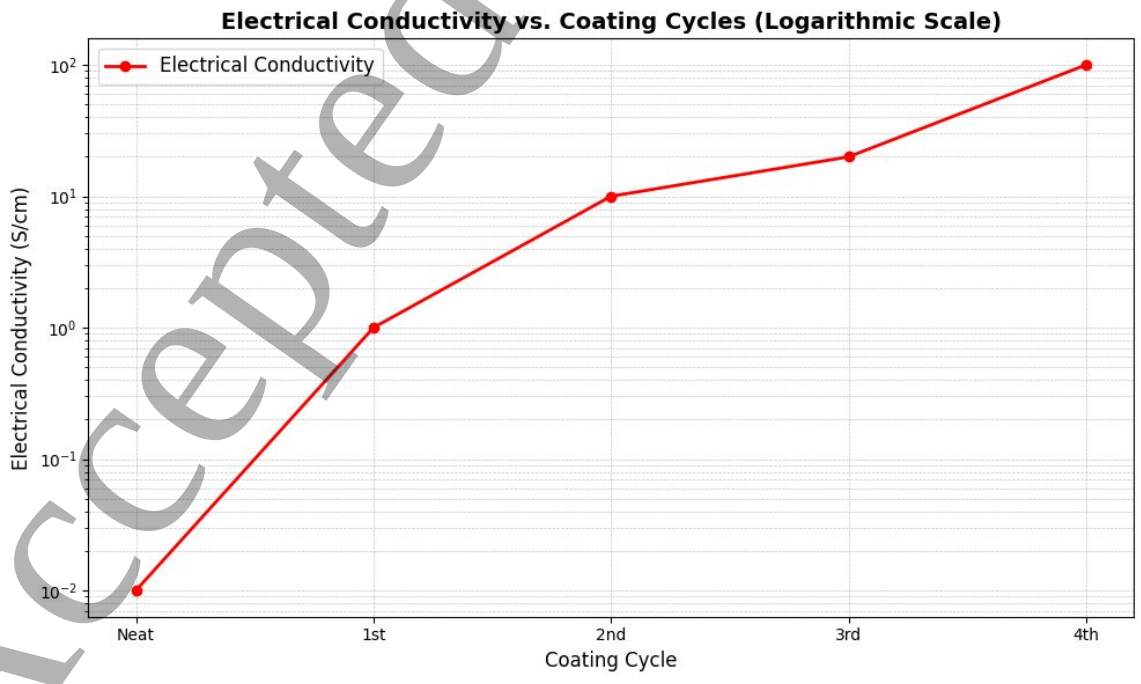
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Status

Smart textile sensors engineered with advanced nanomaterials and nanostructures combine the natural advantages of textiles, such as mechanical flexibility, air permeability, and washability, with diverse functionalities, enabling real-world applications like physiological signal monitoring and motion tracking. MXenes, a family of two-dimensional (2D) transition metal carbides or nitrides, offer a unique combination of mechanical flexibility, strength, solution processability, adjustable surface chemistry, and metallic conductivity, making them highly promising for integration into smart textiles[1]. Abundant recent studies have demonstrated the 2D MXene nanosheets can be combined with other nanomaterials (graphene, CNT, TMDs) to form functional composites for advanced sensing, energy storage, functional catalysis, and green technology. When MXenes and their hybrids, with different structures (fibre, yarn, fabrics), are integrated into the design of textile-based wearable devices, broad applications are prospected [1-4].

Numerous laboratory-scale fabrication techniques have emerged for creating MXene-integrated wearable smart-textile sensors, highlighting their potential for scalable applications. Among them, coating and spinning methods are currently widely adopted for such purpose [5]. Moreover, surface-engineered 2D MXenes and their hybrids displayed excellent dispersion in multiple solvents, allowing them to be strongly attached on the yarns via blade coating, dip-coating, roll coating, spin coating, etc.

Figure 19 demonstrates the electrical conductivity of MXene-coated cellulose fibers with successive dip-coating cycles. As shown, conductivity improves exponentially from 10^{-2} S/cm for untreated fibers to 10^{2} S/cm after the fourth cycle. This trend highlights the ability of dip-coating to create a continuous, uniform MXene layer on fibers, enhancing their conductivity. These results align with the findings of Kim et al. (2024)[6], who demonstrated similar improvements in their experimental analysis. Such enhancements are crucial for high-performance wearable electronic applications, such as energy storage and healthcare monitoring, emphasizing the scalability of the dip-coating process for industrial production.



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Figure 19. Electrical conductivity of MXene-coated cellulose fibers as a function of dip-coating cycles. Conductivity increases exponentially with successive coating cycles, progressing from 10^{-2} S/cm for the untreated fiber (Neat) to approximately 10^{2} S/cm after the 4th cycle. The logarithmic scale highlights the significant enhancement in conductivity, reflecting the formation of a uniform MXene network with additional coatings, as reported by Kim et al. (2024)[6].

For spinning methods, including electrospinning, wet spinning, and melting spinning, functional MXene composites (MXene/metal, MXene/nanocarbons) are mixed with the dissolved polymer matrix, then the mixture is extruded into fibres in coagulation bath or under high-voltage electrostatic field. The MXene-incorporated multi-functional fibres are eventually transformed into textile structures. Alternatively, a number of additive manufacturing techniques (3D printing, inkjet printing, screen printing) allows print-out of MXene-based composites with programable patterns onto textiles substrates [7].

Various textiles structures integrated with MXene composites has been demonstrated recently, including fibre (0D), yarn (1D), fabrics, layered textile (2D), and multi-directional textile (3D) [5]. These structured textile materials exhibit large surface aera, stretchability, and designed sensing properties, due to the adjustable physiochemical properties of MXene composites and engineered textile structure.

Stimulus-responsive attributes of MXene composites allow textiles not only to sense but react to external environment conditions [5, 8-10]. These smart sensors have the capability of collar-changing, shape deforming, energy harvesting. The real-word applications of MXene-integrated textile sensors involves healthcare monitoring and medical treatment (heart rate, antibacterial), environmental detection (humidity, hazardous gases), and human motion (wrist bending, voice recognition). The underlying sensing mechanisms are also proposed, and verified experimentally and theoretically. Machine learning algorithms accelerate the design of MXene-integrated textile with programable sensing properties, i.e., sensitivity, sensing range [9-11].

Current and Future Challenges

It remains to be a great challenge to produce MXene-integrated textile sensors with low cost, large scale, and high performance, through the optimization of functional MXene composites, fabrication techniques, and textile structure, as shown in **Figure 20**.

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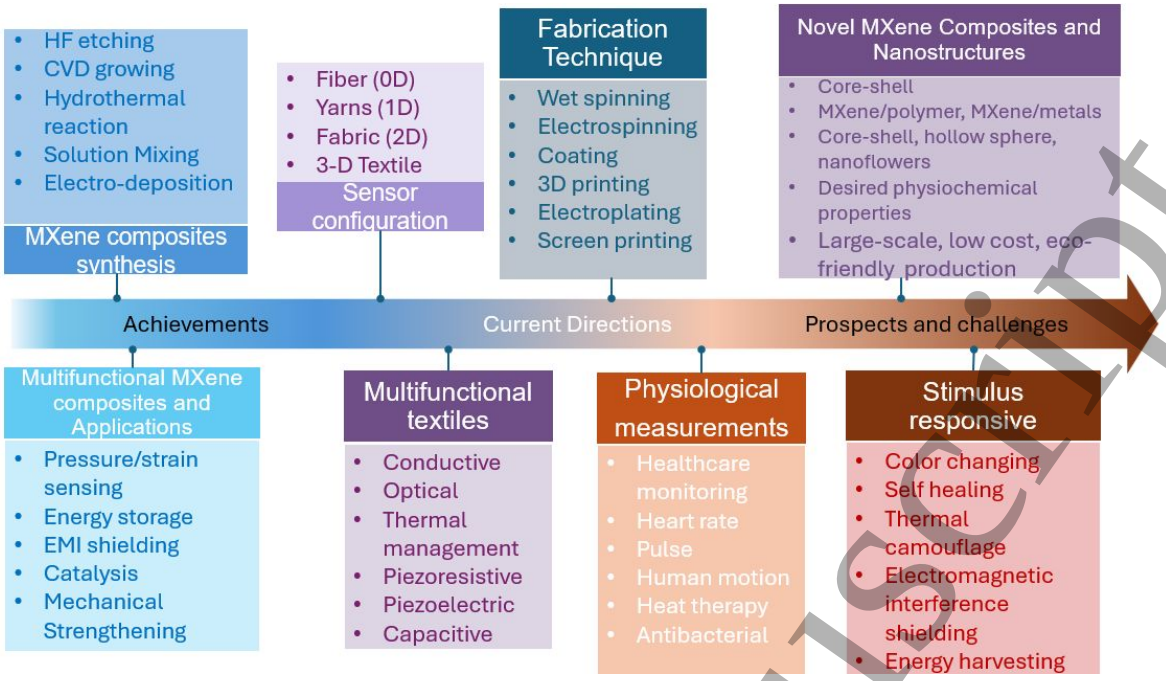


Figure 20. Progression from MXene synthesis to smart-textile applications, illustrating current achievements, emerging directions, and future challenges in sensor development.

In general, the prevalent dip coating fabrication technique, although simple, fast, and scale-up feasibility, suffers from poor mechanical properties, uneven coating thickness, and only surface coverage in the targeted substrate, thus limiting the transfer of high performance of MXene composites to textiles [1, 2, 12-14]. Wet spinning and electrospinning technique, which allows MXene materials to infiltrate the interior of the textiles, has the issues of low production efficiency, low stability, and requires either high voltage or high working temperature. 3D printing technology can adapt to complex and customized textile structures, and large-scale fabrication, but is restricted to low printing speed and moderate spatial resolution [7]. Evaluation standards are needed to assess the performance among diverse types of MXene-integrated textile sensors.

Developing low-cost, environmentally friendly, and efficient fabrication technologies for MXene-based materials is essential for the large-scale production of smart textile sensors. Currently, MAX-phase materials (precursor of MXene) are of high cost, and MXenes are mostly produced at laboratory scale of < 1 kg batches [5, 7]. Predominant synthesis methods of MXene materials usually involves toxic chemicals (hydrofluoric acid) and environmentally non-friendly processes. Thus, large-scale production of MXene (kilograms or even tons in quantities) with low cost and environmental-benign technologies is important. Meanwhile, the quality of MXene (flake size, chemical composition, defects) should be guaranteed at scale-up production. Furthermore, the long-term stability of MXene is problematic, due to its ease of oxidation in open air and humid conditions. Besides, the combination of MXene composites with textile, could affect the aesthetic, air permeability, and comfortability [14, 15]. MXene-based materials could be degraded or lost from textiles after repeated washing or exposure to harsh working environment. At the same time, the sensing performance might be compromised. Therefore, performance durability is required. Physiological measurements with the novel textile sensors should have high effectiveness and reliability, free from disturbance of noise.

More than 60 MXene members have been developed, but so far, the most widely used one is $Ti_3C_2T_x$. Exploring the property and functionalities of other MXene materials and their composites helps to discover new functionalities of smart textiles sensors, and their applications in diverse real-world scenarios.

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Advances in Science and Technology to Meet Challenges

To address the challenges of the preparation of MXene composites, structures, and performance of MXene-integrated smart textile sensors. Advances in MXene synthesis, surface functionalization, sensor fabrication, sensing performance optimization, and data acquisition are required.

To address the issues of toxic, harmful etchant, and subsequent environmental pollution, new synthetic strategies of MXene materials have been established, with the use of new mixed etchant, molten salts, and organic alkaline, and chemical vapor deposition as shown in **Figure 20** [16]. These novel preparation of MXenes allows appropriate control of surface-terminating groups of 2D MXene flakes, which facilitates the constitution of composite materials with heterostructures, for targeted sensing applications.

Humidity and temperature significantly influence the oxidation of MXenes. To enhance their stability under ambient conditions, several strategies have been proposed, including defect passivation and surface encapsulation techniques. These methods involve the passivation of the defects (like vacancy) of MXene flake, using organic solvents for MXene dispersions, and encapsulating polymetric layer (like polydopamine (PDA)) or antioxidant agents (like ascorbic acid) on MXenes [5, 17, 18].

Appropriate composition of MXene inks (additives, solvents) and rheological property (like viscosity, concentration) is pre-requisite for printing MXene materials onto textiles. Desirable MXene inks with the characteristics of additive-free, eco-friendly, high-concentration, elongated shelf life have been developed recently, through printing device configuration, ink's rheological optimization [7]. And the printed MXene electrodes shows excellent chemical stability, evident of absence of electrical performance loss for months. Improving the adhesion between MXene composites and textile is crucial for maintaining the long-term performance of sensors. Currently, textile surface modification (like oxygen plasma treatment) and using conductive and adhesive binders (like PEDOT:PSS) are proved to overcome the adhesion issue [2].

Lastly, developing wearable, smart-sensing platform integrated all-in-one MXene-based sensors relies on the exploration of fundamental properties of MXene composites. For example, novel MXene-reinforced cellulose nanofibril textile was carried out through 3D printing [12]. This sensor exhibits significant responsiveness to multiple external stimuli (electrical/photonic/mechanical) for applications like wearable heating textiles, human health monitoring. A hierarchical core-shell yarn structure (HCPYs), featured by strong mechanical properties and conductivity, was developed for full-textile human motion detection [19]. A composite fibre based on a distinct skin-core structure (MXene@aramid) shows high tensile strength, fast response time, long service life, wide and fast heating temperature, which can be used for smart heating and piezoresistive sensors [20].

Concluding Remarks

We summarized the recent progress on the MXene composites integrated smart-textile sensors, with respect to synthesis of MXenes and their novel composites, design of novel multifunctional 0D/1D/2D/3D nanostructures of MXene composites, and their integration into smart-textile sensors for real-world healthcare and medical monitoring, human motion detection, environmental detection, in addition to the external stimulus responsive capability. Current challenges fall on the understanding of fundamental properties of MXene composites, rational integration of MXenes into textiles substrate, optimization of sensor's structure for targeted performances and applications. Advancements in composite materials, surface chemistry, additive manufacturing, and device physics

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are essential to overcoming these challenges and unlocking the full potential of MXene-based smart textiles.

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References

[1] M. M. Atta and Q. Zhang, "Recent advances in 2D materials for smart textiles," FlatChem, vol. 42, p. 100562, 2023, doi: 10.1016/j.flatc.2023.100562.

[2] V. K. Chauhan, R. Dubey, R. Pandey, P. Thennarasu, and S. K. Dubey, "MXene on textile substrates: A review," Adv. Eng. Mater., vol. 26, no. 7, p. 2301962, 2024, doi: 10.1002/adem.202301962.

[3] T. Li et al., "A flexible pressure sensor based on an MXene–textile network structure," J. Mater. Chem. C, vol. 7, no. 4, pp. 1022–1027, 2019, doi: 10.1039/c8tc04893b.

[4] X. Fu et al., "Knitted $Ti_3C_2T_x$ MXene-based fiber strain sensor for human–computer interaction," J. Colloid Interface Sci., vol. 604, pp. 643–649, 2021, doi: 10.1016/j.jcis.2021.07.025.

[5] C. Jin and Z. Bai, "MXene-based textile sensors for wearable applications," ACS Sens., vol. 7, no. 4, pp. 929–950, 2022, doi: 10.1021/acssensors.2c00097.

[6] C. S. Kang et al., "Facile fabrication and characterization of MXene/cellulose composites for electrical and electrothermal performance," Fashion Textiles, vol. 11, no. 1, p. 1, 2024, doi: 10.1186/s40691-023-00356-6.

[7] T. Li, E. Jabari, K. McLellan, and H. E. Naguib, "Additive manufacturing with 2D MXenes: Techniques, applications, and perspectives," Prog. Addit. Manuf., vol. 8, no. 6, pp. 1587–1617, 2023, doi: 10.1007/s40964-023-00424-9.

[8] Z. Guo, Y. Li, Z. Lu, and W. Liu, "Applications of MXene-based composite fibers in smart textiles," in J. Phys.: Conf. Ser., vol. 1790, no. 1, p. 012066, 2021, doi: 10.1088/1742-6596/1790/1/012066.

[9] Y. Zhao, C. Wu, Y. Wang, J. Lan, and S. Chen, "Research progress of MXene-modified textiles for flexible strain sensing," J. Text. Res., vol. 35, no. 1, pp. 48–60, 2022, doi: 10.13338/j.issn.1006-8341.2022.01.006.

[10] G. Hang et al., "MXene nanosheet composites for flexible pressure sensors: A review," ACS Appl. Nano Mater., vol. 5, no. 10, pp. 14191–14208, 2022, doi: 10.1021/acsanm.2c03268.

[11] X. Zheng et al., "Multifunctional RGO/$Ti_3C_2T_x$ MXene fabrics for energy storage, EMI shielding, electrothermal and motion sensing," Mater. Des., vol. 200, p. 109442, 2021, doi: 10.1016/j.matdes.2020.109442.

[12] W. T. Cao et al., "MXene-reinforced cellulose nanofibril inks for 3D-printed smart fibres and textiles," Adv. Funct. Mater., vol. 29, no. 51, p. 1905898, 2019, doi: 10.1002/adfm.201905898.

[13] S. Maity, K. Singha, and P. Pandit, "Emerging trends in electroconductive textiles," in Smart and Functional Textiles. Elsevier, 2023, pp. 221–266.

[14] J. Yin, N. Liu, and Y. Gao, "Recent progress of MXene in pressure sensing," J. Inorg. Mater., vol. 39, no. 2, pp. 179–185, 2024, doi: 10.15541/jim20230397.

[15] J. Wang, R. Zhang, Y. Zheng, Z. Dong, and Z. Zou, "Progress of MXene-based flexible textile pressure sensors," J. Text. Res., vol. 45, no. 6, pp. 219–226, 2024, doi: 10.13475/j.fzxb.20230605002.

[16] A. Ahmed, M. M. Hossain, B. Adak, and S. Mukhopadhyay, "2D MXene integrated smart-textile interfaces for multifunctional applications," Chem. Mater., vol. 32, no. 24, pp. 10296–10320, 2020, doi: 10.1021/acs.chemmater.0c03392.

[17] R. Eslami et al., "3D dual-network alkalinized MXene/hBN–PVA composites for wearable strain and pressure sensing," Chem. Eng. J., vol. 480, p. 148063, 2024, doi: 10.1016/j.cej.2023.148063.

[18] H. Li and Z. Du, "MXene fiber-based wearable textiles for sensing and energy storage," Fibers Polym., vol. 24, no. 4, pp. 1167–1182, 2023, doi: 10.1007/s12221-023-00104-z.

Accepted Manuscript

[19] W. Zhong et al., "Full-textile human motion detection systems using hierarchical core–shell piezoresistive yarns," ACS Appl. Mater. Interfaces, vol. 13, no. 44, pp. 52901–52911, Nov. 2021, doi: 10.1021/acsami.1c14777.

[20] L. Wang, M. Zhang, B. Yang, and J. Tan, "Lightweight and robust MXene@aramid nanofiber composite fibers for smart fabric sensors," ACS Appl. Mater. Interfaces, vol. 13, no. 35, pp. 41933–41945, Sep. 2021, doi: 10.1021/acsami.1c13645.

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5.5 - Nanomaterials Conductive Inks in E-Textiles: Challenges and Future Perspectives

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Status

The evolution of e-textiles has been significantly propelled by advancements in conductive inks, including emerging materials such as silver, carbon-based nanomaterials, MXene, graphene, and liquid metals. These innovations have enabled the integration of electronic functionalities into textiles, including energy harvesting, sensing, and communication. Among these materials**,** Liquid Metal Inks exhibit the highest electrical conductivity, reaching up to 10^7 S/m, surpassing MXene-based inks and graphene on various substrates, such as cotton and cellulose. This perspective looks into the latest developments in conductive inks for e-textiles, highlighting the performance of MXene-based inks, carbon-based inks, metallic inks, and liquid metal inks. It further discusses challenges associated with durability, cost, scalability, and electrical conductivity. Insights into sustainable practices, future research directions, and practical applications are provided to support the advancement of e-textile technology.

The intersection of textiles and electronics has given rise to e-textiles, a burgeoning field poised to revolutionize industries ranging from healthcare to fashion. At the core of this innovation is the development of conductive inks—materials that facilitate the integration of electronic functionalities into fabrics without compromising their inherent properties. Recent advancements in materials science have introduced innovative conductive inks based on MXenes, carbon nanomaterials, metallic nanoparticles, and liquid metals. These developments provide unprecedented opportunities but also pose significant challenges in manufacturing, scalability, and durability. This perspective offers a comprehensive overview of the state-of-the-art conductive inks for e-textiles, explores the challenges in their integration, and discusses future research directions and applications.

1. Metallic Inks

Particles of noble metals such as gold (Au), copper (Cu), and silver (Ag), are gaining significant attention as potential conductive materials in printed electronics [1-4]. Among these, silver nanoparticles (AgNPs) are the most widely used due to their exceptional conductivity, anti-oxidation characteristics, and remarkable stability at ambient temperatures [5-7]. These properties make AgNPs highly attractive for use in conductive inks, as they can be conveniently incorporated into formulations that adhere more effectively to various substrates compared to other metals. One key aspect in the development of high-performance Ag-based inks is the control of nanoparticle size, shape, and surface chemistry. By manipulating these parameters, it is possible to tailor the electrical,

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optical, and mechanical properties of the inks. For instance, smaller AgNPs tend to exhibit higher conductivity due to their increased surface area, while larger AgNPs may provide enhanced mechanical strength and adhesion to the substrate. Additionally, the surface chemistry of AgNPs can be modified to improve their dispersion stability and compatibility with different solvents and resins used in ink formulations.

Furthermore, the development of novel printing techniques has played a crucial role in advancing the application of Ag-based conductive inks. Traditional printing methods, such as screen printing and gravure printing, have been widely used for the fabrication of printed electronics. However, these techniques often face limitations in terms of resolution, precision, and scalability. To overcome these challenges, advanced printing technologies, such as inkjet printing and aerosol jet printing, have emerged as promising alternatives. These techniques offer the ability to precisely control the deposition of Ag-based inks, enabling the creation of complex patterns and structures with high resolution and accuracy.

Innovations in bio-sourced silver inks

Bio-sourced silver inks represent a significant advancement in the field of sustainable and environmentally friendly printing technologies [8-10]. These inks are formulated using natural polymers and solvents derived from renewable resources, such as plant-based materials or agricultural byproducts. By utilizing bio-sourced components, silver inks can significantly reduce their environmental impact compared to traditional inks that rely on synthetic materials. One of the key advantages of bio-sourced silver inks is their improved inkjet printability. The natural polymers act as effective binders, ensuring that the silver particles are evenly dispersed and stabilized within the ink formulation. This enhanced printability allows for precise and consistent printing results, making bio-sourced silver inks suitable for various applications such as textiles, electronics, and packaging.

Another notable benefit of bio-sourced silver inks is their ability to be cured at lower temperatures [11-13]. Traditional silver inks often require high curing temperatures, which can damage heat-sensitive substrates such as delicate textiles or thin films. Bio-sourced silver inks, on the other hand, can be cured at significantly lower temperatures, making them ideal for printing on a wider range of materials. This versatility opens up new possibilities for innovative applications and designs. Furthermore, bio-sourced silver inks offer improved conductivity and electrical properties compared to traditional inks. The unique characteristics of the natural polymers and silver particles enable these inks to create highly conductive patterns and traces when printed. This makes them particularly suitable for applications in printed electronics, where precise and reliable electrical connections are crucial.

The development of bio-sourced silver inks aligns with the growing demand for sustainable and eco-friendly printing solutions. By offering improved printability, lower curing temperatures, and enhanced electrical properties, bio-sourced silver inks have the potential to transform various industries and contribute to a more environmentally conscious future.

Challenges: Silver inks face several challenges:

- **Cost**: Silver inks are significantly more expensive than other conductive inks, such as those based on carbon, primarily due to the high cost of silver as a raw material.

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- **Stability**: Silver inks are less stable than other conductive inks. They can easily oxidize, leading to decreased conductivity over time. Oxidation can also cause the silver nanoparticles in the ink to migrate, further reducing conductivity.
- **Washability**: Silver inks are less washable than other types of conductive inks, making them difficult to remove from clothing or other fabrics if accidentally spilled.
- **Scalability**: The high cost and limited stability of silver inks make them difficult to scale up for large-scale production.
- **Commercial Viability**: Due to the high cost, limited stability, and poor washability, silver inks are less attractive to manufacturers and consumers, affecting their commercial viability.

2. Carbon-Based Inks

Carbon-based nanomaterials such as carbon nanotubes (CNTs) and graphene are celebrated for their extraordinary electrical, thermal, and mechanical properties. These unique characteristics make them highly suitable for various applications, particularly in the realms of wearable technologies and flexible electronics.

Carbon nanotubes (CNTs): CNTs are cylindrical nanostructures composed entirely of carbon atoms arranged in a hexagonal lattice [14-16]. They exhibit exceptional electrical conductivity, surpassing even that of copper, which makes them ideal for efficient charge transport applications. Their excellent thermal conductivity ensures effective heat dissipation, crucial for wearable devices that generate heat during operation. Additionally, CNTs possess remarkable mechanical strength, contributing to their durability and resistance to wear and tear in electronic textiles (e-textiles).

Graphene: Graphene is a single layer of carbon atoms arranged in a hexagonal lattice, forming a two-dimensional plane [16-19]. Renowned for its outstanding electrical properties, including high carrier mobility and low electrical resistance, graphene is an excellent material for applications requiring fast and efficient charge transfer, such as in transistors and transparent electrodes. Furthermore, graphene boasts superior thermal conductivity, even higher than that of CNTs, making it highly effective for heat management in wearable devices.

Advances in dispersion techniques: One of the main challenges in utilizing CNTs and graphene in wearable applications is their tendency to aggregate due to strong van der Waals forces, which can lead to inconsistent performance and processability issues. To spread carbon nanotubes evenly in ink, scientists use surfactants—chemicals that keep the nanotubes from clumping together. This makes the ink more stable and ensures it works well on fabrics. These inks enable uniform integration of the nanomaterials into flexible e-textile structures, enhancing the reliability and performance of the resulting devices.

Biocompatibility for wearable health monitoring: The inherent biocompatibility of CNTs and graphene opens up exciting possibilities for wearable health monitoring devices. Their high electrical conductivity and sensitivity to biological signals make them suitable for applications such as wearable sensors, biosensors, and medical imaging. By integrating these materials into e-textiles, it is possible to create smart clothing capable of monitoring vital signs, detecting biomarkers, and tracking physiological changes in real time.

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Graphene-silver composite inks: Combining graphene with metallic nanoparticles like silver has led to the development of composite inks that offer high conductivity at reduced costs. These inks leverage the excellent electrical properties of graphene and the superior conductivity of silver to achieve low sheet resistance. The synergistic effect results in inks that are particularly suitable for inkjet printing on textiles, providing good flexibility and mechanical stability. This combination is cost-effective, as the amount of silver required is significantly reduced, making it viable for large-scale manufacturing and commercial applications.

Challenges: Despite their promising attributes, carbon-based inks face several challenges that need to be addressed to fully realize their potential in textile applications:

- **Uniform dispersion:** Ensuring a uniform dispersion of CNTs and graphene within the ink is crucial. Agglomeration can lead to inconsistent electrical properties and poor printability. Optimizing ink formulations with appropriate surfactants, solvents, and mixing processes is essential.
- **Strong adhesion to textile fibers:** The inks must adhere strongly to textile fibers to withstand mechanical stress from bending, stretching, and washing. Weak adhesion can result in the detachment of printed patterns, compromising durability. Surface modification techniques and the use of compatibilizers can enhance adhesion.
- **Interaction with textile substrate:** The interaction between the carbon nanomaterials and the textile substrate affects the durability and washability of the printed patterns. Understanding and optimizing this interaction is key to maintaining functionality over time.

3. MXene-Based Conductive Inks

MXenes are a class of two-dimensional transition metal carbides and nitrides known for their exceptional electrical conductivity and mechanical flexibility [20-23]. Discovered in the early 2010s, MXenes have quickly become significant due to their metallic conductivity, hydrophilicity, and ease of functionalization. Their layered structure facilitates the intercalation of various ions and molecules, enhancing their versatility across multiple applications. Besides their electrical conductivity, MXenes also demonstrate remarkable mechanical flexibility. Their structure allows for easy exfoliation into thin, flexible sheets, which can be bent, rolled, or twisted without losing structural integrity. This adaptability makes MXenes ideal for integrating into flexible devices and wearable technologies.

A notable feature of MXenes is their hydrophilicity, which ensures easy dispersion in water and stable colloidal suspensions. This property is particularly useful for applications in water purification, sensing, and biomedical engineering. MXenes can be improved by adding special molecules. For example, adding alkylamines makes them more stable and stops them from breaking down, while adding tiny metal particles can make them better at conducting electricity for e-textiles. This adaptability lets researchers tailor MXene properties for specific applications, such as enhancing catalytic activity with metal nanoparticles or improving stability and functionality with polymers. Recent advances have focused on developing additive-free conductive inks that achieve 100% utilization of precursor materials, facilitating the scalable fabrication of high-performance e-textiles with multifunctional capabilities.

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The ability to intercalate ions and molecules between MXene layers, thanks to their layered structure and weak van der Waals forces, is promising for energy storage applications, including lithium-ion batteries and supercapacitors. The unique combination of electrical conductivity, mechanical flexibility, hydrophilicity, and functionalizability makes MXenes highly versatile for a wide range of applications. These materials show great potential in fields such as energy storage, catalysis, electronics, water purification, and sensing. As research and development continue, the possibilities for MXenes seem limitless. MXene-based inks enhance EMI shielding, making them suitable for electronics and healthcare applications where protection from electromagnetic noise is crucial. Additionally, their antibacterial properties make them ideal for healthcare environments. The efficient electrothermal conversion of these inks also opens up possibilities for wearable heating applications, offering adjustable warmth in cold environments.

Challenges: Despite their promising attributes, MXene-based inks face several challenges:

- **Complex and hazardous synthesis:** Making MXenes often requires dangerous chemicals like hydrofluoric acid (HF). However, safer options, like using ammonium bifluoride, are being explored to make the process less harmful, the process is complex, requires specialized equipment, and poses significant health and environmental risks.
- **Oxidation and degradation:** MXenes are prone to oxidation, which can degrade their electrical properties over time. This oxidation reduces their conductivity and electrochemical activity, significantly impacting their performance across various applications.
- **Cost and scalability:** The specialized and hazardous nature of MXene production leads to high costs and challenges in scaling production to meet industrial demands.
- **Lack of standardization:** The absence of standardized protocols for MXene synthesis and characterization makes it difficult to ensure consistency and reliability in their properties and performance.
- **Environmental impact:** The environmental concerns associated with the use of hazardous chemicals in MXene synthesis necessitate the development of more sustainable and eco-friendly production methods.

Addressing these challenges through continued research and technological innovation is crucial for unlocking the full potential of MXene-based inks and enabling their broader adoption in various applications.

4. Liquid metal – Gallium and gallium alloys

Gallium and its alloys, notably eutectic gallium-indium (EGaIn) alloys, have captured the attention of researchers in advanced materials due to their remarkable properties [24-29]. These liquid metals are emerging as leading candidates for highly stretchable and self-healing conductive materials, retaining their liquid state at room temperature and showcasing excellent electrical conductivity.

- **Low melting point:** EGaIn alloys have a melting point around 15.7°C (60.3°F), which means they remain liquid at room temperature. This characteristic enables EGaIn and similar alloys to be easily manipulated and shaped, ideal for applications requiring flexibility and conformability.
- **High electrical conductivity:** EGaIn exhibits electrical conductivity comparable to traditional metals like copper and silver, making it an excellent choice for stretchable and flexible

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electronics. Unlike rigid metals, EGaIn can undergo significant deformation without losing electrical functionality.

- **Self-healing capabilities:** Gallium alloys can heal themselves if they get damaged, like cuts or scratches. This is useful for making wearable devices that need to bend and move a lot without breaking. This self-healing ability occurs through the formation of new metallic bonds at the damage sites, enhancing the durability and longevity of these materials.

We constructed **Figure 21** to compare the electrical conductivity of MXene [30], Graphene [31], with liquid metal on a logarithmic scale. The figure shows that liquid metal exhibits the highest conductivity, followed by MXene, while Graphene displays varying conductivity based on the substrate. Among the graphene samples, cotton provides the highest conductivity, while silk exhibits the lowest. The variability in conductivity within each material highlights the importance of substrate selection and material properties for optimizing electrical performance.

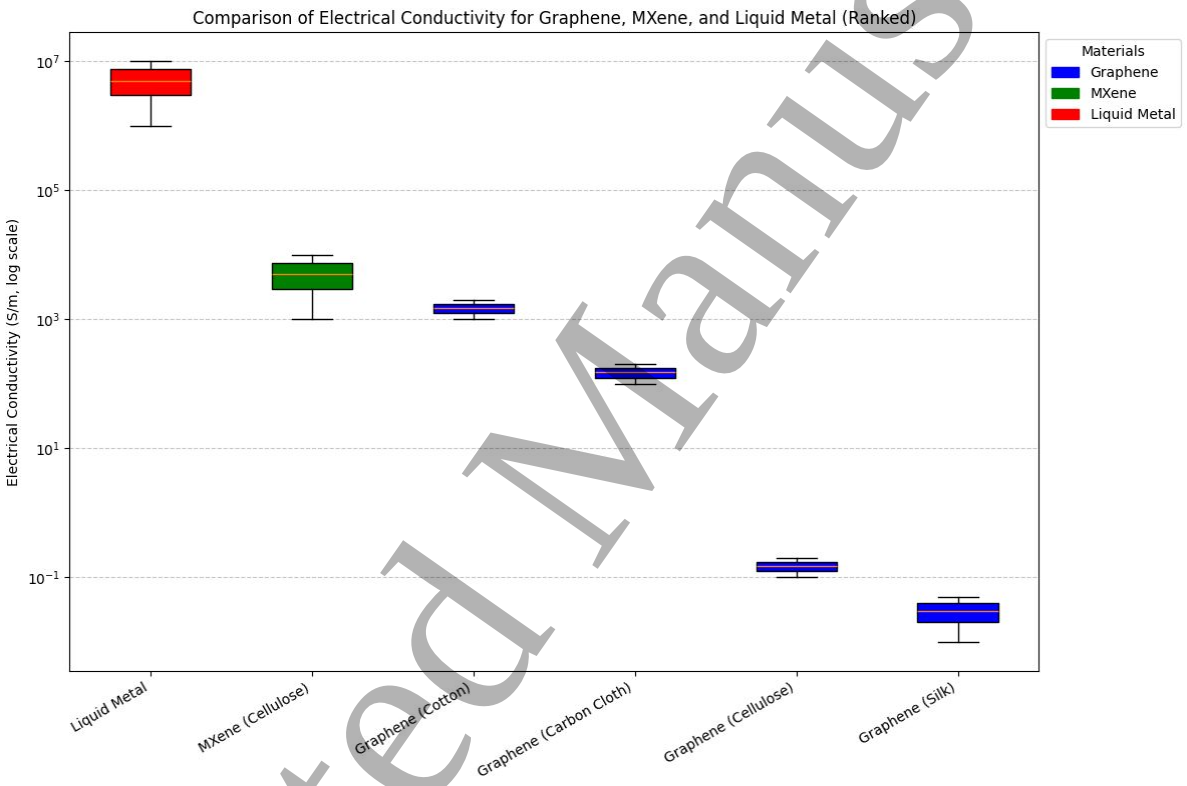


Figure 21. Comparison of electrical conductivity for Graphene, MXene, and Liquid Metal. The box plot illustrates the distribution of electrical conductivity values (S/m) on a logarithmic scale. Liquid Metal exhibits the highest conductivity, followed by MXene (Cellulose) [30], and various Graphene substrates (Cotton, Carbon Cloth, Cellulose, and Silk) [31]. Each material's variability in conductivity is represented, highlighting significant differences across materials and substrates.

These properties make gallium and its alloys highly promising for various applications, including wearable electronics, soft robotics, and more. Their adaptability and robustness enable the development of technologies that require dynamic and adaptive components. Furthermore, gallium alloys have shown potential in fields beyond electronics, such as microfluidics, heat transfer, and biomedical engineering. Their versatility and unique characteristics are valuable for developing innovative solutions to complex technological challenges.

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Challenges

Despite their advantages, the application of liquid metal inks faces several challenges:

- **Patterning issues:** Applying these inks to textiles or other substrates can be difficult due to their fluid nature. Maintaining adhesion without leakage or contamination requires precise control and innovative application techniques.
- **Handling and safety:** The processing of liquid metals demands specialized techniques to ensure safe handling and reliability. The inherent properties of gallium and its alloys necessitate careful management to avoid issues during application.

The future of gallium and gallium alloys in various industries appears vastly promising. By overcoming the existing challenges and continuing to explore their potential, these materials could transform sectors ranging from healthcare to advanced manufacturing. As research progresses, the possibilities for incorporating gallium-based inks in groundbreaking applications continue to expand, potentially revolutionizing how we approach flexible and adaptive technology solutions.

The field of conductive inks for e-textiles holds immense potential to revolutionize industries such as fashion, healthcare, and wearable technology. Materials like MXenes, carbon nanomaterials, metallic nanoparticles, and liquid metals offer unique opportunities for creating e-textiles that can sense, respond, and dynamically interact with their environment.

Concluding remarks

Despite these advancements, challenges persist. Manufacturing methods must ensure cost-effective, scalable, and durable production. E-textiles must withstand wear, washing, and environmental stress while maintaining functionality. Collaborative efforts across materials science, engineering, and design are essential to overcome these barriers.

Future progress will depend on innovative materials and ink formulations that balance performance and sustainability. Advances in roll-to-roll manufacturing and inkjet printing technologies could democratize e-textile production, enhancing accessibility. Moreover, sustainability must be integral, minimizing the environmental footprint from production to disposal. By addressing these challenges, conductive inks can transform textiles into intelligent systems with practical applications, including health-monitoring garments, interactive smart devices, and adaptive environments. These advancements promise to redefine healthcare, human interaction, and environmental engagement, paving the way for a smarter, more sustainable future in e-textiles.

Acknowledgements

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Reference

[1] W. Cui, W. Lu, Y. Zhang, G. Lin, T. Wei, and L. Jiang, “Gold nanoparticle ink suitable for electric-conductive pattern fabrication using inkjet printing technology,” *Colloids Surf. A Physicochem. Eng. Asp.*, vol. 358, pp. 35–41, 2010.

[2] B. K. Park, D. Kim, S. Jeong, J. Moon, and J. S. Kim, “Direct writing of copper conductive patterns by inkjet printing,” *Thin Solid Films*, vol. 515, pp. 7706–7711, 2007.

Accepted Manuscript

[3] Y. Lee, J. Choi, K. J. Lee, N. E. Stott, and D. Kim, "Large-scale synthesis of copper nanoparticles by chemically controlled reduction for inkjet-printed electronics," *Nanotechnology*, vol. 19, 2008.
[4] M. Grouchko, A. Kamyshny, C. F. Mihailescu, D. F. Anghel, and S. Magdassi, "Conductive inks with a built-in mechanism enabling sintering at room temperature," *ACS Nano*, vol. 5, pp. 3354–3359, 2011.
[5] A. Kamyshny and S. Magdassi, "Conductive nanomaterials for printed electronics," *Small*, vol. 10, pp. 3515–3535, 2014.
[6] Q. Huang and Y. Zhu, "Printing conductive nanomaterials for flexible and stretchable electronics: Materials, processes, and applications," *Adv. Mater. Technol.*, vol. 4, p. 1800546, 2019.
[7] J. Zhang, M. Ahmadi, G. Fargas, N. Perinka, J. Reguera, S. Lanceros-Méndez, L. Llanes, and E. Jiménez-Piqué, "Silver nanoparticles for conductive inks: From synthesis to printing technologies," *Metals*, vol. 12, p. 234, 2022.
[8] F. Rodríguez-Félix et al., "Trends in sustainable green synthesis of silver nanoparticles using agri-food waste extracts," *J. Nanomater.*, vol. 2022, p. 8874003, 2022.
[9] Q. Chen, T. Mi, G. Chen, and G. Liu, "Biosynthesis of silver nanoparticles for UV-curing conductive ink using rice straw extract," *Can. J. Chem. Eng.*, vol. 95, pp. 2350–2356, 2017.
[10] A. Boumegnane et al., "Rheological properties and inkjet printability of a green silver-based conductive ink for wearable textile antennas," *Sensors*, vol. 24, p. 2938, 2024.
[11] Q. A. Alsulami et al., "Biodegradable lignin as a reactive raw material in UV-curable systems," *Polym.-Plast. Technol. Mater.*, vol. 59, pp. 1387–1406, 2020.
[12] A. Camus, M. Reali, and C. Santato, "Advances in high-resolution printed transistors based on bio-sourced organic materials," *Curr. Opin. Green Sustain. Chem.*, vol. 34, p. 100594, 2022.
[13] A. Gorman, A. Clayton, T. O'Connell, and D. Johnson, "A recyclable screen ink developed using a sustainability-driven approach," *MRS Adv.*, vol. 8, pp. 311–316, 2023.
[14] K. Kordás et al., "Inkjet printing of electrically conductive carbon nanotube patterns," *Small*, vol. 2, pp. 1021–1025, 2006.
[15] M. Endo, M. S. Strano, and P. M. Ajayan, "Potential applications of carbon nanotubes," in *Carbon Nanotubes: Advanced Topics in the Synthesis, Structure, Properties and Applications*, Springer, 2007, pp. 13–62.
[16] S. H. Chae and Y. H. Lee, "Carbon nanotubes and graphene toward soft electronics," *Nano Converg.*, vol. 1, pp. 1–26, 2014.
[17] D. S. Saidina et al., "Recent developments of graphene-based inks for flexible electronics," *J. Electron. Mater.*, vol. 48, pp. 3428–3450, 2019.
[18] P. He et al., "Screen printing of highly conductive graphene ink for flexible printed electronics," *ACS Appl. Mater. Interfaces*, vol. 11, pp. 32225–32234, 2019.
[19] K. Pan et al., "Sustainable production of highly conductive multilayer graphene ink for wireless connectivity and IoT applications," *Nat. Commun.*, vol. 9, p. 519, 2018.
[20] M. Naguib, V. N. Mochalin, M. W. Barsoum, and Y. Gogotsi, "MXenes: A new family of two-dimensional materials," *Adv. Mater.*, vol. 26, 2014.
[21] X. Li et al., "MXene chemistry, electrochemistry, and energy storage applications," *Nat. Rev. Chem.*, vol. 6, pp. 389–404, 2022.
[22] J. Miao et al., "Flexible, transparent, and conductive wearable electronic skin based on MXene ink," *Carbon*, vol. 222, p. 118950, 2024.
[23] X. Tang et al., "Engineering aggregation-resistant MXene nanosheets as highly conductive and stable inks for all-printed electronics," *Adv. Funct. Mater.*, vol. 31, p. 2010897, 2021.

Accepted Manuscript

[24] B. Chen et al., “Liquid metal–tailored PEDOT:PSS for noncontact flexible electronics with high spatial resolution,” *ACS Nano*, vol. 16, pp. 19305–19318, 2022.
[25] M. Kong et al., “Ambient printing of native oxides for ultrathin transparent flexible circuit boards,” *Science*, vol. 385, pp. 731–737, 2024.
[26] J. Yang et al., “Liquid metal coated textiles with autonomous electrical healing and antibacterial properties,” *Adv. Mater. Technol.*, vol. 8, p. 2202183, 2023.
[27] H. Wang et al., “Wettability of liquid metals on PEDOT:PSS for soft electronics,” *Appl. Surf. Sci.*, vol. 609, p. 155410, 2023.
[28] X. Li et al., “Evaporation-induced sintering of liquid metal droplets with biological nanofibrils for flexible conductivity and responsive actuation,” *Nat. Commun.*, vol. 10, p. 3514, 2019.
[29] H. Jiang et al., “Malleable, printable, and highly conductive MXene/liquid metal plasticine with improved wettability,” *Nat. Commun.*, vol. 15, p. 6138, 2024.
[30] C. S. Kang et al., “Facile fabrication and characterization of MXene/cellulose composites for electrical properties and electric heating performance,” *Fashion Text.*, vol. 11, p. 1, 2024.
[31] V. Orts Mercadillo et al., “Electrically conductive 2D material coatings for flexible and stretchable electronics: A comparative review of graphenes and MXenes,” *Adv. Funct. Mater.*, vol. 32, p. 2204772, 2022.

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5.6 - Innovative Materials for Sensing, Energy Harvesting, and Storage in Wearable Technology

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Status

The current landscape of wearable and textile-integrated electronics is characterised by rapid growth in materials that enable sensing, energy harvesting, energy storage, and therapeutic functions. Earlier sections (5.1–5.5) detail the development of conductive fibres, semiconductors, 2D materials and printing methods. This section focuses on how these materials are presently being deployed in functional wearable devices and the trends emerging from system-level demonstrations, as illustrated in **Figure 22.**

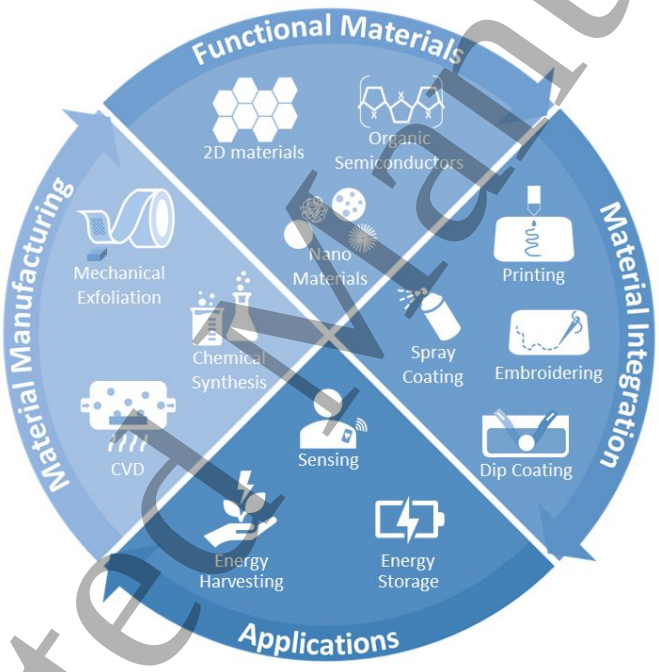


Figure 22. Overview of novel materials in wearables and textiles, including examples of material manufacturing, functional materials, device fabrication techniques, and prevalent applications.

A wide range of fabrication and integration techniques such as dip coating, spray and spin coating, inkjet, and aerosol printing, and textile-specific methods like embroidery are now being used not just to deposit single materials like those discussed earlier, but to assemble complete functional systems directly into garments and wearable devices [1]. By integrating sensors, energy-harvesting [2], storage devices [3], and textile-compatible displays into a single wearable platform, these methods enable fully integrated wearables that maintain flexibility, comfort, and durability. This system-level approach allows multiple material types to operate synergistically, supporting real-world applications such as health-monitoring clothing, self-powered sensors, and multifunctional smart textiles.

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Organic semiconductors continue to expand the capabilities of wearable systems, enabling sensing, energy harvesting, and optoelectronic functionality. Organic photovoltaics are now widely explored for powering wearables, providing on-body energy harvesting under indoor and outdoor lighting and enabling self-sustaining operation when paired with low-power sensors and flexible storage [4]. Complementing this, organic photodetectors offer tuneable spectral response and mechanical flexibility, enabling applications such as heart-rate monitoring, optical biochemical sensing, and ambient light detection [5]. Recent demonstrations of flexible OPDs capable of X-ray detection further extend their potential towards advanced imaging and radiation sensing wearables [6]. Together with continued progress in stretchable OLEDs and conductive polymers, these advances illustrate the growing maturity of organic optoelectronic materials for integrated, functional wearable technologies.

Ultra-thin two-dimensional (2D) materials, including graphene and MXene are gaining significant attention in wearables, both in sensing [7] and energy harvesting and storage [2]. 2D materials have been used in wearables for applications such as respiratory [8] and heart rate [9] sensing. They also enable energy harvesting, supporting development of self-powered devices [9].

Triboelectric nanogenerators (TENGs) offer a promising approach to energy harvesting in textiles and wearables. These devices utilize the triboelectric effect and electrostatic induction to capture mechanical energy from the body. TENGs made from materials, including graphene [10] and nanoparticles [11] have been incorporated into wearables. TENGs and other energy-harvesting materials can be combined with storage devices like sodium-ion batteries for wearables [12]. Fiber-shaped nanomaterials are also popular for energy storage due to their mechanical strength and flexibility [3]. Calcium-oxygen batteries have been developed using carbon nanotubes woven into textiles with commercial braiding machines for wearable energy storage [13], showing promising longevity.

Current and Future Challenges

Despite significant progress in materials for wearables and smart textiles, substantial challenges remain before these materials can be widely adopted. One key challenge is power requirements and energy density. To be widely accepted, wearable devices require lightweight, unobtrusive, and stable energy management. Attempts to create energy storage devices with sufficient energy density while meeting these criteria usually result in lower longevity. Similarly, the production of energy harvesting devices with sufficient power density to directly supply power to wearable devices remains an open challenge in materials science.

Material durability is crucial for incorporation into wearable devices. Since many wearables are used daily, the materials must endure regular use without compromising comfort or safety. Wearables and smart textiles face mechanical stresses including impacts and bending, along with environmental impacts like humidity, temperature, and UV exposure. For smart textiles, washability is important, however laundering introduces additional mechanical and chemical stressors. Electronic materials often need encapsulation for environmental protection, adding complexity and an additional point of failure. These stressors lead to material fatigue and eventual failure, and the actual lifespan of many novel materials remains unclear. Beyond the base materials, embedded

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electronics, including microcontrollers, sensors, and flexible printed circuit boards, pose additional durability challenges. Repeated bending, stretching, and compression can lead to cracking, delamination, or solder fatigue, while encapsulation layers can affect thermal management. The reliability of these components is therefore critical for the overall lifespan of wearable devices and often represents a limiting factor even when the functional materials themselves are robust.

Scalability and production cost are major challenges for incorporating advanced materials into textiles and wearables. Many advanced materials require costly precursors and complex manufacturing processes, making cost-effective mass production difficult. Integrating these materials into textiles also demands specialized equipment and techniques, further increasing costs and complicating large-scale production.

Safety of new materials is also critical to their incorporation in wearable technologies, both during regular use and under failure. Due to their direct contact with the body, materials used in textiles and wearables must be biocompatible. They must not cause irritation or allergic reactions or expose the wearer to harmful or toxic substances. Those incorporating energy storage particularly must protect against overheating, fire, and leakage which pose significant risk to wearers.

Finally, sustainability of wearable and textile materials across their lifecycle remains a challenge. The production of nanomaterials often includes the use of non-renewable materials or materials extracted using environmentally damaging processes. Large amounts of energy are often used to produce these materials, further limiting their sustainability. The common synthesis routes for many organic semiconductors require halogenated solvents, which are toxic to the human body and the environment. There has been an increasing effort to develop “green” alternatives using less toxic solvents and materials [14].

Advances in Science and Technology to Meet Challenges

Standardised testing of smart materials and devise integrated into wearables and textiles would greatly improve the ability to compare materials and their manufacturing techniques. There is currently little consensus on best approaches for moving from material to device. Limited standards do exist for testing durability; however, these are not routinely considered in the literature to date. Testing of energy harvesting and storage devices are not yet standardised, making it difficult directly compare novel materials for power and energy density. Further development and uptake of standardised testing would greatly support progress in this field.

For energy storage applications, technologies using solid-state electrolytes have been proposed to reduce the risk associated with leakage of electrolytes from batteries. Advances in electric double layer capacitors promise a safer, more durable, and more sustainable method of energy storage. However, both of these technologies are limited by low energy densities when compared to traditional battery technology. More research is required to improve the energy density of these and other safe and lightweight energy storage devices so that they can be utilised for powering wearables.

The toxicity of nanomaterials requires thorough investigation before these materials are incorporated in wearables. Some studies suggest that small particles of graphene can have negative

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effects on health [15]. Some early works have sought to predict the toxicity of nanoparticles utilising machine learning [16]. Such technologies could assist with finding nanomaterials suitable for wearables and textiles, offering much opportunity to future researchers in the intersection of computer and materials sciences.

Advances are also needed to improve sustainability at two key stages of the material lifecycle: manufacturing and end-of-life. Researchers are increasingly exploring the use of waste products as precursors for smart material manufacturing [7]; however, these methods remain challenging to scale. Further work is needed to ensure that materials made in large quantities do so with sustainable methods. Advances in recycling are also needed for wearables and textiles at the end of their life, as devices are commonly built from many different materials that remain challenging to separate requiring improved de-embedding techniques[17]. Improved recycling of wearables would greatly improve sustainability by enabling reclamation of rare earth elements.

Concluding Remarks

Incorporating new materials into wearables and textiles allows for a broad range of applications from health and environmental sensing, energy harvesting, and drug delivery. Additional research is required to assess the long-term safety of these materials and the devices made from them. Further advances in energy storage capability, sustainable manufacturing and disposal, and standardised testing of these materials would improve their usefulness and facilitate adoption of such technology.

Reference

[1] J. S. Meena, S. B. Choi, S. B. Jung, and J. W. Kim, “Electronic textiles: New age of wearable technology for healthcare and fitness solutions,” *Mater. Today Bio*, vol. 19, p. 100565, 2023, doi: 10.1016/j.mtbio.2023.100565.

[2] L. Yang et al., “Fully stretchable, porous MXene–graphene foam nanocomposites for energy harvesting and self-powered sensing,” *Nano Energy*, vol. 103, p. 107807, 2022, doi: 10.1016/j.nanoen.2022.107807.

[3] J. He et al., “Flexible energy storage devices to power the future,” *Adv. Mater.*, vol. 36, no. 4, p. 2306090, Jan. 2024, doi: 10.1002/adma.202306090.

[4] M. Jahandar, S. Kim, and D. C. Lim, “Transforming wearable technology with advanced ultra-flexible energy harvesting and storage solutions,” *Nat. Commun.*, vol. 15, no. 1, p. 8149, 2024, doi: 10.1038/s41467-024-52534-9.

[5] Z. Wang, S. Cheng, K. Fukuda, W. Hu, X. Xu, and T. Someya, “Flexible near-infrared organic photodetectors for emergent wearable applications,” *Wearable Electron.*, vol. 1, pp. 53–77, 2024, doi: 10.1016/j.wees.2024.04.001.

[6] A. Bashiri et al., “Flexible organic X-ray sensors: Solving the key constraints of PET substrates,” *Adv. Funct. Mater.*, vol. 35, no. 8, p. 2415723, Feb. 2025, doi: 10.1002/adfm.202415723.

[7] L. Papale, B. Philippa, B. Makarenko, O. K. Varghese, and M. V. Jacob, “Sustainable low-temperature carrier gas-free growth of graphene on non-catalytic substrates,” *RSC Sustain.*, vol. 2, no. 4, pp. 995–1002, 2024, doi: 10.1039/D3SU00417A.

[8] H. Chen et al., “A smart wearable device using graphene material-based sensor for neonatal respiration monitoring,” *J. Sensors*, vol. 2024, p. 2853487, Jan. 2024, doi: 10.1155/2024/2853487.

[9] Q. Yi, X. Pei, P. Das, H. Qin, S. W. Lee, and R. Esfandyarpour, “A self-powered triboelectric MXene-based 3D-printed wearable physiological biosignal sensing system for wireless real-time health

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monitoring," *Nano Energy*, vol. 101, p. 107511, 2022, doi: 10.1016/j.nanoen.2022.107511.
[10] Q. Guo et al., "Multifunctional graphene/leather for versatile wearable electronics," *J. Mater. Chem. A*, vol. 11, no. 22, pp. 11773–11785, 2023, doi: 10.1039/D3TA01087B.
[11] Y. Gao, B. Xu, D. Tan, M. Li, Y. Wang, and Y. Yang, "Asymmetric-elastic-structure fabric-based triboelectric nanogenerators for wearable energy harvesting and human motion sensing," *Chem. Eng. J.*, vol. 466, p. 143079, 2023, doi: 10.1016/j.cej.2023.143079.
[12] R. Liu et al., "An all-in-one sodium-ion thin-film battery with stretchable and self-chargeable functions for wearable electronics," *Chem. Eng. J.*, vol. 484, p. 149513, 2024, doi: 10.1016/j.cej.2024.149513.
[13] L. Ye et al., "A rechargeable calcium–oxygen battery that operates at room temperature," *Nature*, vol. 626, no. 7998, pp. 313–318, 2024, doi: 10.1038/s41586-023-06949-x.
[14] I. McCulloch, M. Chabinyc, C. Brabec, C. B. Nielsen, and S. E. Watkins, "Sustainability considerations for organic electronic products," *Nat. Mater.*, vol. 22, no. 11, pp. 1304–1310, 2023, doi: 10.1038/s41563-023-01579-0.
[15] P. Govindaraj et al., "Health and safety perspectives of graphene in wearables and hybrid materials," *J. Mater. Sci. Technol.*, vol. 155, pp. 10–32, 2023, doi: 10.1016/j.jmst.2023.01.011.
[16] M. Ahmadi, S. M. Ayyoubzadeh, and F. Ghorbani-Bidkorpeh, "Toxicity prediction of nanoparticles using machine learning approaches," *Toxicology*, vol. 501, p. 153697, 2024, doi: 10.1016/j.tox.2023.153697.
[17] M. G. Tadesse, M. T. Abate, J. F. Lübben, and M. Rauch, "Recycling and sustainable design for smart textiles—A review," *Adv. Sustain. Syst.*, vol. 9, no. 8, p. 2401072, Aug. 2025, doi: 10.1002/adsu.202401072.

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5.7 - Material-to-System Translation Challenges and Emerging Textile Innovations

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Status

The wearable computing paradigm describes systems with connectivity and processing capabilities that enable the transmission and analysis of user data. Within this paradigm, the underlying technology largely determines the sophistication and functionality of the wearable. Wearable technologies generally refer to small electronic and mobile computing devices with wireless communication capability that can be incorporated into gadgets, clothing, or, in some cases, invasive formats such as microchips or smart tattoos. Their functionality varies across application domains, including fitness, health, and entertainment.

In-built sensors in wearable technologies enable the monitoring of physical motion and physiological signals. **Textile-integrated sensors represent a distinct variation of wearable technology**, in which sensing elements are embedded directly within fabrics or garments, with the common objective of tracking the wearer's data in real time while preserving comfort and wearability. Over the past two decades, advances in sensing, interconnectivity, and materials have marked a turning point for wearable systems, particularly in health-related applications spanning fitness, clinical monitoring, and rehabilitation. Public awareness of the benefits of continuous health monitoring has increased, alongside growing adoption of activity recognition and physiological monitoring technologies.

Looking ahead, **emerging innovations relevant to textile-based wearables** include improved interconnectivity, distributed energy harvesting, and lightweight, flexible textile platforms that can be worn directly on the body or integrated into everyday clothing and accessories. These developments support the monitoring of vital physiological signals for diagnostic and prognostic purposes, while highlighting the importance of material integration, durability, and system-level design in next-generation wearable and textile technologies [1,2].

Current and Future Challenges

The future of wearable technology is mostly linked with interconnectivity among devices and the ability to sync data between wearables, smartphones, or other devices [3]. Energy harvesting is another big domain, and it pertains to converting body heat, movement, or solar energy into power. Innovative companies like Epeas are working on ambient energy harvesting [4], processing, and sensing solutions to make wireless devices that do not need to be actively charged. Another innovation is non-invasive sensors that will allow hands-free typing using your brain activity [5].

Other breakthrough innovations relate to haptic technology, which can create an experience by applying forces, vibrations, or motions to control virtual objects. Engineers are working on recreating realistic touch sensations while engaging human-computer interactions. Wearable haptic devices

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can also communicate through vibration and are integrated into clothing to give direction and help someone walk, hear, and see in a physical or virtual world [6].

So, what are the major features, functions, and trends that will set next-generation wearables to come from? AI everywhere with a focus on non-wrist-based wearables. The Oura Ring is one of the most popular smart rings on the market, with a focus on fitness, sleep, and recovery tracking [7] [8] [9]. The smart ring market is still small but growing. Modern smartwatches monitor sleep quality, stress levels, heart rate, and ECG sensors for signs of an irregular heartbeat. New smartwatches will monitor for an even wider range of serious health conditions, including hypertension and sleep apnea [10] [3].

Wearable textiles are another innovation that can sense, react, and adapt themselves to external conditions or stimuli, which can work with the human brain for cognition, reasoning, and activating capacity. Wearable technology is among the fastest-growing parts of health, entertainment, and education. In the future, the development of wearable electronics will be focused on multifunctional, user-friendly, and user acceptance and comfort features and shall be based on advanced electronic textile systems [11]. Socks, gloves, and vests with embedded wearable technology to measure movement are just some of the prototypes in development at the Computer Science and AI Lab (CSAIL) at the Massachusetts Institute of Technology. The university is testing sensor-embedded textiles to measure movement with different attributes depending on where they are worn on the body [12].

Advances in Science and Technology to Meet Challenges

The next generation of wearable technology will not be defined by a single software application or hardware breakthrough, but by the convergence of material science, energy harvesting, and edge computing. The traditional wearable architecture (sensing on-device, transmitting raw data via Bluetooth to a smartphone, and processing that data in the cloud) is increasingly unsustainable. It incurs high latency, consumes excessive power during transmission, and creates massive privacy vulnerabilities.

The future of wearable intelligence lies in Edge AI, where data is processed locally on the device itself. This shift requires radical advances in both algorithmic efficiency and hardware architecture. To realize the opportunities in this space, privacy strategies and latency demands dictate that AI must move to the device. Here, Federated Learning is not just optimizations; they are essential to enabling training process locally and the data never leaves the user's device. The value proposition must evolve from monitoring to treating, where technologies like wearable ultrasound, active soft robotics, and closed-loop haptic systems represent the highest value tier in the future healthcare market.

Also, as regulation tightens and consumer awareness grows, privacy will become a competitive differentiator. Manufacturers that adopt privacy-by-design architectures will gain trust and market share over those relying on data exploitation models. To counter the centralization of data in the hands of a few tech giants, new models of decentralized personal data stores are emerging.
Technologies like Solid (Social Linked Data) allow users to store their health data in a personal "pod" over which they retain full control. Users can grant granular access to doctors, researchers, or

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applications without surrendering ownership of the underlying data. Combined with blockchain-based marketplaces and smart contracts, this patient-centric model aligns with Web3 principles, ensuring that the value generated from data accrues to the individual rather than the platform aggregator. This shift could fundamentally disrupt the data economy of the wearable industry, forcing companies to compete on service quality and trust rather than data monopoly.

Concluding Remarks

Current state-of-the-art wearable technologies could be classified based on the placement of the wearable on the human body as head-mounted, body-worn, lower-body, and wrist-worn. In the wrist-worn category, the smartwatch is experiencing a rise, owing to multiple features in one device. On the other hand, the head-mounted category is gaining traction with the increasing acceptance of smart assistants. In the research community, the potential of soft, flexible electronic materials is a key focus. This has led to a range of increasingly sophisticated wearable devices that take a variety of different forms. New fabric-like sensors can measure and transmit mechanical strain on the skin with unprecedented sensitivity. Fabrics represent a unique platform for seamlessly integrating electronics into everyday experiences. The revolution in materials, structures, and functionality at the fiber level enables intimate and imperceptible integration, rapidly transforming fibers and fabrics into next-generation wearable devices and systems. Thus, the future of wearables is soft, transient, autonomous, and intelligent. Achieving this requires a rigorous departure from the rigid, power-hungry, and insecure architectures of the past, embracing a future where technology and biology are indistinguishable. The system-level implications of these material translation challenges are discussed in Section 13.

References

[1] Wearable Technology Market Size, Share, Trends Analysis Report and Segment Forecasts, 2023–2030, Grand View Research, 2024. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/wearable-technology-market

[2] Wearable Technology Market Size, Share and Industry Analysis, Fortune Business Insights, 2024. [Online]. Available: https://www.fortunebusinessinsights.com/wearable-technology-market-106000

[3] A. S. Farooq and P. Zhang, “A comprehensive review on the prospects of next-generation wearable electronics for individualized health monitoring, assistive robotics, and communication,” Sens. Actuators A Phys., vol. 344, p. 113715, 2022, doi: 10.1016/j.sna.2022.113715.

[4] Energy Harvesting Ambient Energy Managers, e-peas, 2024. [Online]. Available: https://e-peas.com/energy-harvesting/

[5] J. G. Makin, D. A. Moses, and E. F. Chang, “Machine translation of cortical activity to text with an encoder–decoder framework,” Nat. Neurosci., 2024, doi: 10.1038/s41593-020-0608-8.

[6] K. Jung, S. Kim, S. Oh, and S. H. Yoon, “HapMotion: Motion-to-tactile framework with wearable haptic devices for immersive VR performance experience,” Virtual Reality, 2024, doi: 10.1007/s10055-023-00910-z.

[7] M. Altini and H. Kinnunen, “The promise of sleep: A multi-sensor approach for accurate sleep stage detection using the Oura Ring,” Sensors, vol. 21, p. 4302, 2021, doi: 10.3390/s21134302.

[8] T. Svensson, K. Madhawa, H. N. T. Hoang, U. Chung, and A. K. Svensson, “Validity and reliability of the Oura Ring Generation 3 with OSSA 2.0 compared to ambulatory polysomnography,” Sleep Med., vol. 115, pp. 251–263, 2024, doi: 10.1016/j.sleep.2024.01.020.

Accepted Manuscript

[9] Smart Ring That Directly Impacts Your Wellbeing, Day and Night, Oura, 2024. [Online]. Available: https://ouraring.com/

[10] Y. Liao, C. Thompson, S. Peterson, J. Mandrola, and M. S. Beg, "The future of wearable technologies and remote monitoring in health care," ASCO Educ. Book, vol. 39, pp. 115–121, 2019, doi: 10.1200/EDBK_238919.

[11] C.-W. Kan and Y.-L. Lam, "Future trend in wearable electronics in the textile industry," Appl. Sci., vol. 11, p. 3914, 2021, doi: 10.3390/app11093914.

[12] I. Wicaksono, P. G. Hwang, S. Droubi, F. X. Wu, A. N. Serio, W. Yan, and J. A. Paradiso, "3DKnITS: Three-dimensional digital knitting of intelligent textile sensor for activity recognition and biomechanical monitoring," in *Proc. 44th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Glasgow, Scotland, United Kingdom, 2022, pp. 2403–2409, doi: 10.1109/EMBC48229.2022.9871651.

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Section 6: Sensor Technologies

6.1 - Magnetic Induction Sensing for Cardiorespiratory Activity Monitoring

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Status

Within magnetic-field–based physiological monitoring, advanced methods based on endogenous bio-magnetic signals—such as magnetocardiography, magnetoencephalography, or magnetomyography—require highly sensitive instrumentation and controlled environments, limiting their practicality for everyday use. In contrast, magnetic induction sensing (MIS) illustrates a magnetic-field–based approach that is well suited for wearable and textile-integrated systems. Because MIS does not require galvanic contact, it aligns with the goals of unobtrusive, long-term monitoring. MIS is particularly suitable for wearables because it uses an externally generated alternating magnetic field that enables robust vital-signs measurements with simple planar coils.

MIS technology traces its roots back to the second half of the 20th century [1], [2], when inductive coupling between a patient's body and a coil was initially explored. Early measurements of chest conductivity demonstrated that respiration caused a 4% fluctuation in conductivity, while cardiac beats induced a 1% change [2].

MIS signals are influenced by both inductive and capacitive coupling mechanisms. Inductive coupling occurs when the magnetic field generated by the sensor interacts with conductive tissues, enabling the detection of physiological changes such as heartbeats and respiratory cycles. Capacitive coupling, on the other hand, arises due to parasitic capacitance between the tissue surface and the sensor, which becomes more pronounced during movements such as breathing [3,4]. The reflected impedance in the volume of interest (VOI) is modulated by different physiological processes like blood perfusion, tissue volume changes, or boundary shifts. The distance between the sensor and chest varies due to breathing and heart activity, which primarily affects the sensitivity to changes in the air gap between sensor and medium-a dominant factor compared to internal structures [7-9].There are various MIS techniques such as *magnetically coupled impedance measurement*, *feedback oscillator and frequency counting*, *amplitude modulation* using a coil as part of a voltage divider, where the measured voltage depends on the reflected impedance of the coil, *static magnetic field measurement* or use of *Inductance-To-Digital Converters* (LDC) [4].

Recent advancements, particularly in the development of inductance-to-digital converters (LDCs), have significantly enhanced the precision and practicality of MIS [4], [18], [19]. The ability to capture subtle physiological signals without direct contact has made MIS particularly suitable for integration into wearable devices, aligning with the growing demand for continuous, real-time health monitoring, such as for cardiorespiratory activity (see **Figure 23**).

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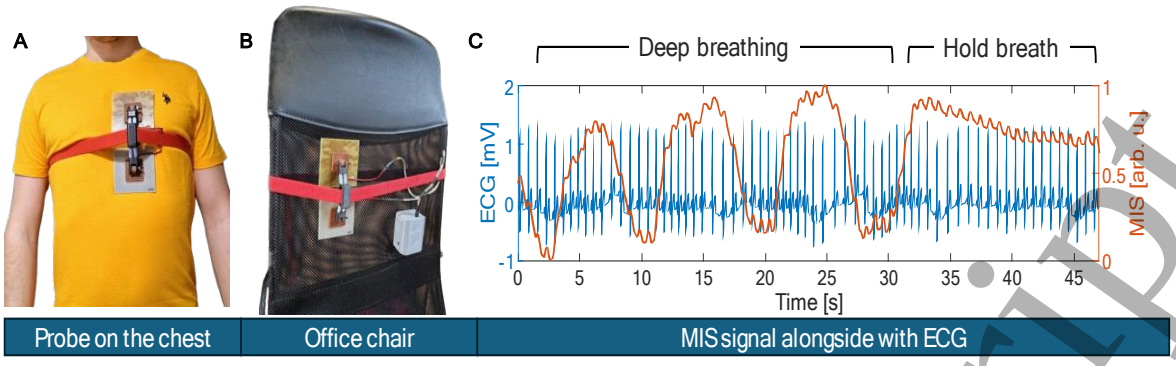


Figure 23. Example of a Magnetic Induction Sensing (MIS) Setup for Capturing Cardiorespiratory Output. (A) MIS device placed on the chest, illustrating a wearable application for cardiorespiratory monitoring. **(B)** MIS device attached to the back of an office chair, demonstrating a non-contact monitoring setup. **(C)** Cardiorespiratory signal captured by the MIS device (red), with distinct peaks corresponding to respiratory cycles and heartbeats. As a reference, there is also shown simultaneously recorded ECG (blue). The captured signal consists of two stages: 1) deep breathing where respiration and heart activity are present and 2) hold breathe where the heart related waveform can be distinguished. The x-axis represents time (s), and the y-axis represents signal amplitude (arb. units).

Current and Future Challenges

Despite the significant progress in MIS technology, several challenges remain. One of the primary issues is the susceptibility of MIS devices to *motion artifacts*, which can degrade signal quality and complicate the interpretation of data. Developing advanced algorithms capable of detecting and filtering out these artifacts is crucial to improving the reliability of MIS, especially in dynamic environments that are common in wearable applications.

Another challenge is the ongoing *miniaturization of MIS devices*. Reducing the size of the technology to fit into everyday objects such as chairs, beds, and car seats would enable seamless health monitoring in non-clinical settings. Such advancements could bring MIS technology into more everyday contexts, making it easier for individuals to benefit from continuous, unobtrusive health tracking.

Power optimization is another important consideration. Minimizing the energy consumption of key components, such as the digital signal controller, is essential for ensuring that MIS devices can function effectively for extended periods, particularly in wearable or mobile applications.

The development of *real-time data processing software is* another challenge that needs to be addressed. This includes the accurate detection of cardiorespiratory signals, such as heart rate, breathing rate, heart rate variability (HRV), and graphing these metrics. Real-time data visualization will enhance the usability of MIS for both clinical professionals and consumers, enabling immediate insights into a user's health status.

While capacitive coupling often contributes useful information in cardiorespiratory monitoring, it typically has less depth of penetration compared to inductive coupling and is less sensitive to changes in internal tissues [12]. Therefore, *separating the information coming from inductive and capacitive coupling is a critical aspect of MIS technology*, requiring sophisticated signal processing techniques to ensure accurate readings.

Moreover, *sensor deformation and tissue impedance changes* further influence the detected signals. Any deformation of the sensor can alter the generated magnetic flux, leading to deviations in the primary winding's self-inductance. On the tissue side, deformation can result in the displacement of organs and interfaces, modulating eddy current paths and impacting the measurements. These tissue impedance changes, dependent on conductivity and permittivity, are also frequency-

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dependent, which adds another layer of complexity to the accurate interpretation of MIS data [3], [15].

Finally, *optimizing the design and performance of planar coils* to improve the quality of the produced signal is vital for enhancing the overall accuracy of MIS. Additionally, exploring the potential to adapt MIS for monitoring other physiological signals beyond cardiorespiratory activity could open new applications for this technology, further broadening its usefulness in healthcare.

Advances in Science and Technology to Meet Challenges

Recent advances in MIS have significantly enhanced the accuracy and practicality of non-contact cardiorespiratory monitoring [4]. One of the key developments has been the integration of high-resolution LDCs [4], [18], [19]. These devices offer improved noise immunity and signal quality, which are crucial for capturing the subtle physiological changes associated with cardiac and respiratory activities. The high resolution provided by these LDCs allows for more precise monitoring, making MIS a competitive alternative to traditional methods like electrocardiography, photoplethysmography or ballistocardiography.

A major technological advancement has been the development of capacitive-coupling shielding, which mitigates unwanted contributions from parasitic capacitance between the sensor and tissue [4]. This shielding enhances measurement specificity and reduces variability caused by environmental or motion-related capacitive effects. In parallel, hardware simplification enabled by LDCs has reduced system complexity relative to traditional oscillator-based designs, supporting more compact and reliable implementations. These refinements are especially valuable in non-contact scenarios, where sensor–body distance and alignment can fluctuate. In some cases, however, such fluctuations are not merely sources of noise but can provide desirable physiological information-for example, mechanical activity arising from cardiorespiratory motion that modulates the coupling between the sensor and the body.

These technological improvements have enabled a diverse range of MIS applications across wearable and ambient contexts. Implementations include portable multimodal cushions for continuous driver monitoring [10], [11], [12], chair setups for cardiorespiratory activity monitoring [3], textile-integrated wearable systems [8], [13], [14], fingertip devices for heart activity monitoring [15] or hemoglobin concentration measurement [16], [17].

Further research should refine the modelling of reflected impedance, which depends on sensor–tissue distance, tissue properties, and mechanical deformation, and improve real-time compensation for these effects. Changes in mutual inductance caused by respiratory or cardiac motion can therefore be more accurately interpreted, supporting robust non-contact monitoring. As MIS technology evolves, continued miniaturization, reduced power consumption, and simplified coil and electronics design are making integration into wearable systems increasingly practical. These hardware improvements, combined with MIS's inherent non-invasiveness and high sensitivity, strengthen its potential for next-generation continuous health monitoring.

Progress in signal processing is equally important. Advanced algorithms for motion-artifact suppression, separation of inductive and capacitive components, and machine-learning–based extraction of respiratory and cardiac metrics are improving signal reliability under real-world conditions. The incorporation of wireless communication and embedded processing enables seamless data transmission and on-device analysis, positioning MIS as a promising platform for continuous, real-time physiological monitoring in everyday environments.

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Concluding Remarks

Magnetic induction sensing offers a non-invasive, reliable, and wearable-friendly solution for continuous cardiorespiratory monitoring. While challenges such as capacitive coupling and advanced signal processing remain, ongoing research promises to overcome these obstacles. As MIS technology continues to advance, it holds the promise of becoming a cornerstone in the next generation of wearable health monitoring devices, contributing to improved health outcomes through continuous real-time monitoring.

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References

[1] R. Vas, “Electronic Device for Physiological Kinetic Measurements and Detection of Extraneous Bodies,” IEEE Trans. Biomed. Eng., vol. BME-14, no. 1, pp. 2–6, Jan. 1967, doi: 10.1109/TBME.1967.4502453.

[2] P. P. Tarjan and R. McFee, “Electrodeless Measurements of the Effective Resistivity of the Human Torso and Head by Magnetic Induction,” IEEE Trans. Biomed. Eng., vol. BME-15, no. 4, pp. 266–278, Oct. 1968, doi: 10.1109/TBME.1968.4502577.

[3] D. Teichmann, J. Foussier, J. Jia, S. Leonhardt, and M. Walter, “Noncontact Monitoring of Cardiorespiratory Activity by Electromagnetic Coupling,” IEEE Trans. Biomed. Eng., vol. 60, no. 8, pp. 2142–2152, Aug. 2013, doi: 10.1109/TBME.2013.2248732.

[4] S. Borik, J. Strych, V. J. Kumar, and B. George, “Measurement of Cardiorespiratory Activity Using Planar Coils and a High-Resolution Inductance-to-Digital Converter,” IEEE Sensors J., vol. 23, no. 18, pp. 21903–21913, Sep. 2023, doi: 10.1109/JSEN.2023.3302417.

[5] M. G. Pepper, D. J. E. Taylor, and M. C. Kwok, “Noninvasive detection of ventricular wall motion by electromagnetic coupling: Part 2: Experimental: cardiokymography,” Med. Biol. Eng. Comput., vol. 29, no. 2, pp. 141–148, Mar. 1991, doi: 10.1007/BF02447099.

[6] D. Teichmann, A. Kuhn, D. De Matteis, T. Bartelt, M. Walter, and S. Leonhardt, “Monitoring of thoracic activity using electromagnetic coupling,” in Proc. 10th Int. Conf. Bioelectromagnetism, Tallinn, Estonia, Jun. 2015.

[7] S. O. Gi et al., “Application of a Textile-based Inductive Sensor for the Vital Sign Monitoring,” J. Electr. Eng. Technol., vol. 10, no. 1, pp. 364–371, Jan. 2015, doi: 10.5370/JEET.2015.10.1.364.

[8] D. Teichmann, A. Kuhn, S. Leonhardt, and M. Walter, “The MAIN Shirt: A Textile-Integrated Magnetic Induction Sensor Array,” Sensors, vol. 14, no. 1, pp. 1039–1056, Jan. 2014, doi: 10.3390/s140101039.

[9] R. Vas, C. R. Joyner, D. E. Pittman, and T. C. Gay, “The Displacement Cardiograph,” IEEE Trans. Biomed. Eng., vol. BME-23, no. 1, pp. 49–54, Jan. 1976, doi: 10.1109/TBME.1976.324615.

[10] L. Leicht, P. Vetter, S. Leonhardt, and D. Teichmann, “The PhysioBelt: A safety belt integrated sensor system for heart activity and respiration,” in Proc. IEEE Int. Conf. Vehicular Electronics and Safety (ICVES), Vienna, Austria, Jun. 2017, pp. 191–195, doi: 10.1109/ICVES.2017.7991924.

[11] O. Linschmann et al., “A Portable Multi-Modal Cushion for Continuous Monitoring of a Driver’s Vital Signs,” Sensors, vol. 23, no. 8, p. 4002, Apr. 2023, doi: 10.3390/s23084002.

[12] P. Vetter, L. Leicht, S. Leonhardt, and D. Teichmann, “Integration of an electromagnetic coupled sensor into a driver seat for vital sign monitoring: Initial insight,” in Proc. IEEE Int. Conf. Vehicular

Accepted Manuscript

Electronics and Safety (ICVES), Vienna, Austria, Jun. 2017, pp. 185–190, doi: 10.1109/ICVES.2017.7991923.

[13] H.-S. Cho, J.-H. Yang, S.-Y. Lee, J.-W. Lee, and J.-H. Lee, "Wearable Fabric Loop Sensor Based on Magnetic-Field-Induced Conductivity for Simultaneous Detection of Cardiac Activity and Respiration Signals," Sensors, vol. 22, no. 24, p. 9884, Dec. 2022, doi: 10.3390/s22249884.

[14] H. R. Koo et al., "The Effect of Textile-Based Inductive Coil Sensor Positions for Heart Rate Monitoring," J. Med. Syst., vol. 38, no. 2, p. 2, Feb. 2014, doi: 10.1007/s10916-013-0002-0.

[15] D. Teichmann, J. Foussier, D. Löschcke, S. Leonhardt, and M. Walter, "MonitoRing – Magnetic induction measurement at your fingertip," J. Phys.: Conf. Ser., vol. 434, p. 012084, Apr. 2013, doi: 10.1088/1742-6596/434/1/012084.

[16] J. R. Bai and V. J. Kumar, "Use of Magneto Plethysmogram Sensor for Real-Time Estimation of Hemoglobin Concentration," IEEE Sensors J., vol. 21, no. 4, pp. 4405–4411, Feb. 2021, doi: 10.1109/JSEN.2020.3029179.

[17] J. R. Bai and V. J. Kumar, "Optimal Design to Ensure Maximum Coupling Between Magnetic Flux and Arterial Blood in a Magneto Plethysmo Gram Sensor Head," IEEE Sensors J., vol. 21, no. 2, pp. 1417–1423, Jan. 2021, doi: 10.1109/JSEN.2020.3017664.

[18] A. Brezulianu et al., "IoT Based Heart Activity Monitoring Using Inductive Sensors," Sensors, vol. 19, no. 15, p. 3284, Jul. 2019, doi: 10.3390/s19153284.

[19] A. Byberi, R. K. Amineh, and M. Ravan, "Wearable Inductive Sensing of the Arm Joint: Comparison of Three Sensing Configurations," Magnetism, vol. 2, no. 3, pp. 195–210, Jun. 2022, doi: 10.3390/magnetism2030015.

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6.2 - Wearable Radar Sensors

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Status

Numerous methods exist for monitoring vital signs and biomarkers, with wearable devices experiencing remarkable advancements in recent years. Since the early 2010s, the mainstream market's acceptance of these devices has significantly increased, particularly with the surge in popularity of smartwatches and wearable patches. The sensors employed in these widely used wearables are often restricted to a single monitoring method, predominantly photoplethysmography (PPG). However, PPG has drawbacks, such as sensitivity to ambient light, limited skin penetration, and variations in accuracy due to skin colour differences [1, 2].

In comparison, radar technology offers significant advantages, including non-contact measurement capability that allows measurements through clothing, deeper skin penetration, and insensitivity to skin color variations. Radar systems measure the perturbation of the skin surface or chest wall caused by pulsatile blood flow, allowing for the simultaneous monitoring of multiple vital signs, including heart rate (HR), respiratory rate (RR), and blood pressure (BP) [3, 4]. The implementation of radar as a wearable device is currently feasible through three main architectures: Frequency-Modulated Continuous Wave (FMCW), Ultra-Wideband (UWB), and Continuous Wave (CW). A number of studies have discussed these architectures in detail within the context of monitoring vital signs [5, 6].

In the past, radar systems were primarily used to detect the presence of large targets, such as aircraft and vehicles. As technology advanced, these systems became capable of extracting more detailed information, including the size, shape, velocity, and direction of the targets. These advancements were achieved by modifying the fundamental properties of radar systems, such as radar architecture and operational frequency [7]. Since the 1970's, numerous studies have explored the use of radar technology for monitoring physiological signals [8]. These applications can be classified into three categories based on the distance between the radar antenna and the human body: non-contact, near-contact, and body-contact systems. While a majority of studies focused on non-contact radar systems, only a limited number of works explored contact-based systems. In this roadmap, we will examine the current status, challenges, and advancements in contact-based radar sensors.

Current and Future Challenges

Current research on near-contact and body-contact wearable devices are primarily implemented using the three main architectures – FMCW, UWB and CW. The FMCW architecture, which utilizes a commercial radar IC, operates in the 57 to 63 GHz band and is placed approximately 1 cm from the human body. This configuration, positioned on the wrist, measures small skin movements reflecting arterial pulsation. While it provides fairly accurate measurements of heart rate, respiratory rate, and pulse waveform features for cuffless blood pressure estimation, the indirect measurement of skin perturbation can introduce errors [9].

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The UWB radar system, on the other hand, measures physiological waveforms from arterial pulses at multiple locations using a 3.8 GHz centre frequency UWB pulse with a 1 ns duration. The antennae are body-coupled via a ceramic insulator. Although UWB systems deliver accurate results, the complexity of hardware and signal processing poses significant challenges for their implementation in wearable sensors [10].

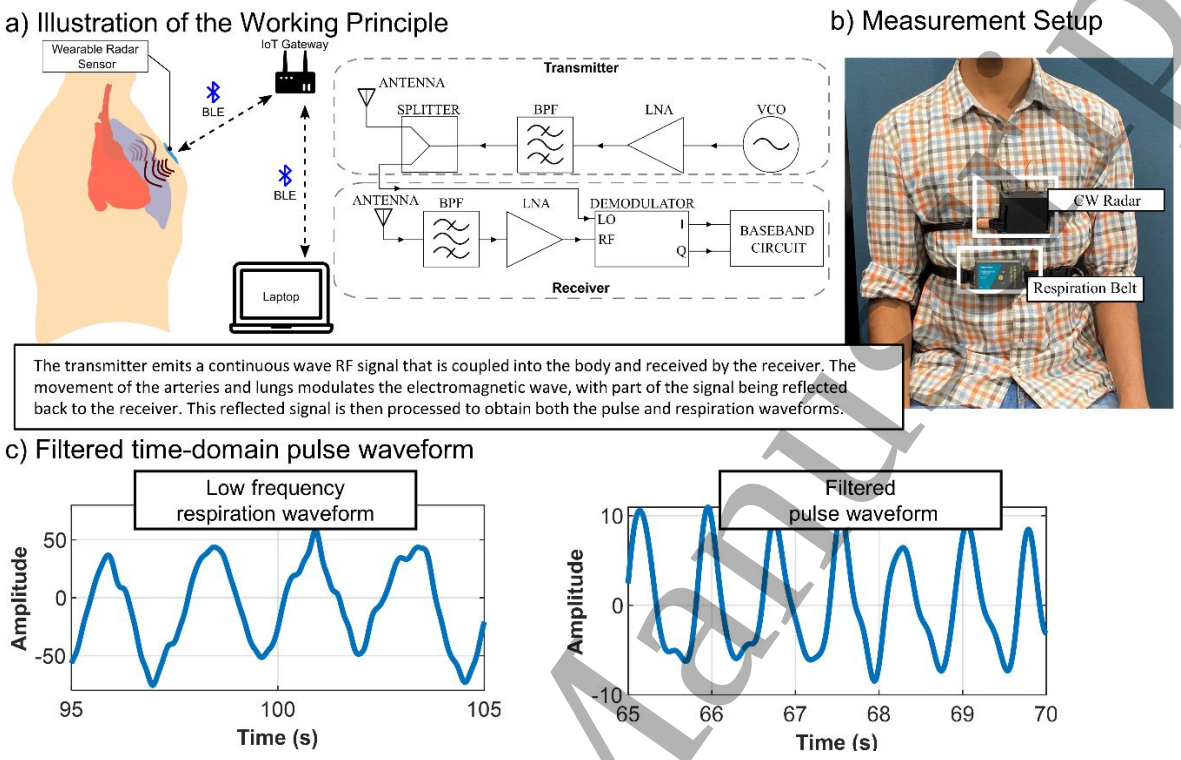


Figure 24. A wearable radar system for vital signs monitoring. (a) Illustration of CW architecture in a wearable radar system, **(b)** example monitoring setup, **(c)** extracted physiological waveforms.

An alternative architecture, continuous wave radar, offers a simpler approach with minimal hardware requirements. This system can effectively obtain pulse waveforms and enhance skin penetration by utilizing the sub-GHz spectrum for radar operation. The CW signal is coupled into the body through body-coupled antennas, allowing for the measurement and extraction of arterial movements to determine HR and RR. **Figure 24** illustrates the simple CW radar architecture alongside the corresponding physiological signals [11].

A primary challenge in the development of wearable radar systems is the human body itself acting as the propagation channel, unlike the free-space environments where most current radar applications are focused. The complex scattering environment caused by the human body needs to be accurately modelled to improve the accuracy of sensing parameters. There is a significant trade-off in system design, involving choices of operating frequency, transmit power, and radar architecture, which in turn influence the selection of appropriate antennas. Balancing these factors is crucial for optimizing the performance and usability of wearable radar devices. Our studies show that a CW architecture at 800MHz-1GHz frequencies provides a good balance in these factors by providing accurate results to obtain physiological waveforms as demonstrated in **Figure 24** [11].

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Advances in Science and Technology to Meet Challenges

The integration of radar technology into wearable devices offers a promising future for non-invasive monitoring of physiological signals. However, to fully utilize the potential of radar-based wearables, significant challenges must be addressed, particularly those arising from the unique characteristics of the human body as a propagation medium. The primary advancements needed can be categorized into the following areas:

Study of the Human Body as a Propagation Environment: A critical advancement for wearable radar systems involves a comprehensive study of the human body as a propagation channel. This understanding is vital for enhancing the accuracy and reliability of measurements beyond traditional parameters such as heart rate, respiratory rate, and blood pressure. The human body poses unique challenges, including high signal attenuation in tissue, which complicates distinguishing between desired signals and unwanted backscatter.

Advanced Signal Processing Techniques: Addressing the complex propagation characteristics of the body requires advancements in signal processing techniques. Traditional methods like arctangent demodulation may not be sufficient, as they do not fully account for the unique properties of biological tissues. Developing new algorithms that consider these factors is crucial for accurate signal reconstruction and differentiation, thereby improving the reliability of the data obtained from radar-based wearables.

Improved Antenna Design: Advancements in antenna design and materials science are also essential. The development of flexible, body-conforming antennas can enhance the interface between the radar system and the human body, reducing signal loss and increasing sensitivity. These improvements can significantly enhance the performance of wearable radar devices, enabling more precise monitoring of physiological signals.

Optimizing Frequency of Operation, Radar Architecture Selection, Resolution, and Safety: A crucial area is optimizing the frequency of operation, radar architecture selection, resolution, and ensuring user safety. Finding the right balance among these parameters can greatly enhance system resolution and broaden the scope of applications beyond physiological monitoring, such as imaging.

Concluding Remarks

Wearable radar devices offer significant advantages over traditional methods like photoplethysmography by providing detailed information on human body movements and vital signs. Understanding in-body parameters, coupled with adequate antenna design, optimized operating frequency, and advanced signal processing techniques, has the potential to revolutionize wearable monitoring. These advancements could enhance the accuracy and reliability of vital sign monitoring and pave the way for detecting various biomarkers and potential imaging applications.

References

[1] R. Mukkamala et al., “Evaluation of the accuracy of cuffless blood pressure measurement devices: Challenges and proposals,” Hypertension, vol. 78, no. 5, pp. 1161–1167, 2021.

[2] M. W. Sjoding, R. P. Dickson, T. J. Iwashyna, S. E. Gay, and T. S. Valley, “Racial bias in pulse oximetry measurement,” N. Engl. J. Med., vol. 383, no. 25, pp. 2477–2478, 2020.

[3] D. Buxi, J.-M. Redouté, and M. R. Yuce, “Blood pressure estimation using pulse transit time from bioimpedance and continuous wave radar,” IEEE Trans. Biomed. Eng., vol. 64, no. 4, pp. 917–927, Apr. 2017.

Accepted Manuscript

[4] D. Buxi et al., “Systolic time interval estimation using continuous wave radar with on-body antennas,” IEEE J. Biomed. Health Inform., vol. 22, no. 1, pp. 129–139, Jan. 2018.
[5] C. Gu, “Short-range noncontact sensors for healthcare and other emerging applications: A review,” Sensors, vol. 16, no. 8, p. 1169, Aug. 2016.
[6] C. Li, V. M. Lubecke, O. Boric-Lubecke, and J. Lin, “A review on recent advances in Doppler radar sensors for noncontact healthcare monitoring,” IEEE Trans. Microw. Theory Techn., vol. 61, no. 5, pp. 2046–2060, May 2013, doi: 10.1109/TMTT.2013.2256924.
[7] M. I. Skolnik, “An introduction and overview of radar,” in Radar Handbook, 3rd ed. New York, NY, USA: McGraw-Hill, 2008, ch. 1, pp. 1–1.
[8] C. Caro and J. Bloice, “Contactless apnoea detector based on radar,” The Lancet, vol. 298, no. 7731, pp. 959–961, 1971.
[9] J. E. Johnson, O. Shay, C. Kim, and C. Liao, “Wearable millimeter-wave device for contactless measurement of arterial pulses,” IEEE Trans. Biomed. Circuits Syst., vol. 13, no. 6, pp. 1525–1534, Dec. 2019.
[10] T. Lauteslager, M. Tommer, T. S. Lande, and T. G. Constandinou, “Coherent UWB radar-on-chip for in-body measurement of cardiovascular dynamics,” IEEE Trans. Biomed. Circuits Syst., vol. 13, no. 5, pp. 814–824, Oct. 2019.
[11] M. P. Ebrahim, N. Tom, J.-M. Redouté, and M. R. Yuce, “A low-frequency portable continuous-wave radar system for vital signs monitoring,” IEEE Sensors J., vol. 23, no. 8, pp. 8876–8886, Apr. 2023.

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6.3 - Advancements in Wearable EEG Technology: Applications and Challenges

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Status

Electrical bio-signal sensors, including electrocardiogram (ECG), electromyogram (EMG) and electroencephalogram (EEG), have formed the foundation of physiological monitoring for over a century. Early developments in recording cardiac [1], muscular [2], and brain activity [3] established the basis of modern electrophysiology and demonstrated the value of electrical signals for assessing physiological function. Later advances in low-noise amplifiers, integrated electronics, digital processing, and wireless data transmission enabled the miniaturization of these sensors, facilitating the emergence of consumer-grade wearable systems capable of continuous, real-world monitoring beyond laboratory and clinical settings [4].

Within this sensor family, EEG has become increasingly important because it is the only non-invasive modality capable of capturing brain activity in everyday environments. This unique capability underpins its applications in mental-state assessment, wearable brain–computer interfaces (BCIs), and neurorehabilitation, motivating focused attention on EEG as a rapidly evolving sensing technology with substantial potential for future impact. Commercial wearable EEG devices such as Muse [5], Emotiv [6], NeuroSky MindWave [7], Dreem [8], Cognionics Quick-20 [9], BitBrain [10], Epitel's REMI [11] and Neurable[12] illustrate the technological maturity of the field. Lightweight designs like headbands, adhesive patches, and around-the-ear systems commonly position electrodes over frontal (Fp1, Fp2, AF7, AF8) and occipital (O1, O2) regions to support unobtrusive EEG acquisition in everyday conditions (**Figure 25**). These devices provide practical alternatives to traditional wet-electrode systems and have been validated against research- and medical-grade EEG, demonstrating comparable signal quality and reliability [13]. The shift from rigid caps to flexible, customizable designs has expanded the feasibility of long-term, at-home EEG monitoring across diverse user populations.

Wearable EEG continues to gain relevance due to its broad and growing application space. Current uses span wellness (meditation and self-regulation [14], stress reduction through biofeedback [15]), cognitive assessment (mental-fatigue evaluation [16]), and gaming (improving attention spans in children through neurofeedback [17]). In clinical care, wearable EEG supports home sleep monitoring as an alternative to polysomnography [18] and seizure detection [19]. EEG wearables also enable BCI-based communication for locked-in patients [20] and control of prosthetic and robotic devices [21]. In research, wearable EEG facilitates large-scale event-related potential studies outside laboratory environment [22]. Together, these applications highlight the persistent and increasing value of accessible neural sensing. Continued improvements in electrode materials, signal robustness, and device integration will broaden real-world usability and expand the range of neural biomarkers that can be captured unobtrusively.

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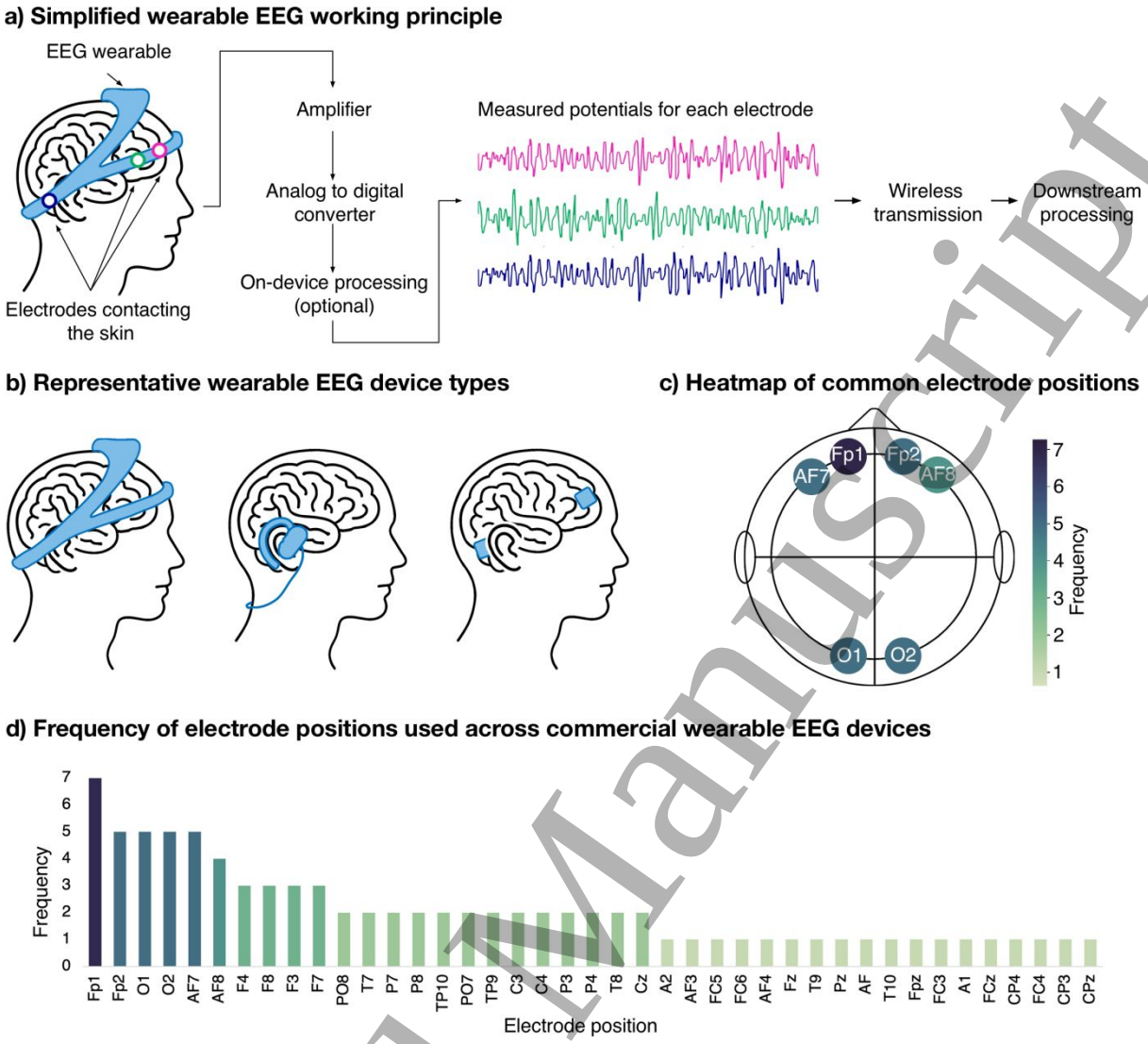


Figure 25. (a) Simplified working principle of wearable EEG systems. Scalp potentials are captured through dry or textile electrodes, amplified using low-noise front ends, digitized with an analog-to-digital converter, and optionally processed on-device before wireless transmission for downstream analysis. **(b) Representative wearable EEG device types.** Schematic illustrations showing common form factors, including headbands/headsets, around-the-ear devices and forehead patch systems. **(c) Most common electrode positions used in commercial wearable EEG devices.** Heatmap and head diagram highlighting frequently used sites, including Fp1, Fp2, AF7, AF8, O1, and O2. **(d) Frequency of electrode positions across commercial wearable EEG devices.** Bar chart summarizing electrode usage based on device specifications from BitBrain Air, BitBrain Diadem, BitBrain Ikon, BitBrain Hero, Muse S, Muse 2, Cognionics Quick-20, Emotiv Epoc+, Emotiv Insight, Emotiv MN8, Dreem, Epitel's REMI, NeuroSky MindWave, and Neurable.

Current and Future Challenges

Despite advancements in EEG wearables, several challenges continue to limit reliable, long-term sensing outside controlled settings. A primary issue is maintaining high signal quality in real-world environments, as EEG is highly susceptible to motion artifacts and environmental interference. Head movement, electrode displacement, ocular activity, and sweat can distort the small-amplitude cortical signals. While adaptive filters and subspace reconstruction can help, complete artifact removal without distorting neural information remains unresolved [23]. Electrode comfort, stability, and contact impedance remain major limitations in wearable EEG. Traditional wet electrodes offer excellent fidelity but are unsuitable for long-term use. Dry and semi-dry electrodes, while essential for wearable systems, still exhibit high and unstable impedance, motion sensitivity, and inconsistent contact, particularly in hairy regions [24]. Semi-dry designs may also release electrolyte unevenly

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over time. These issues reduce signal reliability, making stable, low-impedance contact across different hair, skin, and movement types a key materials and design challenge. Hardware constraints further impact performance. Wearable EEG requires high-gain, low-noise amplification and continuous multichannel acquisition, which place significant demands on power-limited, compact devices. Miniaturization often introduces trade-offs between data fidelity and energy efficiency [25]. As a result, limited battery capacity restricts long-term recording, especially when high sampling rates or continuous wireless transmission are needed for real-time applications. Reproducibility and generalizability remain persistent scientific challenges. Many wearable EEG studies rely on small, homogeneous samples and lack standardized validation frameworks. Device-dependent variability and inconsistent signal quality complicate comparisons between systems [26]. Large-scale open datasets and benchmarking efforts are essential to establish reproducibility and reliability in real-world conditions. Finally, EEG monitoring introduces ethical and privacy considerations. Neural data can reveal sensitive information related to cognition, attention, emotion, and mental health. Ensuring secure data handling, privacy-preserving analytics, informed consent, and appropriate governance is essential as neural information becomes increasingly commercially valuable [27].

Advances in Science and Technology to Meet Challenges

Emerging innovations in materials science, electronics, and computational methods are rapidly addressing the key barriers facing wearable EEG technologies. Advances in electrode materials and form factors are improving comfort, stability, and long-term wearability. Flexible headbands, textile electrodes, and ear-EEG systems provide unobtrusive alternatives to traditional caps for daily monitoring [28], [29]. Bioadhesive and hybrid materials enhance contact quality, while microstructured adhesives maintain stable impedance during motion. Innovations such as controlled-release semi-dry reservoirs, hydrogels, carbon-fiber bristles, microneedle arrays, 3D-printed electrodes, and graphene- or PEDOT:PSS-based fabrics further support comfortable, low-impedance, motion-resistant EEG acquisition [30]. Advances further enable compact, energy-efficient EEG systems. Miniaturized analog front-ends, low-noise amplifiers, and on-chip ADCs support high-quality acquisition in small form factors, while integrated circuits that combine amplification, filtering, artifact rejection, and compression reduce both power use and wireless bandwidth requirements [25]. Improved signal processing and AI-based artifact correction are also enhancing wearable EEG reliability. Convolutional, recurrent, and attention-based machine learning models improve the detection and suppression of motion and muscle artifacts. Hybrid pipelines using wavelet decomposition, Independent Component Analysis, or adaptive subspace reconstruction robustly remove complex noise patterns. Sensor-fusion strategies that combine EEG with IMU signals strengthen artifact prediction during gait and head movement, and emerging low-power implementations enable real-time, on-device suppression [23]. Standardization and benchmarking efforts are progressing as well. Comparative assessments of wearable EEG signal quality and reproducibility are informing emerging validation guidelines[26]. These efforts support the development of shared data standards, test protocols, and cross-device calibration to improve reproducibility in real-world applications. Finally, ethical and privacy-focused innovation is becoming central to device design. Wearable EEG systems increasingly integrate secure data handling and on-device processing to protect sensitive neural information. Privacy-by-design architectures, combined with embedded AI for real-time inference, reduce reliance on continuous data transmission and support responsible deployment of neurotechnology [27].

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Concluding Remarks

In conclusion, EEG wearables have demonstrated significant potential across a wide range of applications, from consumer wellness and cognitive assessments to clinical monitoring and brain-computer interfaces. However, challenges such as improving signal quality, ensuring usability in real-world conditions, and addressing data privacy concerns must be addressed to realize their full potential. Continued advancements in electrode technology and device integration will be crucial in expanding the scope and effectiveness of wearable EEG systems.

Acknowledgements

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References

[1] W. Einthoven, “Die galvanometrische Registrirung des menschlichen Elektrokardiogramms, zugleich eine Beurtheilung der Anwendung des Capillar-Elektrometers in der Physiologie,” *Pflügers Arch. Gesammte Physiol. Menschen Tiere*, vol. 99, no. 9–10, pp. 472–480, Nov. 1903, doi: 10.1007/BF01811855.

[2] E. D. Adrian and D. W. Bronk, “The discharge of impulses in motor nerve fibres: Part II. The frequency of discharge in reflex and voluntary contractions,” *J. Physiol.*, vol. 67, no. 2, pp. i3–151, Mar. 1929.

[3] H. Berger, “Über das Elektrenkephalogramm des Menschen,” *Arch. Psychiatr. Nervenkr.*, vol. 87, no. 1, pp. 527–570, Dec. 1929, doi: 10.1007/BF01797193.

[4] D. Kim, J. Min, and S. H. Ko, “Recent developments and future directions of wearable skin biosignal sensors,” *Adv. Sensor Res.*, vol. 3, no. 2, Feb. 2024, doi: 10.1002/adsr.202300118.

[5] Muse, “Muse.” Accessed: Dec. 1, 2025. [Online]. Available: https://choosemuse.com/

[6] Emotiv, “Emotiv.” Accessed: Dec. 1, 2025. [Online]. Available: https://www.emotiv.com/

[7] NeuroSky, “NeuroSky.” Accessed: Dec. 1, 2025. [Online]. Available: https://neurosky.com/

[8] Beacon Biosignals, “Dreem headband.” Accessed: Dec. 1, 2025. [Online]. Available: https://beacon.bio/dreem-3s

[9] Cognionics, “Cognionics Quick-20R v2.” Accessed: Dec. 1, 2025. [Online]. Available: https://www.cgxsystems.com/quick-20r-v2

[10] Bitbrain, “Bitbrain.” Accessed: Dec. 1, 2025. [Online]. Available: https://www.bitbrain.com/

[11] Epitel, “Epitel.” Accessed: Dec. 1, 2025. [Online]. Available: https://www.epitel.com/

[12] Neurable, “Neurable.” Accessed: Dec. 1, 2025. [Online]. Available: https://www.neurable.com/

[13] F. Marini, C. Lee, J. Wagner, S. Makeig, and M. Gola, “A comparative evaluation of signal quality between a research-grade and a wireless dry-electrode mobile EEG system,” *J. Neural Eng.*, vol. 16, no. 5, p. 054001, Sep. 2019, doi: 10.1088/1741-2552/ab21f2.

[14] J. T. Teo, S. J. Johnstone, and S. J. Thomas, “Use of portable devices to measure brain and heart activity during relaxation and comparative conditions: Electroencephalogram, heart rate variability, and correlations with self-report psychological measures,” *Int. J. Psychophysiol.*, vol. 189, pp. 1–10, Jul. 2023, doi: 10.1016/j.ijpsycho.2023.04.002.

[15] H. Alkaf, A. Khandoker, H. Jelinek, and K. Khalaf, “NeuroSky Mindwave Mobile Headset 2 as an intervention for reduction of stress and anxiety measured with pulse rate variability,” in *Proc. Comput. Cardiol. (CinC)*, Dec. 2020, doi: 10.22489/CinC.2020.350.

[16] O. E. Krigolson et al., “Using Muse: Rapid mobile assessment of brain performance,” *Front. Neurosci.*, vol. 15, Jan. 2021, doi: 10.3389/fnins.2021.634147.

Accepted Manuscript

[17] D. Z. Blandon, J. E. Munoz, D. S. Lopez, and O. H. Gallo, "Influence of a BCI neurofeedback videogame in children with ADHD: Quantifying the brain activity through an EEG signal processing dedicated toolbox," in *Proc. 2016 IEEE 11th Colombian Comput. Conf. (CCC)*, Sep. 2016, pp. 1–8, doi: 10.1109/ColumbianCC.2016.7750788.

[18] P. J. Arnal et al., "The Dreem headband as an alternative to polysomnography for EEG signal acquisition and sleep staging," *bioRxiv*, Jun. 10, 2019, doi: 10.1101/662734.

[19] M. Nasseri et al., "Signal quality and patient experience with wearable devices for epilepsy management," *Epilepsia*, vol. 61, no. S1, Nov. 2020, doi: 10.1111/epi.16527.

[20] U. Chaudhary, B. Xia, S. Silvoni, L. G. Cohen, and N. Birbaumer, "Brain–computer interface–based communication in the completely locked-in state," *PLoS Biol.*, vol. 15, no. 1, p. e1002593, Jan. 2017, doi: 10.1371/journal.pbio.1002593.

[21] N. T. Vo, "Performance of a prosthetic arm using MindWave NeuroSky sensor," in *Proc. 2023 8th Int. Sci. Conf. Applying New Technol. Green Buildings (ATiGB)*, Nov. 2023, pp. 52–56, doi: 10.1109/ATiGB59969.2023.10364464.

[22] O. E. Krigolson, C. C. Williams, A. Norton, C. D. Hassall, and F. L. Colino, "Choosing Muse: Validation of a low-cost, portable EEG system for ERP research," *Front. Neurosci.*, vol. 11, Mar. 2017, doi: 10.3389/fnins.2017.00109.

[23] P. Arpaia et al., "A systematic review of techniques for artifact detection and artifact category identification in electroencephalography from wearable devices," *Sensors*, vol. 25, no. 18, p. 5770, Sep. 2025, doi: 10.3390/s25185770.

[24] F. Xiong et al., "Advancements in dry and semi-dry EEG electrodes: Design, interface characteristics, and performance evaluation," *AIP Adv.*, vol. 15, no. 4, Apr. 2025, doi: 10.1063/5.0228644.

[25] M. Kim, S. Yoo, and C. Kim, "Miniaturization for wearable EEG systems: Recording hardware and data processing," *Biomed. Eng. Lett.*, vol. 12, no. 3, pp. 239–250, Aug. 2022, doi: 10.1007/s13534-022-00232-0.

[26] T. Radüntz, "Signal quality evaluation of emerging EEG devices," *Front. Physiol.*, vol. 9, Feb. 2018, doi: 10.3389/fphys.2018.00098.

[27] S. Frey et al., "GAPses: Versatile smart glasses for comfortable and fully-dry acquisition and parallel ultra-low-power processing of EEG and EOG," *IEEE Trans. Biomed. Circuits Syst.*, vol. 19, no. 3, pp. 616–628, Jun. 2025, doi: 10.1109/TBCAS.2024.3478798.

[28] H. Moumane, J. Pazuelo, M. Nassar, J. Y. Juez, M. Valderrama, and M. Le Van Quyen, "Signal quality evaluation of an in-ear EEG device in comparison to a conventional cap system," *Front. Neurosci.*, vol. 18, Sep. 2024, doi: 10.3389/fnins.2024.1441897.

[29] X. Wang, W. Huang, C. He, H. Wu, J. Lin, and L. Cheng, "A flexible EEG acquisition headband with high reliability and high signal-to-noise ratio," *IEEE Sensors J.*, vol. 24, no. 9, pp. 14370–14379, May 2024, doi: 10.1109/JSEN.2024.3381789.

[30] S. Ahmed et al., "Stick-and-play bioadhesive hairlike electrodes for chronic EEG recording on human," *npj Biomed. Innov.*, vol. 2, no. 1, p. 9, Mar. 2025, doi: 10.1038/s44385-025-00009-x.

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Section 7: Signal Processing

7.1 - Signal Processing

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Status

Real-time biomedical monitoring with wearable and textile-based sensors has enormous potential to improve healthcare [1]. These sensors are increasingly used in both clinical and everyday environments because they offer convenient and unobtrusive ways to acquire continuous physiological data [1]. Modern wearables can measure key vital signs such as heart rate, blood pressure, and oxygen saturation outside of traditional clinical settings and support illness monitoring and early detection (**Figure 26**) [2]. As technology continues to advance, broader and more impactful applications of wearable sensing are expected to emerge. Because these systems operate in highly dynamic, real-world environments, the signals acquired are often affected by motion, variable sensor–skin contact, and other sources of noise. Robust signal-processing methods are therefore essential to ensure that meaningful physiological information can be reliably extracted. In this subsection, we focus on foundational signal-processing techniques—specifically noise reduction and feature engineering—that are central to preparing wearable data for downstream analysis. More advanced topics such as multimodal fusion, real-time computation, and AI-based modeling are discussed in later subsections of this chapter.

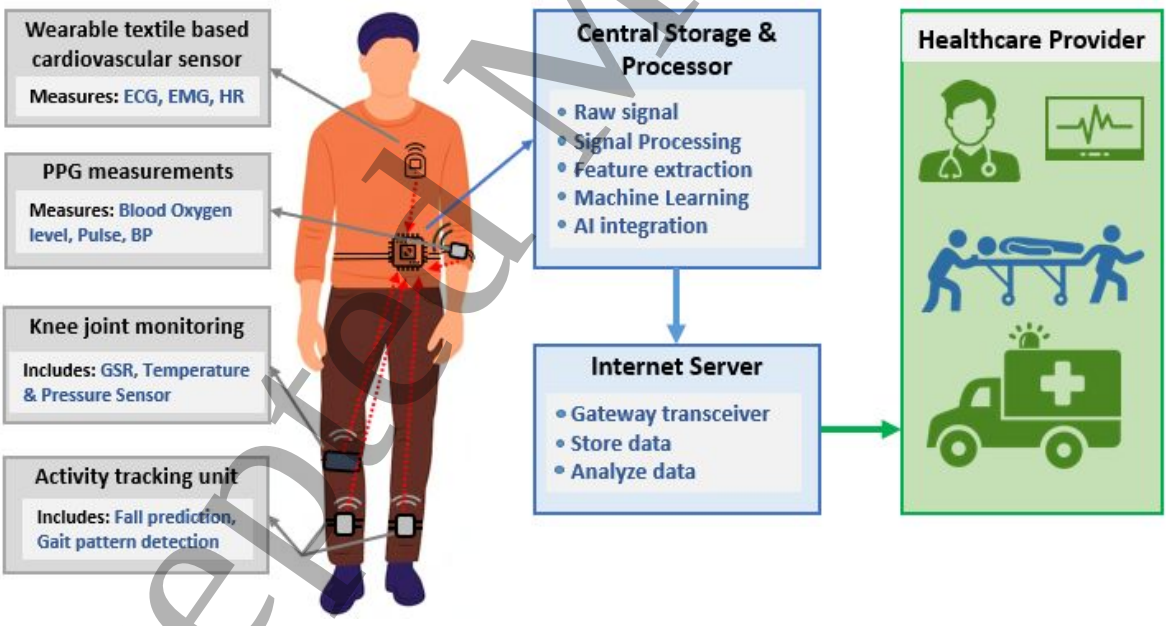


Figure 26. Overview of wearables in remote health monitoring systems. Signal processing plays a vital role in design decisions around the central storage and processing units for extracting meaningful information from the data acquired by the sensors.

Noise Reduction

Many kinds of interference or artifacts can be observed during bio-signal measurements, which may have an impact on the precision and quality of the recorded signals. Motion artifacts, loss-of-contact artifacts originating from loss of physical electrode contact, power line interference, and baseline

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drift are a few of the most frequent kinds of artifacts found in wearable sensor data [3]. Noise reduction techniques can be used to eliminate such undesirable signals from the bio-signal data, resulting in an increased signal-to-noise ratio of the wearables data.

Baseline Drift

Baseline drift is a low-frequency signal variation that affects the baseline voltage of physiological signals captured by wearable sensors and is brought on by ambient interference or motion artifacts. One example is power line interference, which is the result of electrical activity from power lines interfering with the signal being captured, producing noise at frequencies of 50 or 60 Hz. Temperature, humidity, or changes in electrode-skin contact can all also lead to baseline drift, which can cause gradual unidirectional changes in the recorded signal over time.

Numerous filtering techniques have been suggested to counteract baseline drift, including infinite impulse response (IIR) and finite impulse response (FIR) filters, wavelet transforms independent component analysis (ICA), signal averaging, and filtering methods like bandpass, notch, and adaptive filters [4][5]. For example, the IIR bandpass filter is frequently used to preprocess photoplethysmography (PPG) signals because it is simple to design, effective at detrending baseline drift, and reduces undesired distortion. Most baseline drift filtering techniques are based on the frequency characteristics of the wearables data signal and noise.

Motion Artifacts

Motion artifacts are data disturbances resulting from the wearer's movement. These are time-varying, nonstationary electrical signals that differ from background noise, and are especially common during physical activity [4]. Motion artifacts can be detected using a variety of techniques, such as visual inspection, signal processing methods, and machine learning algorithms [6]. Clean signals and motion artifacts can often share a superimposed frequency zone, particularly for PPG signals, which makes it challenging to address motion artifacts with classical filters like FIR and IIR that work well for removing baseline drift and/or ambient noise as described above. Statistical parameters such as Shannon entropy, mean and variance of the intrinsic mode function of the empirical mode decomposition (EMD), and adaptive noise cancellation (ANC) with thresholding techniques have been utilized for effective motion artifact removal [7]. **Figure 27** illustrates an example of EMD, decomposing the signal corrupted by motion artifacts into different frequency component signals that function to isolate the clean signal. Some popular signal processing techniques for motion artifact removal in PPG signals include ANC, Independent Component Analysis (ICA), Singular Value Decomposition (SVD), Wavelet Transform (WT), and cycle-by-cycle Fourier Series Analysis (FSA). ANC works better than traditional filters for addressing motion artifacts in PPG due to its adaptably changing coefficients which can mitigate motion artifacts quite accurately [4]. Additionally, machine-learning methods like convolutional neural networks (CNNs) have been employed to eliminate motion artifacts from biosignal data [7].

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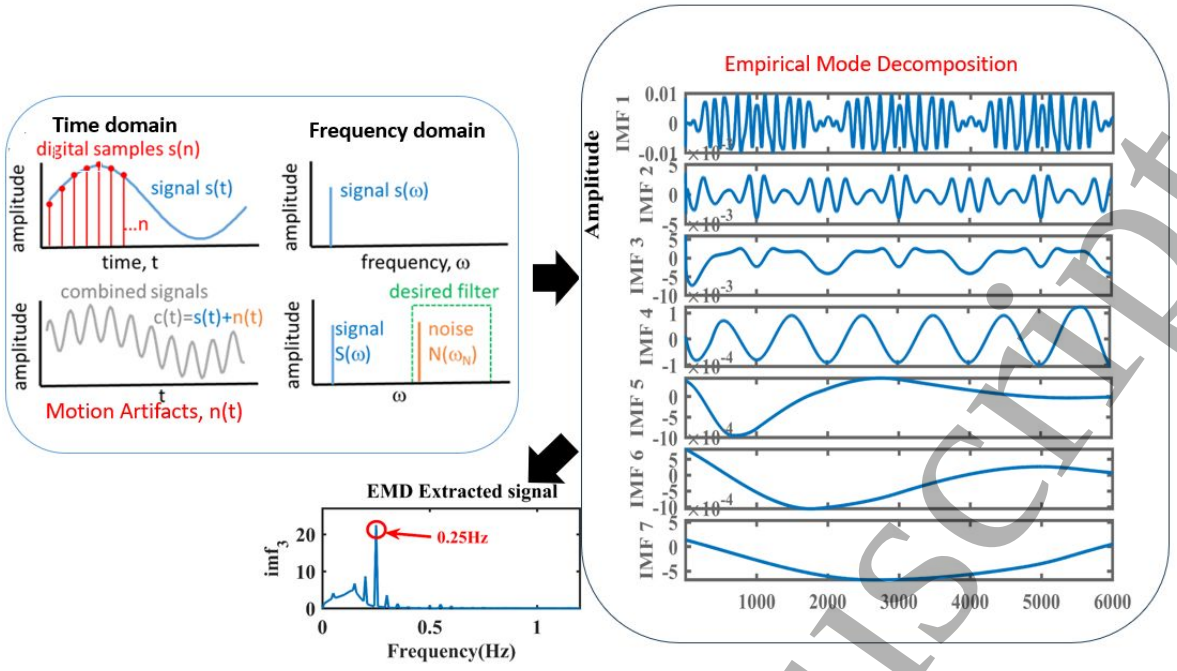


Figure 27. Empirical mode decomposition (EMD) overview. The signal s(t) is a physiological signal that is corrupted by motion artifacts represented as n(t). The EMD technique decomposes the corrupted signal into different frequency bands known as intrinsic mode function (IMF) and can extract the physiological signal from the signal corrupted by motion artifacts.

Feature Engineering

Filtered wearables signals still require additional post-processing to make the information meaningful. Thus, another aspect of wearables data signal processing is feature engineering, which entails identifying pertinent features in the sensor data and relating them to particular physiological indicators, such as skin temperature, heart rate, heart rate variability, and respiration rate. Relevant features can be extracted from the wearable sensor data by methods including peak detection, linear and nonlinear regression, and time/frequency domain analysis. From the filtered waveform itself, time domain properties can be obtained. These can be specific to a waveform, such as heart rate derived from electrocardiography (ECG) data, statistical measures like mean and standard deviation, or information theory measures like signal entropy. For ECG data, for example, characteristics such as R-R interval, QRS complex, respiratory rate, heart rate, and heart rate variability can be extracted through peak finding methods applied to the filtered waveform in the time domain, as well as applications of basic statistical techniques to the data such as mean and standard deviation. Converting the time domain signal into the frequency domain enables other features to be calculated, such as the mean frequency and energy content of different bands. Examples of frequency characteristics are power spectral density and Fourier transform coefficients. More specifically, discrete-time Fourier transform (DFT) has been used for discrete signals, FFT has been used as an efficient implementation of FT, and short-time Fourier transform (STFT) has been used for non-stationary signals. The most common type of temporal-frequency feature for nonstationary signals is the discrete wavelet transform (DWT) coefficient. Overall, effective signal processing and feature engineering methods are necessary for the real-world implementation of wearables that are accurate and dependable for biomedical monitoring, allowing for continuous and remote health assessment for a variety of applications [8].

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Challenges in Wearables Signal Processing

For biomedical signals to be monitored in real-time, advanced data analysis and signal processing methods are required. Signal processing algorithms are used to remove noise, extract distinguishable features, and identify biomarkers that are indicative of health conditions [2]. Wearable textile sensors are particularly plagued by motion artifacts given that their form factor is optimized to function as a piece of clothing, which by its nature has less tight contact with skin than other wearable form factors. Further, it can be difficult to adapt conventional signal processing methods to online, miniaturized, and wireless wearable form factors. Related to this challenge is the design trade-off between algorithm performance and power consumption [9]. As a result, wearables may struggle to meet the stringent performance specifications of conventional medical devices.

In terms of methods for feature engineering, the bulk of methods developed thus far are based on frequency data, with wavelet transforms being especially popular [9]. However, wavelet decomposition doesn't always offer the most optimal—or even most appropriate—feature set for all signal types and applications [9]. There is room for improvement and a need for exploring methodologic trade-offs of feature engineering techniques. However, the difficulty and cost of evaluating algorithm performance in healthcare applications makes comprehensive evaluation of these trade-offs difficult.

Additional opportunities in wearables signal processing include developing methods of multi-modal or multi-nodal sensor fusion– combining different data streams from different types of sensors, or combining data from the same types of sensors placed in various locations, respectively. Here, challenges arise in multiple signal alignment, mismatches in the data dimensionality and/or data density/sampling frequency of different data modes, and employing appropriate multimodal data fusion methods (integration at both the decision and feature levels). Recently, eventDTW (eDTW) was proposed as a novel method for multi-modal alignment of signals of varying sampling frequencies [11].

The aforementioned obstacles and constraints must be overcome before wearable textile-based sensors can be widely and reliably used in a range of healthcare applications. The goal of ongoing research is to develop novel materials, designs, production techniques, and innovative robust signal processing algorithms that will help address these issues and enhance the functionality of wearable textile-based sensors for long-term biomedical monitoring application areas.

Recent Wearables Signal Processing Advancements

Recent years have seen rapid development in wearable algorithms, creating new opportunities to improve healthcare. Co-evolving with hardware technologies, embedded signal-processing algorithms have several advantages such as reduced power consumption, decreased volumes of data required to be transmitted and analyzed offline, reduced system latency, and higher quality recordings (e.g., with on-board motion artifact reduction) [7].

Advancements in sensor data fusion technologies combined with miniaturization of hardware have also propelled the development of multi-modal wearables. A recent study demonstrated that utilizing different advanced signal-processing algorithms that are suitable for different data types can overcome the challenges of handling multi-dimensional datasets [10]. For example, a wearable tactile sensor attached to multiple target muscle groups of the human body was capable of

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capturing different frequency physiological signs such as respiration (~ 0.1 Hz), cardiac activity (~10 Hz), and hand gestures (~1 Hz) [10]. With the advancement of wearable algorithms for multi-modal sensing, areas for further research include dimensionality reduction, signal processing, pattern recognition, and data fusion techniques.

Furthermore, the enormous volume of data produced by these multi-modal sensors demands new methods for signal processing via machine learning and artificial intelligence (AI), enabling the extraction of useful and novel insights. Machine learning is also being applied for efficient motion artifact reduction. For example, the detection and tracking of cardiovascular disease has advanced significantly with wearable sensors and machine learning due to newly efficient noise reduction methods [10]. Machine learning algorithms have improved wearable sensors' signal analysis, resulting in more precise feature extraction and signal processing and enabling the extraction of a wider range of physiological information from wearable sensors. These developments in wearable algorithms driven by machine learning provide opportunities for better healthcare, early disease detection, and customized treatments. To fully realize the potential of these integrated technologies and open the door to a new era of medical monitoring, more research and technological development are essential. Particularly, there is an open opportunity to develop automated tools to assist designers in selecting the best signal processing method for specific hardware and health application combinations.

Concluding Remarks

Wearable textile-based sensor technology is gaining popularity because of its flexibility, remote accessibility, portability, and the ability to collect data continuously and in real time. While advancements in signal processing methods have increased sensor accuracy and usability, challenges remain. Crucial elements like algorithm accuracy, varying deployment conditions, hardware limitations, and data privacy remain pertinent. Future advancements should concentrate on addressing these issues through interdisciplinary collaboration, the implementation of strict validation processes, and the establishment of clear regulatory frameworks.

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References

[1] J. Zhao, Y. Fu, Y. Xiao, Y. Dong, X. Wang, and L. Lin, “A naturally integrated smart textile for wearable electronics applications,” Adv. Mater. Technol., vol. 5, no. 1, p. 1900781, Jan. 2020, doi: 10.1002/admt.201900781.

Accepted Manuscript

[2] J. Dunn, R. Runge, and M. Snyder, “Wearables and the medical revolution,” Pers. Med., vol. 15, no. 5, pp. 429–448, Sep. 2018, doi: 10.2217/pme-2018-0044.
[3] D. Fouassier, X. Roy, A. Blanchard, and J. Hulot, “Assessment of signal quality measured with a smart 12-lead ECG acquisition T-shirt,” Ann. Noninvasive Electrocardiol., vol. 25, no. 1, p. e12682, Jan. 2020, doi: 10.1111/anec.12682.
[4] D. Yang et al., “A novel adaptive spectrum noise cancellation approach for enhancing heartbeat rate monitoring in a wearable device,” IEEE Access, vol. 6, pp. 8364–8375, 2018, doi: 10.1109/ACCESS.2018.2805223.
[5] M. Živanović and M. González-Izal, “Simultaneous powerline interference and baseline wander removal from ECG and EMG signals by sinusoidal modeling,” Med. Eng. Phys., vol. 35, no. 10, pp. 1431–1441, Oct. 2013, doi: 10.1016/j.medengphy.2013.03.015.
[6] C. M. Vidhya, Y. Maithani, and J. P. Singh, “Recent advances and challenges in textile electrodes for wearable biopotential signal monitoring: A comprehensive review,” Biosensors, vol. 13, no. 7, p. 679, Jun. 2023, doi: 10.3390/bios13070679.
[7] J. Lee, D. D. McManus, S. Merchant, and K. H. Chon, “Automatic motion and noise artifact detection in Holter ECG data using empirical mode decomposition and statistical approaches,” IEEE Trans. Biomed. Eng., vol. 59, no. 6, pp. 1499–1506, Jun. 2012, doi: 10.1109/TBME.2011.2175729.
[8] S. Majumder, T. Mondal, and M. J. Deen, “Wearable sensors for remote health monitoring,” Sensors, vol. 17, no. 1, p. 130, Jan. 2017, doi: 10.3390/s17010130.
[9] A. J. Casson, “Opportunities and challenges for ultra-low-power signal processing in wearable healthcare,” in Proc. 23rd Eur. Signal Process. Conf. (EUSIPCO), Nice, France, Aug. 2015, pp. 424–428, doi: 10.1109/EUSIPCO.2015.7362418.
[10] X. Jiang, R. Chen, and H. Zhu, “Recent progress in wearable tactile sensors combined with algorithms based on machine learning and signal processing,” APL Mater., vol. 9, no. 3, p. 030906, Mar. 2021, doi: 10.1063/5.0043842.
[11] Q. Jiang, B. Wang, O. Avram, E. Olgin, and J. Dunn, “EventDTW: An improved dynamic time warping algorithm for aligning biomedical signals of nonuniform sampling frequencies,” Sensors, vol. 20, no. 9, p. 2700, 2020, doi: 10.3390/s20092700.

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7.2 - Data Fusion and Multi-sensor Integration

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Status

Significant advances in sensor technology, material science, and data processing have enabled the miniaturization and widespread adoption of wearable electronic devices for health and fitness tracking[1]. Current wearables, such as smart watches and fitness trackers, integrate multiple sensors to provide insight into physical activity, sleep patterns, and cardiovascular health. To achieve this, devices host a multitude of sensors which individually targeting separate biological signals, such as accelerometers for motion tracking, and photoplethysmography for continuous heart rate measurements. However, efforts to combine these independent data streams can further enable novel types of measurements[2], [3], [4], improve the accuracy of existing approaches[5], and provide a more comprehensive view of the user's health and activity[6], [7], [8].

Figure 28 illustrates categories of sensors commonly implemented within wearables, and examples of novel measurements and applications enabled through their fusion. Fundamental measurements of motion, temperature, optical, electrical, chemical activity can be combined to form physiological estimates of blood pressure based on signal timings[9], [10], form methods for overcoming inaccuracies such as motion artifacts[11], [12], and be linked to diseases and clinical needs via machine learning and AI models for better pattern recognition, anomaly detection, and predictive analytics[1], [6], [13].

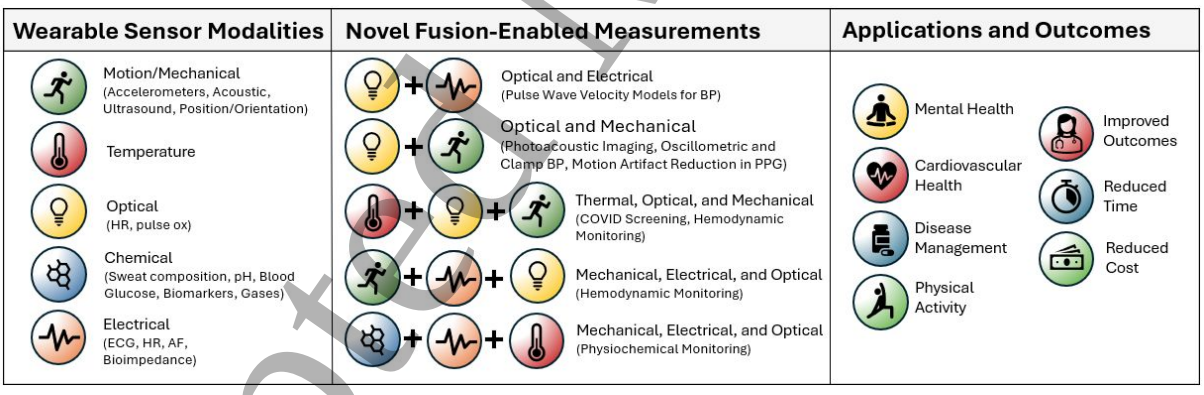


Figure 28. Fundamental types of measurements in current wearables, and examples of fusion-enabled measurements through two or more sensor channels. Combinations of sensor measurements aim to more comprehensively evaluate user status to improve the screening and management of chronic diseases.

Current and Future Challenges

Wearable sensors often provide imperfect, non-invasive estimates of internal physiology. Increasing the number and type of sensors within wearable devices is a strategy to overcome this limitation through cross-referencing, advanced physiological models, and improving accuracy in the face of confounders. However, increasing the number of sensors also presents several unique engineering and data processing challenges, including physical size, data bandwidth/volume, and establishing the

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accuracy and calibration of continuous metrics compared to single-time-point invasive 'gold standards'.

Off-the-self components on the millimetre scale allow for many sensors to be distributed throughout a device. However, the accuracy of combinatorial measurements can require more stringent co-location of sensors and necessitate the continued miniaturization and integration of multiple sensors within single ASIIC designs and packaged ICs. Integration of multiple sensors, each capable of sampling in ranges of Hz to MHz, can also quickly pose a data pipeline and processing challenge. The ability to store large volumes of data on-board the wearable requires large memory IC's, while the ability to stream data off in real-time can bottleneck NFC and BLE communication protocols. Power consumption and time synchronization between different data channels and devices also becomes of great importance, especially when comparing waveform morphologies and features on the millisecond time scale.

Processing, visualizing, and analysing extremely large continuous datasets along with the need to label events and reference to 'gold standards' can quickly become a challenge. The 'gold standard' comparisons for certain cardiovascular vital signs, such as blood pressure, cardiac output, ejection fraction, and systemic vascular resistance, are also pointwise measurements and/or are invasive. This poses challenges in validation with real-time continuous data sets and gaining access to the proper clinical environments[14]. Lastly, as wearables progress to real-world environments an increasing focus is needed on confounding sources of error such as motion artifacts, exercise, age, and the impact of common diseases on sensor accuracy.

Advances in Science and Technology to Meet Challenges

Addressing these challenges requires ongoing research, technological innovation, and interdisciplinary collaboration. Further miniaturization of sensors through ASIIC design and heterogenous integration/packaging will improve functionality and enable increasing sensor channels. Additionally, heterogenous integration of new sensor technologies, such as VCSELS, spectrometers, and APDs, will further expand the accuracy and number of fusion-enabled measurements. The further integration of these sensors with supporting circuitry infrastructure (power management, communication, microcontrollers) will lead to reduced power consumption.

Advances in data processing techniques and coding environments will make the visualization and analysis of vast data sets more assessable, along with the ability to train and evaluate more advanced machine learning and artificial intelligence models. This will be facilitated by standardization of data formats and implementation of higher band width communication protocols. The incorporation of machine learning cores on microcontrollers will also allow on-board processing of complex data sets and the real-time application of AI models.

Lastly, more thorough regulatory requirements and guidelines will be needed to set the standard for validation processes involving novel multi-sensor devices. Such guidance needs to be specific to measurement targets, such as blood pressure, but generalizable enough to stay relevant in quickly advancing sectors where the combination of sensor types and calibration techniques are vast and expanding.

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Concluding Remarks

The successful resolution of these challenges will enable more effective and widespread use of data fusion in wearable technology, ultimately benefiting users through enhanced health monitoring and personalized insights. Overall, the field of data fusion and multi-sensor integration in wearables and smart textiles is crucial for advancing personalized health and wellness solutions, and further innovations hold the potential to significantly enhance both individual health management and broader healthcare systems.

Acknowledgements

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References

[1] L. Zhao et al., "Emerging sensing and modeling technologies for wearable and cuffless blood pressure monitoring," *npj Digit. Med.*, vol. 6, no. 1, p. 93, 2023, doi: 10.1038/s41746-023-00835-6.
[2] C. Xu et al., "A physicochemical-sensing electronic skin for stress response monitoring," *Nat. Electron.*, vol. 7, no. 2, pp. 168–179, 2024, doi: 10.1038/s41928-023-01116-6.
[3] X. Gao et al., "A photoacoustic patch for three-dimensional imaging of hemoglobin and core temperature," *Nat. Commun.*, vol. 13, no. 1, p. 7757, 2022, doi: 10.1038/s41467-022-35455-3.
[4] E. S. Sani et al., "A stretchable wireless wearable bioelectronic system for multiplexed monitoring and combination treatment of infected chronic wounds," *Sci. Adv.*, vol. 9, no. 12, p. eadf7388, Aug. 2024, doi: 10.1126/sciadv.adf7388.
[5] T. A. Swain, M. A. McNarry, A. W. H. Runacres, and K. A. Mackintosh, "The role of multi-sensor measurement in the assessment of movement quality: A systematic review," *Sports Med.*, vol. 53, no. 12, pp. 2477–2504, 2023, doi: 10.1007/s40279-023-01905-1.
[6] S. Qiu, B. P. Y. Yan, and N. Zhao, "Stroke-volume-allocation model enabling wearable sensors for vascular age and cardiovascular disease assessment," *npj Flex. Electron.*, vol. 8, no. 1, p. 24, 2024, doi: 10.1038/s41528-024-00307-1.
[7] A. Kollias, K. G. Kyriakoulis, A. Komnianou, P. Stathopoulou, and G. S. Stergiou, "Prognostic value of home versus ambulatory blood pressure monitoring: A systematic review and meta-analysis of outcome studies," *J. Hypertens.*, vol. 42, no. 3, 2024. [Online]. Available: https://journals.lww.com/jhypertension/fulltext/2024/03000/prognostic_value_of_home_versus_ambulatory_blood.1.aspx
[8] Q. Zhang et al., "Technology development for simultaneous wearable monitoring of cerebral hemodynamics and blood pressure," *IEEE J. Biomed. Health Inform.*, vol. 23, no. 5, pp. 1952–1963, 2019, doi: 10.1109/JBHI.2018.2876087.
[9] D. Franklin et al., "Synchronized wearables for the detection of haemodynamic states via electrocardiography and multispectral photoplethysmography," *Nat. Biomed. Eng.*, vol. 7, no. 10, pp. 1229–1241, 2023, doi: 10.1038/s41551-023-01098-y.
[10] J. Liu, B. Yan, S.-C. Chen, Y.-T. Zhang, C. Sodini, and N. Zhao, "Non-invasive capillary blood pressure measurement enabling early detection and classification of venous congestion," *IEEE J. Biomed. Health Inform.*, vol. 25, no. 8, pp. 2877–2886, 2021, doi: 10.1109/JBHI.2021.3055760.
[11] M. Lin et al., "A fully integrated wearable ultrasound system to monitor deep tissues in moving

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subjects," *Nat. Biotechnol.*, vol. 42, no. 3, pp. 448–457, 2024, doi: 10.1038/s41587-023-01800-0.
[12] J.-Y. Yoo et al., "Wireless broadband acousto-mechanical sensing system for continuous physiological monitoring," *Nat. Med.*, vol. 29, no. 12, pp. 3137–3148, 2023, doi: 10.1038/s41591-023-02637-5.
[13] J. Kim et al., "Skin-interfaced wireless biosensors for perinatal and paediatric health," *Nat. Rev. Bioeng.*, vol. 1, no. 9, pp. 631–647, 2023, doi: 10.1038/s44222-023-00090-0.
[14] G. S. Stergiou et al., "European Society of Hypertension recommendations for the validation of cuffless blood pressure measuring devices," *J. Hypertens.*, vol. 41, no. 12, 2023. [Online]. Available: https://journals.lww.com/jhypertension/fulltext/2023/12000/european_society_of_hypertension_recommendations.4.aspx

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7.3 - Data Fusion and Multi-Sensor Integration

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Status

Advancements in microelectronics and wireless communications have catalysed the development of Body Sensor Networks (BSNs) [1]. These networks integrate wearable and environmental sensors across multiple devices, thereby enhancing the functionality and reliability of wearable technologies. Knowledge-driven sensing is typically confined to generic tasks; for instance, signal processing techniques are frequently used to fuse data from accelerometers, gyroscopes, and magnetometers to enable precise orientation tracking within Inertial Measurement Units (IMUs). Early data-driven approaches primary excelled with homogeneous or conceptually similar sensors, leveraging fundamental physical principles for sensor fusion and feature extraction, complementing classical and light-weight machine learning (ML) algorithms. Products like MVN Biomech by Xsens use multiple IMUs to capture kinematic measurements such as limb flexion angles, providing robust features for ML-driven applications in rehabilitation or sports analytics [2].

While homogeneous sensor fusion enhances system reliability, improves signal-to-noise ratios, and boosts resolution through multi-view sensing and redundancy, there is a drive to harness the capabilities of diverse sensor information to overcome the limitations of homogeneous sources [3]. For example, integrating inertial data can mitigate interference from motion artifacts in wearable photoplethysmogram (PPG) measurements [4]. Heterogeneous sensor fusion, which integrates measurements from disparate physiological processes, has been advanced by deep learning (DL) [1,3,5,6-8]. This technology enables automatic feature learning, facilitating the fusion of disparate data types into abstract shared feature spaces. Consequently, BSNs employing DL-driven fusion of heterogeneous information excel in performing complex tasks like human pose estimation [5], human activity recognition (HAR) [9-12], gesture recognition [13,14] and emotion detection [10].
Within the BSN framework, sensors or 'edge devices' handle data sampling, cleaning, and occasionally feature extraction. Edge devices transmit information to gateway devices, typically smartphones. For complex sensing tasks, gateway devices serve as conduits to cloud-servers where more intensive computation can take place [6,15].

Current and Future Challenges

The demands of processing multiple data streams and coordinating a variety of edge devices amplify many of the existing challenges inherent to single-sensor systems. Nevertheless, multi-sensor systems do present some unique challenges, primarily stemming from the complexity of heterogeneous sensor fusion.

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In decision-level sensor fusion, decisions made from individual sensor streams are combined to reach a final determination, as shown in **Figure 29.** While this approach efficiently distributes BSN computations, it often yields inconsistent outcomes for heterogeneous BSNs and does not fully exploit the complementary nature of multimodal data [11]. In contrast, data-level and feature-level fusions represent fine-grained methods, merging either raw data streams or extracted features. Homogeneous fine-grained fusion generally demands moderate computational effort because algorithms used to align information into a ubiquitous format can be knowledge driven. While these fusion techniques are robust, they necessitate thorough calibration and precise synchronisation [3,5]. Heterogeneous fine-grained fusion requires higher computational effort because it necessitates the learning of shared feature spaces that can effectively encapsulate conceptually diverse information. Convolutional neural networks (CNNs) [7] and transformer networks [8] have been effective in this capacity. However, due to substantial computational demands, DL-driven fusion often requires processing in the cloud [6]. Using cloud services in BSNs not only introduces undesirable latency but also raises substantial privacy concerns [11,15].

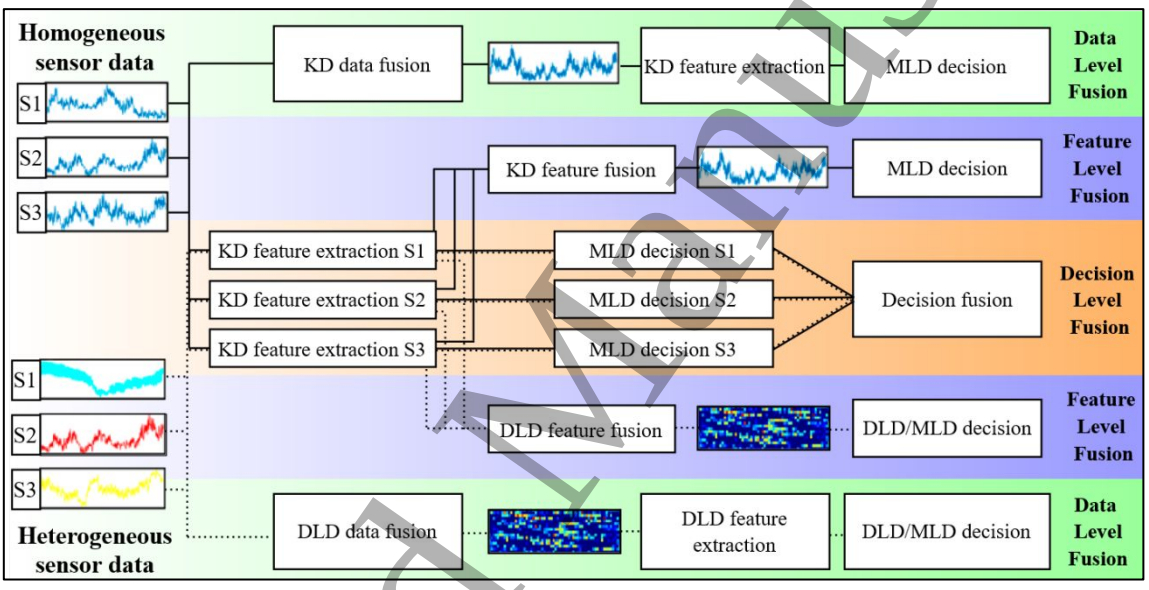


Figure 29. Data, feature and decision level fusion pipelines for data-driven decisions in body sensor networks involving homogeneous and heterogeneous sources. Deep learning-driven (DLD) approaches are computationally expensive and often require cloud computing, whereas machine learning (MLD) and knowledge driven (KD) operations are lightweight and can be performed on edge or gateway devices. DLD fusion is used for heterogeneous sources to form abstract feature representations whereas KD fusion is used for homogeneous sources to form human-interpretable representations.

While the capacity for BSN customisation facilitates a wide range of sensing solutions, it also creates a notably fragmented ecosystem. The lack of standardisation amongst DL-driven heterogeneous sensor fusion methods results in abstract feature representations that are seldom transferable to other domains without extensive re-development, data collection and re-training.

Advances in Science and Technology to Meet Challenges

To address the computational challenges associated with deploying sophisticated DL-driven fusion on gateway devices, researchers are turning to the latest DL accelerators (DLAs), notably neuromorphic platforms [6,9,13,14,16-18]. Gateway devices may reduce latency and power consumption by offloading AI-computations to dedicated DLA components. Major smartphone manufacturers such as Huawei, Samsung, Apple, and Google have integrated neural processing unit

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DLAs to enhance tasks like image recognition and natural language processing [15]. Neuromorphic computing platforms, representing the cutting edge of DLAs, have shown remarkable capabilities in executing AI computations with higher speed and lower power consumption. Inspired by the neural structures of the human brain, neuromorphic computing platforms collocate processing and memory functions by emulating neuron and synapse interactions. They use Spike Neural Networks (SNNs) to activate neurons based on accumulated charge thresholds overtime, facilitating highly parallelizable and event driven DL. Fra et al. 2022 used various SNNs on Loihi, a neuromorphic chip by Intel, to perform HAR by fusing inertial data from a smart watch and smart phone, achieving a reduction in energy consumption by nearly three orders of magnitude compared to non-spiking networks [9]. Ceolini et al. 2020 used a spiking CNN on Loihi to fuse electromyography (EMG) signals with camera frames for hand-gesture recognition, matching the accuracy of a portable graphics processing unit (GPU) system but with up to 600 times more efficient energy-delay product [13]. Liu et al. 2022 developed a nanowire-channel intrinsically stretchable neuromorphic transistor (NISNT) for energy efficient, accurate and ergonomic gesture recognition, fusing tactile and visual information from multiple sensors incorporated within a wearable glove [14]. By integrating neuromorphic DLAs into gateway devices, BSNs can reduce their dependence on cloud computing, enabling real-time execution of complex multi-sensing tasks with enhanced privacy, improved energy efficiency, and uncompromised accuracy.

A combination of transfer learning (TL), continuous learning (CL), and federated learning (FL) [1,10-12,19] can address the issue of domain deviation in BSNs, where domains can be characterized by the sensing environment, user base and sensor properties. TL enables DL models trained in one source domain to be adapted for different target domains. CL facilitates online transfer via unsupervised domain adaptation (UDA), which involves incrementally fine-tuning a pre-trained model using real-world data. This process typically aims to homogenise the distributions of the learned features across the source and target domains since the real-world data is unlabelled [19]. Shi et al. 2023 proposed a universal Transfer Fusion (TF) framework which dynamically evaluates domain deviations to identify suitable components of the learned feature fusion space for effective transfer [10]. This TF framework, validated on emotion recognition using heterogeneous fusion (electrocardiogram, electrodermal activity, respiration trace) and on HAR with homogeneous fusion (IMUs), achieved a 6.71% accuracy increase compared to conventional UDA approaches. Enhancing this learning paradigm, FL allows separate BSN clients to learn continuously from shared experiences by transferring knowledge to a centralized cloud-based global model. This approach bypasses privacy and bandwidth challenges by only sharing model weights as they adapt to their respective domains over a series of communication rounds [19]. FL has proven effective in heterogeneous sensor fusion; for instance, an FL-based Fall Detection (FL-FD) system using a 2D CNN to learn common image representations for IMU and camera streams achieved 99.927% accuracy for binary fall detection on a global model after 100 communication rounds [11]. Another study applied a temporal-CNN with FL to learn high-quality and transferable feature embeddings from multi-sensory input, including electroencephalogram (EEG), IMU and Wi-Fi channel-state information for applications in sleep stage classification and HAR [12]. These techniques collectively enhance the scalability of BSNs by reducing the insular nature of learned fusion features and improving their transferability across different domains.

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Concluding Remarks

BSNs aim to replicate the seamless user experience of single-wearable systems, delivering continuous, personalized and real-time feedback with ergonomic, light-weight devices. Achieving this level of integration poses unique challenges in applications involving heterogeneous sensor fusion due to the heavy reliance on DL for learning shared feature representations of disparate measurements. The substantial computational demands of DL can be offset by integrating DLAs, notably neuromorphic platforms, into gateway devices. Moreover, the challenges posed by the lack of standardisation and limited generalisability of fusion models can be addressed through innovations in continuous TL and FL. These advancements will not only enhance the functionality and efficiency of BSNs but also ensure their adaptability across a broad range of domains and applications.

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References

[1] R. Gravina, P. Alinia, H. Ghasemzadeh, and G. Fortino, “Multi-sensor fusion in body sensor networks: State-of-the-art and research challenges,” Inf. Fusion, vol. 35, pp. 68–80, May 2017, doi: 10.1016/j.inffus.2016.09.005.

[2] Y. Adesida, E. Papi, and A. H. McGregor, “Exploring the role of wearable technology in sport kinematics and kinetics: A systematic review,” Sensors, vol. 19, no. 7, p. 1597, Apr. 2019, doi: 10.3390/s19071597.

[3] L. N. Nguyen, P. Susaria, A. Mukherjee, M. L. Cañellas, C. A. Casado, X. Wu, S. Olli, D. B. Jayagopi, and M. B. López, “Non-contact multimodal indoor human monitoring systems: A survey,” Inf. Fusion, vol. 110, p. 102457, Oct. 2024, doi: 10.1016/j.inffus.2024.102457.

[4] D. Biswas, N. Simões-Capela, C. Van Hoof, and N. Van Helleputte, “Heart rate estimation from wrist-worn photoplethysmography: A review,” IEEE Sens. J., vol. 19, no. 16, pp. 6560–6570, Aug. 2019, doi: 10.1109/JSEN.2019.2914166.

[5] K. P. Seng, L.-M. Ang, E. Peter, and A. Mmonyi, “Machine learning and AI technologies for smart wearables,” Electronics, vol. 12, no. 7, p. 1509, Mar. 2023, doi: 10.3390/electronics12071509.

[6] E. Covi, E. Donati, X. Liang, D. Kappel, H. Heidari, M. Payvand, and W. Wang, “Adaptive extreme edge computing for wearable devices,” Front. Neurosci., vol. 15, May 2021, doi: 10.3389/fnins.2021.611300.

[7] R. Memmesheimer, N. Theisen, and D. Paulus, “Gimme signals: Discriminative signal encoding for multimodal activity recognition,” in Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS), Oct. 2020, pp. 10394–10401, doi: 10.1109/IROS45743.2020.9341699.

[8] R. Girdhar, A. El-Nouby, Z. Liu, M. Singh, K. V. Alwala, A. Joulin, and I. Misra, “ImageBind: One embedding space to bind them all,” in Proc. IEEE/CVF Conf. Comput. Vis. Pattern Recognit. (CVPR), Jun. 2023, pp. 15180–15190, doi: 10.1109/CVPR52729.2023.01457.

[9] V. Fra, E. Forno, R. Pignari, T. C. Stewart, E. Macii, and G. Urgese, “Human activity recognition: Suitability of a neuromorphic approach for on-edge AIoT applications,” Neuromorph. Comput. Eng., vol. 2, no. 1, p. 014006, Jan. 2022, doi: 10.1088/2634-4386/ac4c38.

Accepted Manuscript

[10] H. Shi, H. Zhao, and W. Yao, “A transfer fusion framework for body sensor networks (BSNs): Dynamic domain adaptation from distribution evaluation to domain evaluation,” Inf. Fusion, vol. 91, pp. 338–351, Mar. 2023, doi: 10.1016/j.inffus.2022.10.026.
[11] P. Qi, D. Chiaro, and F. Piccialli, “FL-FD: Federated learning-based fall detection with multimodal data fusion,” Inf. Fusion, vol. 99, p. 101890, Nov. 2023, doi: 10.1016/j.inffus.2023.101890.
[12] A. Saeed, F. D. Salim, T. Ozcelebi, and J. Lukkien, “Federated self-supervised learning of multisensor representations for embedded intelligence,” IEEE Internet Things J., vol. 8, no. 2, pp. 1030–1040, Jan. 2021, doi: 10.1109/JIOT.2020.3009358.
[13] E. Ceolini, C. Frenkel, S. B. Shrestha, G. Taverni, L. Khacef, M. Payvand, and E. Donati, “Hand-gesture recognition based on EMG and event-based camera sensor fusion: A benchmark in neuromorphic computing,” Front. Neurosci., vol. 14, Aug. 2020, doi: 10.3389/fnins.2020.00637.
[14] L. Liu, W. Xu, Y. Ni, Z. Xu, B. Cui, J. Liu, H. Wei, and W. Xu, “Stretchable neuromorphic transistor that combines multisensing and information processing for epidermal gesture recognition,” ACS Nano, vol. 16, no. 2, pp. 2282–2291, Feb. 2022, doi: 10.1021/acsnano.1c08482.
[15] H. Park and S. Kim, “Overviewing AI-dedicated hardware for on-device AI in smartphones,” in Artificial Intelligence and Hardware Accelerators, Cham, Switzerland: Springer, Jan. 2023, pp. 127–150, doi: 10.1007/978-3-031-22170-5_4.
[16] M. R. Azghadi, C. Lammie, J. K. Eshraghian, M. Payvand, E. Donati, and B. Linares-Barranco, “Hardware implementation of deep network accelerators toward healthcare and biomedical applications,” IEEE Trans. Biomed. Circuits Syst., vol. 14, no. 6, pp. 1138–1159, Dec. 2020, doi: 10.1109/TBCAS.2020.3036081.
[17] C. D. Schuman, S. R. Kulkarni, M. Parsa, J. P. Mitchell, P. Date, and B. Kay, “Opportunities for neuromorphic computing algorithms and applications,” Nat. Comput. Sci., vol. 2, no. 1, pp. 10–19, Jan. 2022, doi: 10.1038/s43588-021-00184-y.
[18] P. Yadav, A. Mishra, and S. Kim, “Neuromorphic hardware accelerators,” in Artificial Intelligence and Hardware Accelerators, Cham, Switzerland: Springer, Mar. 2023, pp. 225–268, doi: 10.1007/978-3-031-22170-5_8.
[19] L. Chato and E. Regentova, “Survey of transfer learning approaches in the machine learning of digital health sensing data,” J. Pers. Med., vol. 13, no. 12, p. 1703, Dec. 2023, doi: 10.3390/jpm13121703.

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7.4 - Cardiovascular Health Tracking through Edge-AI for Bio-signal Processing

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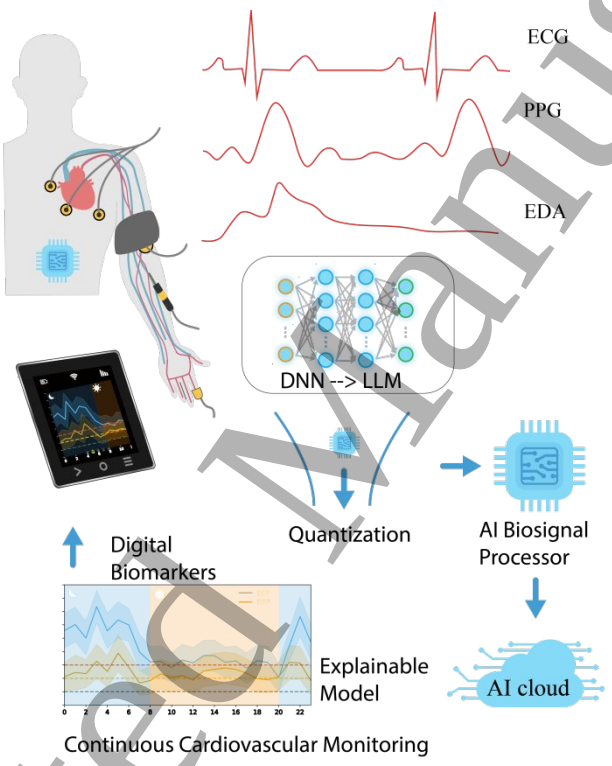
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Status



re **Figure 30.** Embedding cardiovascular health tracking in real-life settings will need large advancements in tinyML, and multimodal biosensors within wearables with underlying time series algorithms running hybrid onboard and, cloud computing to satisfy the needs of real time assessment, explainable decision support and powerful predictive models.

Non-communicable diseases (NCDs) represent the leading health challenge of the 21st century, responsible for approximately two-thirds of all global deaths reported. Cardiovascular diseases (CVDs) contribute to 50% of NCD-related fatalities and pose a significant obstacle to achieving sustainable health progress[1,2]. The United Nations set a target within Sustainable Development Goal 3 to lower premature mortality from NCDs, focusing on 30% lower CVDs by 2030 [3]. Achieving it requires preventive interventions that are affordable, non-invasive and suitable for continuous monitoring, such as digital health and wearable technologies[4].

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The integration of AI and digital signal processing (DSP) in cardiovascular health monitoring has progressed from simple, rule-based systems [5] to advanced deep learning models capable of complex data interpretation [6], real-time monitoring, and personalised healthcare solutions [7]. These devices used simple DSP techniques to monitor heart rate and rhythms. As computing power increased, machine learning algorithms (e.g., decision trees, support vector machines) were used on electrocardiogram (ECG) data to improve the detection of heart conditions such as atrial fibrillation and ventricular fibrillation [10]. Integrating AI into wearable devices expanded the scope of remote patient monitoring [8], especially when combined with multiple data streams—ECG, photoplethysmogram (PPG), and seismocardiogram (SCG) to estimate blood pressure and blood oxygenation. Combining multiple vital signs and imaging data provides a holistic view of cardiovascular health. AI-driven predictive models now forecast potential heart failure, myocardial infarctions, and stroke risks, enabling preventive care[9].

While state-of-the-art algorithms using recent advances in deep learning and machine learning algorithms have shown high performance in the prediction of vitals, and the prediction of severe disease onset and anomalous events, the on-device implementation of these algorithms for point-of-care use has not been widespread. **Figure 30** illustrates a representative end-to-end architecture for continuous cardiovascular monitoring, integrating multimodal biosignal acquisition, AI-based inference, quantization for edge deployment, and hybrid edge–cloud processing to generate interpretable digital cardiovascular biomarkers.

Current and Future Challenges

Using digital health tools such as textile-integrated and wearable vital sign monitoring systems at the point of care enables the delivery of pervasive and equitable healthcare, ensuring consistent, high-quality care for both in-hospital patients and outpatients alike [11].

Implementing AI on edge devices for vital sign monitoring presents several technical, operational, and regulatory challenges. Note that in this roadmap, *edge AI* refers specifically to on-device or textile-proximal inference performed under strict power, memory, and computational constraints. This is distinct from gateway-level processing, typically executed on smartphones or dedicated hubs, and from cloud-based analytics, which enable large-scale model training and longitudinal population-level analysis. These challenges stem from the limited resources of edge devices, the complexity of AI models, and the critical nature of healthcare data. The main roadblock in this path is the trade-off between required memory and computational efficiency in a resource-constrained application of battery-powered wearable systems. AI models, especially deep learning algorithms, are computationally expensive. Tiny Machine Learning (TinyML) has recently made it possible for low-power embedded devices to perform real-time Machine Learning (ML) directly on the device. Despite the recognised advantages of TinyML, putting it into practice involves overcoming several distinct challenges such as battery life, latency during real-time processing and model accuracy after algorithm quantisation. High-latency processing due to complex algorithms or insufficient computational resources can delay critical health insights or warnings. Constant data processing can drain the battery of edge devices, limiting operation. Recent demonstrations of Edge-AI for cardiovascular monitoring show that algorithmic complexity, model size, and MCU capability must be co-designed to enable real-time, low-power wearable systems. On-device workloads typically range from lightweight arrhythmia detection and ECG segmentation using compact 1D-CNNs (<100 kB) running on Cortex-M4–class microcontrollers (Tier A: ultra-low-power MCUs, e.g., STM32L4,

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nRF52840), validated in embedded AF classification studies [12], [13]. More demanding pipelines, such as pulse-transit-time (PTT) extraction and cuffless blood pressure (BP) estimation, require mid-range MCUs (Tier B: mid-capacity MCUs with >0.5 MB RAM, e.g., STM32F7/U5, Ambiq Apollo4 Plus) with ~0.1- 0.5 MB model capacity. For example, it was demonstrated that real-time PTT and BP inference at 500 Hz on an STM32F7 had a <10 % performance loss compared to cloud inference, confirming feasibility on wearable-class edge hardware [14]. ML-optimized BLE system-on-chips (Tier C: edge-ML capable MCUs with ~1 MB RAM + 2 MB NVM, e.g., Nordic nRF54H20) support ~0.5- 2 MB models suitable for multimodal fusion (ECG+PPG+IMU) in patches or watches, with commercial modules now marketed specifically for edge inference in wearables [15]. For more advanced workloads—such as multimodal ECG/PPG/SCG fusion or early heart-failure trending—low-tens-of-milliwatt RISC-V clustered processors (Tier D: edge MPUs with NN/DSP acceleration, e.g., GreenWaves GAP9) can host 0.5- 4 MB CNN/Transformer models; notably, a recent single-ear ECG wearable executed its full R-peak/HR/HRV pipeline on-device using GAP9 [16]. Reducing energy consumption while maintaining the accuracy and efficiency of AI algorithms is a challenge that demands advanced optimization techniques like model quantization, pruning, or lightweight neural networks. This process reduces the precision of the model's weights and activations from high-precision (such as 32-bit floating point) to lower-precision (such as 8-bit integers), making the model more efficient in terms of power consumption, memory, and computation [17]. While quantization improves power efficiency through hardware-accelerated operations, it reduces model accuracy by simplifying learnt representations. Rigorous quantisation of a model can result in extensive savings of power, memory, and computational cost. However, this is borne at the expense of the task accuracy of the model. Across tiers, key hardware requirements include ≥128 kB to 1 MB SRAM, DSP/SIMD or NN acceleration, and ~1–50 mW power envelopes, with practical model deployment achieved through quantization and pruning. These deployments collectively demonstrate that edge MCUs support meaningful cardiovascular inference along a scalable application gradient, that is, Tier A devices enabling HR/HRV and rhythm screening; Tier B enabling PTT/BP inference; Tier C enabling multimodal fusion in BLE wearables; and Tier D supporting advanced CNN/Transformer models—fulfilling the hardware–algorithm matching needed for real-world wearable scenarios.

For vital sign monitoring, the accuracy of AI models is critical because even small errors can lead to incorrect diagnoses or missed health events. Therefore, it's essential to strike a balance between quantization levels and the specific needs of the application. To circumvent this issue, many edge devices rely on intermittent or low-bandwidth network connections, which can complicate data transmission and coordination with cloud systems. However, seamless integration between edge AI models and cloud-based systems is essential to offload heavy computations or synchronize long-term monitoring data. Maintaining this balance while optimizing for latency and bandwidth constraints is still a challenge.

Trustworthy AI is another significant challenge to be addressed as on-edge AI signal processing implies in many cases losing the raw signal, explainable ML is imperative to translate algorithms from bench to bedside. AI and data-driven systems must be proved through exhaustive medical validation in clinical trials and robustness shall be verified on each system through methods such as certified training for proving boundaries and uncertainty quantifications [18] or ad-hoc model explanations that deliver new knowledge from models [19] e.g., causal graphical models, adversarial testing, domain adaptation testing and model explainability methods.

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Advances in Science and Technology to Meet Challenges

Recent AI algorithm advancements, such as quantization, pruning, and federated learning, along with lightweight neural networks, have made AI more practical for edge devices in healthcare, particularly in vital sign monitoring [20][21]. Future efforts should address more efficient versions of transformer models that can run on edge devices. For example, TinyBERT and MobileBERT are smaller, more efficient models that could be adapted to healthcare scenarios where real-time natural language processing (NLP) and medical data analysis are needed on wearable or portable devices [22].

At the same time, breakthroughs in hardware technology, including hardware accelerators, low-power processors, and the potential adaptation of large language models for edge use, are enabling more sophisticated and power-efficient AI-driven healthcare solutions. Dedicated hardware accelerators are designed to speed up AI computations on edge devices by optimizing specific operations like matrix multiplications, which are common in neural networks. These accelerators help in executing complex AI models for real-time healthcare tasks while consuming less power. This includes the ARM Cortex-M Processors with NEON Technology, Google Edge TPU and NVIDIA Jetson Nano[23] to name a few. GAP9 Integrated Circuit (IC) by GreenWaves Technologies [24] is a game-changing processor for edge AI, particularly for healthcare applications. It is designed to deliver 10x better energy efficiency compared to its predecessor (GAP8). This allows for continuous, battery-efficient monitoring of health signals like ECG, pulse oximetry, and blood pressure on edge devices without needing frequent recharging. GAP9 features multi-core parallel processing that allows for efficient handling of multiple tasks simultaneously, such as monitoring multiple vital signs (e.g., heart rate, oxygen levels) while maintaining high performance and low power use. These innovations are paving the way for real-time, continuous monitoring that can help detect early signs of health issues, enabling timely interventions and improving patient outcomes. Alternatively, edge devices might handle pre-processing tasks and run lightweight AI models, while more computationally demanding tasks, such as processing large language models, could be offloaded to the cloud when necessary [25]. This hybrid model ensures efficiency without sacrificing accuracy in healthcare monitoring.

Concluding Remarks

Vital signs monitoring using edge devices holds transformative potential for patient monitoring and management, especially from a public health perspective. These devices, including smartwatches, embedded clothing or wearable patches provide continuous, real-time data on key physiological information such as heart rate, respiratory rate, blood oxygen levels, and physical activity leading to the early detection of conditions like arrhythmias, hypertension, hypoxemia, or myocardial infarction, thus enabling to reduce the risk of severe health outcomes.

However, several technical, operational, and regulatory breakthroughs still pose challenges, particularly related to the computational limits of edge devices. Innovations like TinyML, quantization, hardware accelerators, and more efficient AI models (e.g., TinyBERT) are crucial for optimizing power consumption, real-time processing, and accuracy in resource-constrained environments.

Further research in explainable and certifiable models is required to embed this knowledge in medical grade systems.

Achieving such a level of cardiovascular tracking would enable subsequent aggregated data from wearables to identify at-risk populations and monitor trends not only on heart health but stress, and

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social participation, aiding in early intervention and targeted public health strategies. These computational constraints directly inform the regulatory and lifecycle considerations discussed in Section 12.

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References

[1] R. Jagannathan, S. A. Patel, M. K. Ali, and K. V. Narayan, "Global updates on cardiovascular disease mortality trends and attribution of traditional risk factors," *Curr. Diab. Rep.*, vol. 19, pp. 1–12, 2019.

[2] C. W. Tsao *et al*., "Heart disease and stroke statistics—2022 update: A report from the American Heart Association," *Circulation*, vol. 145, no. 8, pp. e153–e639, 2022.

[3] B. X. Lee *et al*., "Transforming our world: Implementing the 2030 agenda through sustainable development goal indicators," *J. Public Health Policy*, vol. 37, pp. 13–31, 2016.

[4] R. J. Widmer, N. M. Collins, C. S. Collins, C. P. West, L. O. Lerman, and A. Lerman, "Digital health interventions for the prevention of cardiovascular disease: A systematic review and meta-analysis," *Mayo Clin. Proc.*, vol. 90, pp. 469–480, 2015.

[5] K. C. Siontis, P. A. Noseworthy, Z. I. Attia, and P. A. Friedman, "Artificial intelligence–enhanced electrocardiography in cardiovascular disease management," *Nat. Rev. Cardiol.*, vol. 18, pp. 465–478, 2021, doi: 10.1038/s41569-020-00503-2.

[6] A. Y. Hannun *et al*., "Cardiologist-level arrhythmia detection and classification in ambulatory electrocardiograms using a deep neural network," *Nat. Med.*, vol. 25, no. 1, pp. 65–69, 2019.

[7] S. P. Shashikumar *et al*., "Early sepsis detection in critical care patients using multiscale blood pressure and heart rate dynamics," *J. Electrocardiol.*, vol. 50, no. 6, pp. 739–743, Nov.–Dec. 2017, doi: 10.1016/j.jelectrocard.2017.08.013.

[8] A. Pantelopoulos and N. G. Bourbakis, "A survey on wearable sensor-based systems for health monitoring and prognosis," *IEEE Trans. Syst., Man, Cybern. C*, vol. 40, no. 1, pp. 1–12, Jan. 2010.

[9] G. Prieto-Avalos *et al*., "Wearable devices for physical monitoring of heart: A review," *Biosensors*, vol. 12, no. 5, p. 292, 2022, doi: 10.3390/bios12050292.

[10] S. Shajari, K. Kuruvinashetti, A. Komeili, and U. Sundararaj, "The emergence of AI-based wearable sensors for digital health technology: A review," *Sensors*, vol. 23, no. 23, p. 9498, 2023, doi: 10.3390/s23239498.

[11] T. Tan and G. Cao, "Efficient execution of deep neural networks on mobile devices with NPU," in *Proc. ACM/IEEE Conf.*, pp. 283–298, 2021, doi: 10.1145/3412382.3458272.

[12] M. Żyliński *et al*., "Design and implementation of an atrial fibrillation detection algorithm on the ARM Cortex-M4 microcontroller," *Sensors*, vol. 23, no. 17, 2023, doi: 10.3390/s23177521.

[13] Z. Jia *et al*., "TinyML design contest for life-threatening ventricular arrhythmia detection," *IEEE Trans. Comput.-Aided Des. Integr. Circuits Syst.*, vol. 43, no. 1, pp. 127–140, Jan. 2024, doi: 10.1109/TCAD.2023.3309744.

[14] S.-H. Liu, B.-Y. Wu, X. Zhu, and C.-L. Chin, "Using a bodily weight-fat scale for cuffless blood pressure measurement based on the edge computing system," *Sensors*, vol. 24, p. 7830, 2024, doi: 10.3390/s24237830.

Accepted Manuscript

[15] Nordic Semiconductor, "nRF54H20: Multi-core wireless SoC with edge ML support," Product Brief, 2024.
[16] GreenWaves Technologies, "BioGAP: Single-ear wearable ECG patch using GAP9 for on-device R-peak, HR, and HRV computation," White Paper, 2023.
[17] B. Jacob *et al*., "Quantization and training of neural networks for efficient integer-arithmetic-only inference," in *Proc. IEEE/CVF Conf. Comput. Vis. Pattern Recognit. (CVPR)*, 2018, pp. 2704–2713, doi: 10.1109/CVPR.2018.00286.
[18] Y. Mao, M. N. Müller, M. Fischer, and M. Vechev, "Understanding certified training with interval bound propagation," in *Proc. Int. Conf. Learn. Representations (ICLR)*, 2024. [Online]. Available: http://arxiv.org/abs/2306.10426
[19] A. Cisnal *et al*., "Robust feature selection for continuous blood pressure estimation in multiple populations: Towards cuffless ambulatory BP monitoring," *IEEE J. Biomed. Health Inform.*, 2024, doi: 10.1109/JBHI.2024.3411693.
[20] K. Dheman, M. Giordano, C. Thomas, P. Schilk, and M. Magno, "i-CardiAx: Wearable IoT-driven system for early sepsis detection through long-term vital sign monitoring," in *Proc. IEEE/ACM Int. Conf. Internet-of-Things Design Implement. (IoTDI)*, Hong Kong, 2024, pp. 97–109, doi: 10.1109/IoTDI61053.2024.00013.
[21] M. Giordano, K. Dheman, and M. Magno, "SepAI: Sepsis alerts on low-power wearables with digital biomarkers and on-device tiny machine learning," *IEEE Sens. J.*, 2024, doi: 10.1109/JSEN.2024.3424655.
[22] X. Jiao *et al*., "TinyBERT: Distilling BERT for low-latency inference," in *Proc. 58th Annu. Meet. Assoc. Comput. Linguistics (ACL)*, 2021.
[23] A. Mishra and K. Devlekar, "Developing AI-powered digital health applications using NVIDIA Jetson," NVIDIA Developer Blog, 2021. [Online]. Available: https://developer.nvidia.com/blog/developing-ai-powered-digital-health-applications-using-jetson/
[24] M. Zanghieri *et al*., "sEMG-driven hand dynamics estimation with incremental online learning on a parallel ultra-low-power microcontroller," *IEEE Trans. Biomed. Circuits Syst.*, vol. 18, no. 4, pp. 810–820, 2024, doi: 10.1109/TBCAS.2024.3415392.
[25] S. U. Amin and M. S. Hossain, "Edge intelligence and Internet of Things in healthcare: A survey," *IEEE Access*, vol. 9, pp. 45–59, 2021, doi: 10.1109/ACCESS.2020.3045115.

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Section 8: Connectivity and Data Management

8.1 - Connectivity Technologies for Smart Textiles and Wearables

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Status

Connectivity is the backbone of wearable and textile technologies, enabling real-time data transfer and interaction between devices. Originally, wearables, such as pedometers, were standalone devices with basic offline operations. However, they have evolved into advanced textile systems, known as smart textiles, that can monitor physiological parameters such as heart rate, body temperature, and movement through sensors integrated directly into the fabric and share these data in real time with devices for analysis using wireless communication technologies such as Bluetooth Low Energy (BLE). Examples of smart textiles are electrocardiogram-monitoring shirts [1].

These new technologies exemplify the shift toward seamless connectivity along with low power consumption and extended operational life. Particularly, technologies such as near field communication (NFC) and infrared (IR) are finding niche applications, such as secure authentication and gesture control in smart textiles [2].

These innovations demonstrate the field's progression toward enhancing functionality and user comfort in areas such as healthcare, sports, and safety. As wearables and textiles continue to evolve, the diverse connectivity technologies powering them must be evaluated for their strengths and trade-offs (see Table 2) to determine their suitability and utility for specific applications.

Table 2. Properties of various connectivity technologies in wearable and textile innovations. *Bold rows highlight the key comparative factors used to evaluate each technology, which are plotted in* ***Figure 31.*** *to visualize their performance differences.*

	Infrared (IR) [3]	Bluetooth Low Energy (BLE) [3]	Zigbee [4]	Near Field Communication (NFC) [5]
Wireless access scheme	One-to-one	One-to-one locally	Mesh networking	One-to-one (close proximity)
Access point	Lightweight custom remote-control module	Almost all modern smartphones	Dedicated Zigbee coordinator	Any NFC-enabled smartphone or reader
Ease of setup	**Low; align, calibrate, and set up signal**	**High; pair with Bluetooth devices**	**Moderate; set up and link devices for mesh**	**Moderately high; configure with writer**

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			network	
Range	**Up to 1 m for precise data transmission (low)**	**Up to 100 m (moderately high)**	**Up to 60 m with a single device, much greater with mesh networking (high)**	**Up to 0.2 m (very low)**
Frequency	300 GHz–400 THz (optical)	2.4 GHz	2.4 GHz / 868MHz / 915 MHz	13.56 MHz
Reliability	**None; easily disrupted by obstructions**	**Moderate; confirmation with log tracking**	**Moderately high; supports fault tolerance in mesh**	**High; proximity ensures minimal interference**
Access capability	Any IR device in the range and the line of sight	Any Bluetooth device in the range	Any Zigbee-enabled device in the network	NFC-enabled devices (e.g., smartphones)
Affordability (as of 28 January 2025)	**Moderate (<$50)**	**High (<$10 per module)**	**Low ($100–$200)**	**Very high (<$20 for multiple tags)**
User interface	Simple tactile switches	Universal system with smartphones	Smartphone or specialized devices	Smartphone interaction
Ease of use	**Ensure line of sight and flip switches or click buttons to share data (low)**	**Pair with devices once and it works in the background (high)**	**Link once to the Zigbee network and it works in the background (moderately high)**	**Simply tap on a sensor whenever data needs to be shared (moderate)**
Energy efficiency	**Moderate**	**Moderate–High**	**Moderate–Low (role-dependent)**	**Very High**
Peak current draw	20–50mA (Pulse)	5–15 mA	20–40 mA	0 mA (Passive)

In smart textiles, the range between the sensor and its receiving device, provided by the relevant technology, is paramount for user convenience. BLE can achieve a range of up to 100m in ideal conditions [3], making it suitable for wearables that require moderate to extensive coverage, such as health-monitoring garments or fitness devices. In comparison, a single Zigbee device, such as the XBee S2C module, has a range of up to 60 m under optimal conditions [4]. However, Zigbee's mesh networking capabilities allow for an extended effective range by connecting multiple devices in a home network, thereby enhancing fault tolerance and ensuring reliable communication in interconnected textile systems. In contrast, IR communication is limited to short-range, line-of-sight operation (~1 m) for precise continuous data communication, which diminishes its practicality for dynamic or flexible textile applications [3]. However, it's extremely low energy consumption makes it viable for event-based signalling, such as transmitting an SOS alert or emergency notification, in

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which only a brief, one-time data transmission is required instead of a continuous stream. Similarly, NFC is constrained by its extremely short range (~0.2 m), positioning it primarily for close-proximity applications, such as instantaneous authentication or single-instance data transfer in smart uniforms or accessories.

Another critical issue in the development of wearable textile sensors for healthcare is power consumption, as battery depletion in critical applications could disrupt continuous monitoring when a patient's life is at risk. Therefore, low-power, energy-efficient technologies are becoming increasingly important in the design of untethered wearable textiles that support mobility. NFC tags can operate in battery-free (passive) mode by harvesting energy from incoming RF emissions, enabling wireless communication without the need for charging or continuous battery replacement [6]. However, passive NFC tags will always transmit the same stored information unless it is rewritten by a powered device thus mostly making it useful for identification purposes. IR communication requires a very low current (<1mA) however during communication time the current drawn jumps up to 50mA, but its shortcoming is mostly due to a direct line of sight needed between the transmitter and receiver. Meanwhile, Zigbee provides highly reliable communication through its mesh network but consumes more power on its end devices to be operational [4]. Additionally, leaving the vicinity of the fixed mesh network will stop transmission unlike BLE which may be connected to a mobile gateway such as a phone. BLE also offers a more energy-efficient solution compared to standard Bluetooth by operating intermittently, only turning on when data needs to be transmitted. While it has lower data transfer rates than standard Bluetooth, it provides a much lower power consumption, which makes it ideal for wearable devices that need to conserve battery life while remaining compatible with smartphones and other consumer devices.

When it comes to ease of use and setup, NFC and BLE stand out for their simplicity, as they both integrate easily with existing consumer devices such as smartphones, eliminating the need for specialized hardware. In addition, NFC requires minimal setup, as its tags only need to be configured for a specific purpose. With a simple tap, users can reliably initiate communication, as the close proximity minimizes the risk of transmission errors. BLE is also user-friendly, offering moderate to extensive coverage from the device to the smartphone without requiring a significant infrastructure investment. Zigbee, while highly capable, demands a more complex setup, particularly for mesh networking, which requires dedicated coordinators and additional configurations. IR is the least user-friendly technology, as it requires precise alignment for effective communication due to its short range and line-of-sight dependency, making it unsuitable for dynamic wearable applications.

The radar chart in **Figure 31** underscores how connectivity technologies align with different wearable applications, emphasizing the trade-offs between range, power, and usability. It highlights Bluetooth as the most well-rounded option for wearable applications, offering a strong balance of range, energy efficiency, and usability. While the other technologies excel in specific areas, Bluetooth's versatility and ease of integration position it as a widely used choice for most wearable textile innovations. However, these distinctions highlight the importance of tailoring technology selection to specific use cases depending on energy usage, range, and application.

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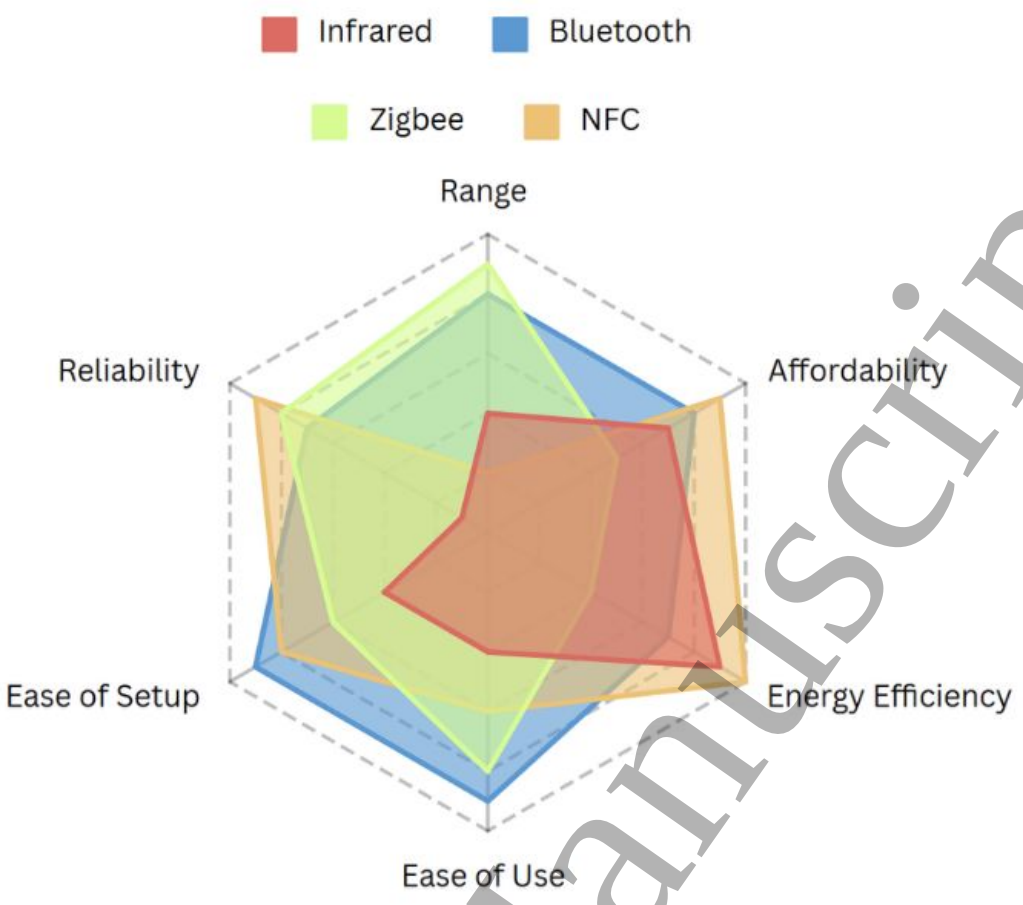


Figure 31. Comparison of wireless technologies for wearable textile innovations based on connectivity range, affordability (setup cost), energy consumption, ease of setup, ease of use, and connection reliability. Bluetooth offers the most balanced profile, while each technology excels in specific areas. Zigbee provides extended range with proper mesh networking, and NFC is the most cost effective and energy-efficient option.

Current and Future Challenges

Interference and security vulnerabilities pose significant challenges to the reliability and safety of wireless communication in wearable technologies, affecting both data integrity and user experience. IR communication, despite its advantages, relies on direct line-of-sight operation, making it unsuitable for dynamic environments where obstructions can easily disrupt connectivity. This constraint limits its practicality in wearable applications that require flexible movement. Additionally, IR communication is vulnerable to eavesdropping, with experiments demonstrating that sensitive data, such as user credentials, can be intercepted even from long distances or behind obstacles [7].

Furthermore, BLE and Zigbee both operate within the 2.4 GHz Industrial, Scientific, and Medical (ISM) frequency band, making them vulnerable to interference from Wi-Fi networks and from each other. This cross-technology interference can degrade network performance, leading to increased packet loss and latency. While BLE employs Adaptive Frequency Hopping (AFH) to mitigate interference by dynamically avoiding congested channels, its standard implementation is not always effective in highly dynamic or dense electromagnetic environments due to its limited channel monitoring and selection mechanisms [8].

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Additionally, Zigbee's reliance on a dedicated coordinator for network management adds to its setup complexity and maintenance overhead, making it less user-friendly than plug-and-play solutions such as Bluetooth [4]. Another significant issue with Zigbee concerns its power consumption. While it is designed for low-energy operation, maintaining an active mesh network with multiple nodes requires continuous communication, leading to higher energy drain than initially anticipated. These factors limit Zigbee's effectiveness in wearable technologies, particularly for applications requiring mobility and real-time data transmission. Addressing these challenges will be crucial to improving Zigbee's integration into smart textiles and health monitoring wearables.

Enhancing the end-to-end user experience remains a significant challenge, as consumers are unlikely to follow a monitoring regime if it poses a significant hindrance in their daily lives. For example, NFC's extremely short range of only a few centimeters makes it impractical for continuous monitoring or applications requiring real-time data transmission [5]. While it is secure and energy-efficient, its range limitations restrict its potential applications in wearables that require seamless connectivity. Moreover, bulky sensor–transmitter units in wearables, particularly in health-monitoring applications, reduce user comfort and mobility, especially during prolonged use. The integration of electronics into textiles often results in rigid components that hinder flexibility, making such textiles less suitable for everyday wear. Comfort and wearability remain persistent challenges, as current designs struggle to balance lightweight, low-power solutions with reliable connectivity. The need for miniaturized components that seamlessly integrate into textiles without compromising functionality is a crucial factor in the development of next-generation wearable technologies.

Advances in Science and Technology to Meet Challenges

To address the ongoing challenges in the advancement of wearable textile technologies, scientific and technological innovations are being directed toward improving such technologies' connectivity, security, ease of use, and integration within dynamic environments. Specifically, for improved usability of IR communication in dynamic environments, the integration of optical fibers into textiles is being explored to provide a structured pathway for IR signals at various points throughout the textile, eliminating the need for specific alignment between the transmitter and the receiver. This approach enhances connectivity and reliability in wearable applications, although it might introduce further complexities, such as in textile fabrication and maintenance. Additionally, the vulnerability of IR communication to eavesdropping due to the possible interception of unregulated transmissions from long distances has been addressed by developing encryption techniques and disposable session keys generated through microcontroller timers, ensuring secure data transmission with minimal processing overhead [7]. These advancements make IR a more viable option for wearable textiles, with diverse applications.

While BLE employs AFH to dynamically avoid congested channels in order to mitigate Bluetooth's susceptibility to interference from other wireless protocols operating within the 2.4 GHz ISM band, further advancements in interference management are being developed to enhance BLE's reliability. Improved channel selection algorithms and interference awareness schemes enable BLE to continuously monitor channel conditions and make probabilistic decisions for better channel allocation. Experimental evaluations have demonstrated that these enhancements can reduce

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packet loss to less than 3% in high-density environments, significantly improving BLE's performance in wearable applications [8].

As Zigbee technology evolves and becomes more widely used, its setup process is being simplified to make it more user friendly and accessible for wearable applications. Improved configuration tools and automation in network management are reducing its deployment complexity, allowing for its easier integration into smart textiles. Zigbee's mesh networking capability remains a key advantage, enabling fault-tolerant data delivery across multiple interconnected devices [4]. This makes it particularly useful for health-monitoring applications, where multiple sensors within a garment need to communicate reliably without requiring direct connection to a central hub. This design is perfect for developing a home ecosystem for at-risk consumers who would require immediate aid.

Expanding NFC's potential in wearables requires design innovations that improve user convenience and seamless interaction. One such innovation involves integrating NFCs into dedicated pockets within garments to securely house the user's phone, allowing effortless NFC communication with embedded textile sensors [9]. This approach ensures that the devices remain aligned and within range, making NFC more practical to use. Instead of requiring power from the textile itself, the system can leverage the phone's capabilities for communication by continuously reading the variable NFC coil. Additionally, continuous advancements in miniaturization are enhancing the wearability of smart textiles. The ongoing reduction in transistor size has enabled the development of ultracompact, energy-efficient microcontrollers and sensors that integrate seamlessly into fabrics [10]. Innovations in flexible electronics, including stretchable conductive materials and ultrathin circuits, further improve the comfort and practicality of wearable devices. These developments will ensure that next-generation wearables will remain lightweight and nonintrusive while highly functional.

Concluding Remarks

Connectivity technologies are playing a pivotal role in shaping the future of wearable textiles, with each technology offering distinct advantages and challenges. While Bluetooth remains the most practical option for widespread use due to its compatibility, affordability, and energy efficiency, technologies such as NFC and Zigbee hold promise for specialized applications. Overcoming the limitations of each connectivity technology—whether through advancements in miniaturization, hybrid systems, or infrastructure development—will be critical in achieving seamless, reliable, and cost-effective wearable systems in the future. The integration of these technologies will not only enhance user experience but also pave the way for smarter and more versatile textile innovations.

References

[1] M. Ulbrich et al., "The IMPACT shirt: Textile integrated and portable impedance cardiography," Physiol. Meas., vol. 35, no. 6, p. 1181, May 2014, doi: 10.1088/0967-3334/35/6/1181.
[2] J. Wang, Z. Xie, G. Lu, J. A. Liu, and J. T. W. Yeow, "An infrared photothermoelectric detector enabled by MXene and PEDOT:PSS composite for noncontact fingertip tracking," Microsyst. Nanoeng., vol. 9, Art. no. 21, Feb. 2023, doi: 10.1038/s41378-022-00454-3.
[3] R. Qazi et al., "Scalable and modular wireless-network infrastructure for large-scale behavioural neuroscience," Nat. Biomed. Eng., vol. 6, no. 6, pp. 771–786, Jun. 2022, doi: 10.1038/s41551-021-00814-w.

Accepted Manuscript

[4] K. F. Haque, A. Abdelgawad, and K. Yelamarthi, “Comprehensive performance analysis of Zigbee communication: An experimental approach with XBee S2C module,” Sensors, vol. 22, no. 9, p. 3245, Apr. 2022, doi: 10.3390/s22093245.
[5] X. Sun et al., “Wearable near-field communication sensors for healthcare: Materials, fabrication and application,” Micromachines, vol. 13, no. 5, p. 784, May 2022, doi: 10.3390/mi13050784.
[6] J. Kim et al., “Battery-free, stretchable optoelectronic systems for wireless optical characterization of the skin,” Sci. Adv., vol. 2, no. 8, Art. no. e1600418, Aug. 2016, doi: 10.1126/sciadv.1600418.
[7] M. Kim and T. Suh, “Eavesdropping vulnerability and countermeasure in infrared communication for IoT devices,” Sensors, vol. 21, no. 24, p. 8207, Dec. 2021, doi: 10.3390/s21248207.
[8] B. Pang et al., “Bluetooth low energy interference awareness scheme and improved channel selection algorithm for connection robustness,” Sensors, vol. 21, no. 7, p. 2257, Mar. 2021, doi: 10.3390/s21072257.
[9] V. Galli et al., “Passive and wireless all-textile wearable sensor system,” Adv. Sci., vol. 10, no. 25, Art. no. 2206665, May 2023, doi: 10.1002/advs.202206665.
[10] M. Babu and R. S. Pallavi, “Advancements in wearable and smart textiles: An overview of technologies involved,” Int. J. Adv. Res. Comput. Commun. Eng., vol. 12, no. 4, pp. 1206–1211, Apr. 2023, doi: 10.17148/IJARCCE.2023.124206.

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8.2 - Advances in Wireless Connectivity for Body Area Networks

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Status

Wearable connectivity emerged as a platform for exchanging information on-body, as opposed to connecting to a remote receiver (e.g. a mobile base-station) [1]. From its early days and to this moment, many developments are focused on inter-connecting sensors, initially from the wearable devices to an off-body gateway [2], to a rise in multi-sensor/wearable networks focused on on-body communications. The data gathered from optimally-located on-body sensors, as opposed to very constrained devices such as wristbands, could be of high value in biomedical, sport science, and even telecommunications/security applications; this concept of "Body-Nets" [3] motivated a plethora of research activities into materials and devices, extending to metamaterials and networking [4], for reliably collecting the data and communicating it wirelessly, in a relatively harsh and very mobile environment (the human body).

Wearable networks are predominantly used for communication, with emerging applications in sensing and wireless power transfer [5]. This has directly influenced the research direction which closely followed the available frequency bands, for example aligning with the Industrial Scientific and Medical (ISM) bands, specifically those under the IEEE 802.11, overlapping with Wi-Fi/Bluetooth (Low Energy) applications. This can be seen in **Figure 32**, grouping the published works across IEEEXplore by frequency. Notably, there is a rising interest in mmWave (>24 GHz) demonstrations, despite their limited adoption in commercial wireless communication applications.

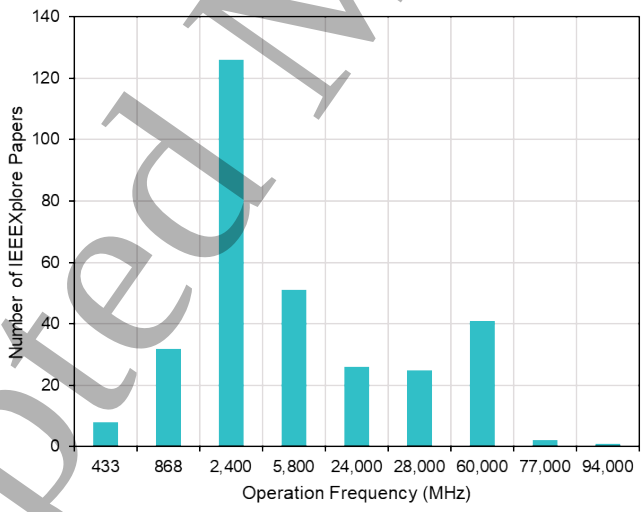


Figure 32. Number of wearable communications studies in the IEEEXplore library (filtered by Articles/Magazines), grouped by the frequency targeted by each study; a noticeable rise is around the ISM/IEEE 802.11 bands of 2.4, 5.8, and 60 GHz bands.

Current and Future Challenges

The challenges of wearable BANs can be broadly grouped under the electromagnetic challenges of RF/wireless communication around a lossy and electrically challenging environment, and around the material/mechanical considerations of such systems, as they move towards large-area electronics. While centred around formfactor and mechanical properties, i.e. soft, breathable, and deformable

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devices, these challenges extend to all aspects of electronic devices including connectivity, energy solutions, and sensing mechanisms. RF-enabled [5] tags which include direct RF sensing and power transfer as a result appeared as an attractive platform for connected body area networks [6].

Advances in Science and Technology to Meet Challenges

A key research advance which crosses beyond the traditional definition of wireless networks is wearables/clothing-assisted RF propagation. Owing the challenges faced by sending electromagnetic signals efficiently around the body, the desirable characteristic of clothing, that is its large surface, has been adopted by researchers to deliver wireless networks that overcome the losses illustrated in **Figure 33a.** The developments followed the frequency spectrum initially focusing on relatively low frequencies of near-field inductive coupling, i.e. Near-Field Communication (NFC) [6], to realise a body-worn network where power and data are exchanged with many nodes through an embroidered network of coils, seen in **Figure 33b.**

With the move to mmWave bands and potential high data rate wearable applications, broadband solutions were required. Single-wire transmission lines (SWTLs), in **Figure 33d** re-emerged as an alternative to frequency-specific metamaterials, usable up to 50 GHz and enabling 1+ GBPS signalling [8]. Most recently, wearables were exploited as a platform to enhance in-body communication, i.e. between different implants. As the human body is a highly lossy environment, propagating the 2.4 GHz Bluetooth signals from an implant to a wearable metamaterial enabled the signals to be routed with a relatively low loss around the human body, as illustrated in **Figure 33e** [9]. These networks all featured low-loss links which lend themselves to simultaneous wireless information and power transfer (SWIPT) [10], and integrated sensing using functional materials which can detect biomarkers, vital signs, or temperature, directly through the RF signals [11].

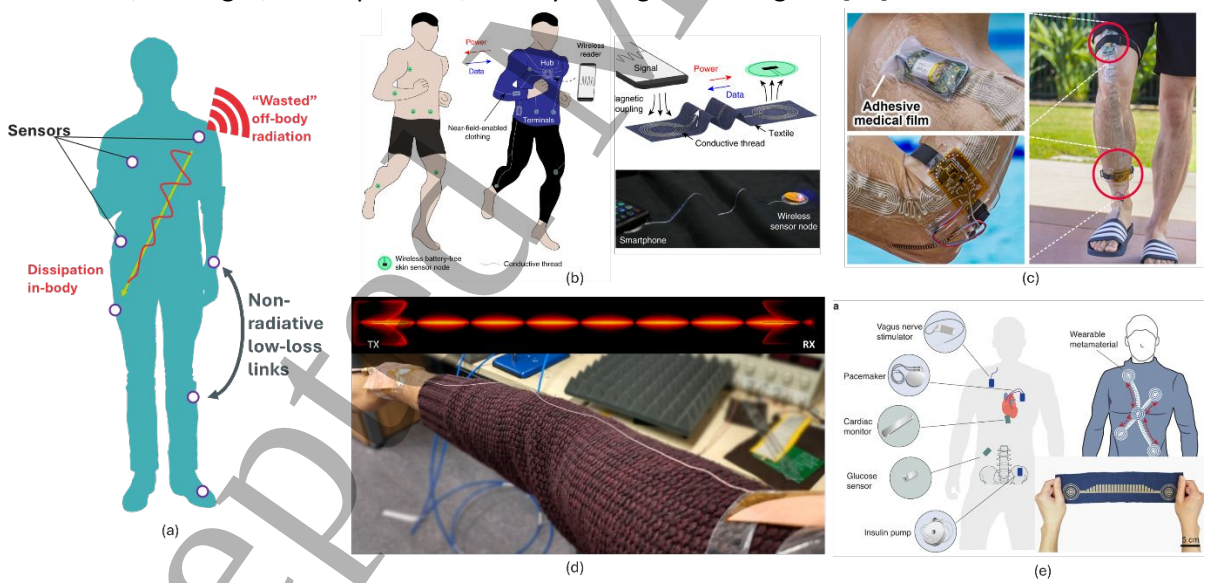


Figure 33. Non-radiative links for robust inter-wearable communication: **(a)** illustration of the challenges in traditional radiative on-body links; **(b)** an NFC-based 13.56 MHz waveguiding network using embroidered coils [11] (CC-BY); **(c)** an amphibious version of the NFC technology, exploiting its limited interaction with water [12] (CC-BY); **(d)** a mmWave 1-50 GHz on-body surface wave link for high data-rate applications [8] (CC-BY); **(e)** a 2.4 GHz BLE-based implant-to-implant communication link assisted by wearables [9] (CC-BY).

Concluding Remarks

Over the last 20+ years, BANs have evolved from retrofitted communication protocols which provide limited data streams to novel hardware solutions with integrated sensing. Moving forward, there is a

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need for design-for-sustainability and manufacturability [12], where wearable networks are guided by sustainability considerations and not just electronic performance. Through the co-design of materials, antennas, and communication circuits, multi-functional and heterogeneous devices and networks can realise their true potential, in next-generation wearables.

Acknowledgements

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References

[1] J. Yao, R. Schmitz, and S. Warren, "A wearable point-of-care system for home use that incorporates plug-and-play and wireless standards," *IEEE Trans. Inf. Technol. Biomed.*, vol. 9, no. 3, pp. 363–371, Sep. 2005, doi: 10.1109/TITB.2005.854507.

[2] P. S. Hall and Y. Hao, "Antennas and propagation for body centric communications," in *Proc. 1st Eur. Conf. Antennas Propag. (EuCAP)*, Nice, France, 2006, pp. 1–7, doi: 10.1109/EUCAP.2006.4584864.

[3] B. Chu, W. Burnett, J. Chung, *et al*., "Bring on the bodyNET," *Nature*, vol. 549, pp. 328–330, Sep. 2017, doi: 10.1038/549328a.

[4] Z. Li, X. Tian, C.-W. Qiu, *et al*., "Metasurfaces for bioelectronics and healthcare," *Nat. Electron.*, vol. 4, pp. 382–391, Jun. 2021, doi: 10.1038/s41928-021-00589-7.

[5] M. Wagih *et al*., "Microwave-enabled wearables: Underpinning technologies, integration platforms, and next-generation roadmap," *IEEE J. Microw.*, vol. 3, no. 1, pp. 193–226, Jan. 2023, doi: 10.1109/JMW.2022.3223254.

[6] S. Niu, N. Matsuhisa, L. Beker, *et al*., "A wireless body area sensor network based on stretchable passive tags," *Nat. Electron.*, vol. 2, pp. 361–368, Aug. 2019, doi: 10.1038/s41928-019-0286-2.

[7] R. Lin, H. J. Kim, S. Achavananthadith, *et al*., "Wireless battery-free body sensor networks using near-field-enabled clothing," *Nat. Commun.*, vol. 11, Art. no. 444, Jan. 2020, doi: 10.1038/s41467-020-14311-2.

[8] M. Wagih, "Broadband low-loss on-body UHF-to-millimeter-wave surface-wave links using flexible textile single-wire transmission lines," *IEEE Open J. Antennas Propag.*, vol. 3, pp. 101–111, 2022, doi: 10.1109/OJAP.2021.3136654.

[9] X. Tian, Q. Zeng, S. A. Kurt, *et al*., "Implant-to-implant wireless networking with metamaterial textiles," *Nat. Commun.*, vol. 14, Art. no. 4335, Jul. 2023, doi: 10.1038/s41467-023-39850-2.

[10] M. Wagih, G. S. Hilton, A. S. Weddell, and S. Beeby, "Dual-band dual-mode textile antenna/rectenna for simultaneous wireless information and power transfer (SWIPT)," *IEEE Trans. Antennas Propag.*, vol. 69, no. 10, pp. 6322–6332, Oct. 2021, doi: 10.1109/TAP.2021.3070230.

[11] M. Wagih, J. Shi, M. Li, *et al*., "Wide-range soft anisotropic thermistor with a direct wireless radio frequency interface," *Nat. Commun.*, vol. 15, Art. no. 452, Jan. 2024, doi: 10.1038/s41467-024-44735-z.

[12] H. H. Shi, Y. Pan, L. Xu, *et al*., "Sustainable electronic textiles towards scalable commercialization," *Nat. Mater.*, vol. 22, pp. 1294–1303, Oct. 2023, doi: 10.1038/s41563-023-01615-z.

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Section 9: Interdisciplinary Collaboration towards Next-Generation Wearable Sensing Technologies for Healthcare 6.0

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Status

We have witnessed in recent years the remarkable advances in wearable technologies including real-time data processing of physiological parameters, the detection of biomarkers with chemical sensors, cloud-based communication, and the rapid evolvement of wearable electronics towards biocompatible, multifunctional, and miniaturized sensors [1]. New findings in material science, nanotechnology, microelectronics, and data science are enabling wearable sensors to detect more biomarkers, e.g., nanoplasmonic sensors for high-sensitivity photoplethysmography monitoring [2, 3], nucleic acid-based electrochemical sensors for real-time biomarker analysis [4], flexible magnetic field nanosensors for body movement and nanoparticle-based detection of hormone and protein [5-7]. Towards next-generation wearable technologies in the framework of Healthcare 6.0 which highlights precise medicine and data-driven approaches, there is a very clear need for interdisciplinary approaches for the design, fabrication, and clinical application of high-performance wearable sensors and analytics (**Figure 34**). In this roadmap, Healthcare 6.0 is conceptualized as an evolution beyond Healthcare 4.0 and 5.0, emphasizing continuous, decentralized, and adaptive care ecosystems enabled by intelligent, body-integrated systems. Textile-integrated wearables play a foundational role by enabling persistent physiological sensing, contextual intelligence, and closed-loop personalization in everyday life.

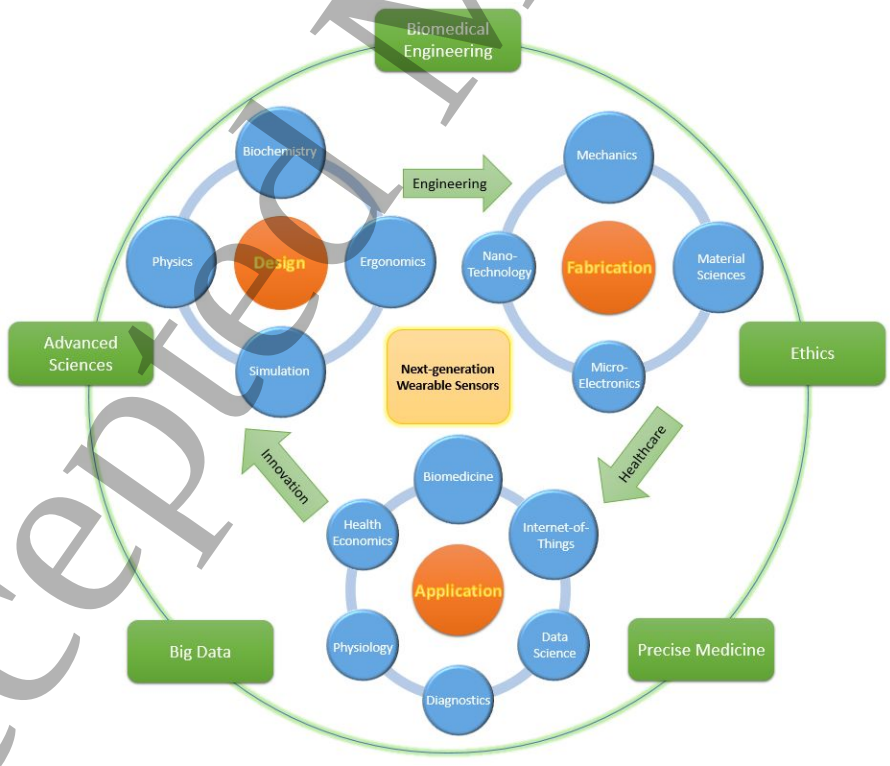


Figure 34. Multidisciplinary innovation lifecycle of wearable technology

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Current and Future Challenges

Clinical application of wearable sensors remains limited by technical obstacles (e.g., sensor reliability, signal quality, and integration with clinical workflows) as well as ethical and regulatory concerns (data privacy, reliability across different cohorts, evidence from clinical trials, policy updates, etc.), underscoring the importance of interdisciplinary collaboration. The fabrication of miniaturized wearable sensors involves expensive nanomaterials, complicated processes and advanced equipment, with unmet need for low-cost, easy-to-perform approaches towards mass production. Additionally, limitations in power sources such as batteries constrain the functionality and longevity of wearable devices. New biomedicine and clinical findings propose requirements for multifunctional wearable sensors that can detect micro to macromolecules and multimodal bio-signals, where the collaboration of clinicians, biochemists, and biomedical engineers can work to realise new and advanced solutions. Finally, the Internet-of-Medical-Things (IoMT) and the Internet-of-Bio-Nano-Things (IoBNT) -based healthcare monitoring have not yet been large-scale validated and integrated in the health services due to ethical concerns including privacy, cybersecurity, and data quality. Data protection is an urgent unmet challenge as IoMT and IoBNT devices are susceptible to cyber-attacks that could compromise both patient data and device functionality.

Advances in Science and Technology to Meet Challenges

Recent endeavours to address the research gaps are made up of multidisciplinary research and interdisciplinary collaborations in sensor design, fabrication, and clinical application (**Figure 34**).

1. Sensor Design

Computational simulation can efficiently transform the findings of advanced sciences (physics, biochemistry, material science etc.) into engineering solutions for wearable sensors with minimal workload and cost. In addition to electronic and biomechanical simulations, the simulation of molecular dynamics, quantum calculations, molecular docking, virtual screening, and hybrid methodologies can play key roles in optimizing the design of wearable sensors, especially biosensors [8]. Biocompatible and antimicrobial properties are underscored in the context of long-term monitoring and COVID-19 pandemics. Ergonomic comfort is an increasingly important consideration in the design of wearable sensor arrays and devices [9]. For example, Shao et al. recently developed a 126 channel accelerometer array to capture high resolution tactile signals during hand movements, where the shape of the flexible PCB was ergonomically designed with bowed regions that maximize flexibility, helping prevent cable contact interference during hand interactions, and allowing unconstrained movements [10].

2. Sensor Fabrication

The fabrication of wearable sensors requires complex microfabrication techniques and materials processing methods that ensures precision and functionality. These methods include thin-film deposition, soft lithography, surface modification, and nanostructuring. The addition of advanced materials such as porous materials, eutectogel, nanofibers, and liquid metals can achieve nanogenerator-based self-powered wearable sensors with high performance in harsh environment [11-14]. 3D printable self-adhesive materials may provide better skin-adhesion and biocompatibility [15]. Advanced microelectronics and microfabrication technologies, e.g., nanoimprint

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/nanosphere/nanotransfer photolithography, material coating, property modification, and micro-/nanopatterning, provide solutions for miniaturization and integration of wearable sensors, including multifunctional probes, microfabricated electrodes, intracellular chips [16], and multiplexed sensing platforms [17].

3. Clinical Application

As a core element of IoMT and IoBNT, wireless communication is indispensable for real-time signal processing and data analysis based on cloud computing [18]. The AI-enhanced wearable electromechanical sensing systems have been applied in tactile perception, gesture/gait recognition, and healthcare [19]. The fusion of wearable sensing data and electronic health records (EHRs) can generate a big data environment to enhance the effectiveness and patient-specificity of AI-assisted diagnostic models and clinical decision-making especially for widespread chronic diseases [20].

Innovations in data encryption and privacy technologies are crucial for safeguarding patient information and ensuring confidentiality in real-world application of wearable sensors. Advanced cybersecurity measures such as blockchain-based authentication and AI-driven threat detection systems can enhance protection against cyber-attacks [21]. Looking forward, quantum computing holds a promise for further advancing these solutions by offering unparalleled data processing capabilities, which can enhance encryption and threat detection.

Concluding Remarks

Based on interdisciplinary collaboration, the future application of multifunctional wearable sensor array will enable 7-day 24-hour multimodal monitoring and reshape the landscape of healthcare towards data-driven precise medicine [22]. Biomedical engineering practice plays a translational role in the innovative lifecycle of wearable sensing technology by bridging advanced sciences towards clinical application, which utilizes the latest findings in microelectronics, material science, nanotechnology and microfabrication to optimize the design and fabrication of wearable sensors towards medical-level devices. Multimodal big data should be instrumental in enabling in-depth investigation of pathophysiology and for generating new diagnostic tools. Multidisciplinary research is certainly warranted on biocyber interface, multimodal data fusion, cloud-based data processing, data management and clinical interpretation to address the concerns in privacy, cybersecurity, and ethics in the context of IoMT and IoBNT, which will accelerate the iteration of regulatory frameworks.

In next 1-3 years, the priority is the integration and application of established technologies (TRLs: 6-9), including IoMT, microelectronics-based miniaturized sensors, and big data, with commercialized sensors, monitoring devices, and cloud-based data analysis platforms as milestones. In next 4-5 years, emerging technologies (TRLs: 3-5) including nanotechnologies, biocyber interface and IoBNT will potentially be prototyped, with lab testing and clinical validation as milestones. Furthermore, in next 6-10 years, emerging concepts (TRLs: 3-5) including big data-driven healthcare and wearable sensor array will be in shape, with a vision of technology-enhanced healthcare and medicine based on multidisciplinary collaboration.

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References

[1] H. Liu, L. Wang, G. Lin, and Y. Feng, "Recent progress in the fabrication of flexible materials for wearable sensors," Biomater. Sci., vol. 10, no. 3, pp. 614–632, 2022, doi: 10.1039/D1BM01136G.
[2] A. Uniyal, G. Srivastava, A. Pal, S. Taya, and A. Muduli, "Recent advances in optical biosensors for sensing applications: A review," Plasmonics, vol. 18, no. 2, pp. 735–750, Apr. 2023, doi: 10.1007/s11468-023-01803-2.
[3] J. Mathew, D. Zheng, J. Xu, and H. Liu, "Systematic review on fabrication, properties, and applications of advanced materials in wearable photoplethysmography sensors," Adv. Electron. Mater., vol. 10, no. 8, Art. no. 2300765, Aug. 2024, doi: 10.1002/aelm.202300765.
[4] C. Ye, H. Lukas, M. Wang, Y. Lee, and W. Gao, "Nucleic acid-based wearable and implantable electrochemical sensors," Chem. Soc. Rev., vol. 53, no. 15, pp. 7960–7982, 2024, doi: 10.1039/D4CS00001C.
[5] S. Mostufa, P. Yari, B. Rezaei, K. Xu, and K. Wu, "Flexible magnetic field nanosensors for wearable electronics: A review," ACS Appl. Nano Mater., vol. 6, no. 15, pp. 13732–13765, Aug. 2023, doi: 10.1021/acsanm.3c01936.
[6] F. Rossi et al., "Progress in nanoparticle-based electrochemical biosensors for hormone detection," Nanoscale, 2024.
[7] B. Bao, Y. Hua, R. Wang, and D. Li, "Quantum-based magnetic field sensors for biosensing," Adv. Quantum Technol., vol. 6, no. 5, Art. no. 2200146, May 2023, doi: 10.1002/qute.202200146.
[8] Z. Khoshbin, M. R. Housaindokht, M. Izadyar, M. R. Bozorgmehr, and A. Verdian, "Recent advances in computational methods for biosensor design," Biotechnol. Bioeng., vol. 118, no. 2, pp. 555–578, Feb. 2021, doi: 10.1002/bit.27618.
[9] Y. Teyeme, B. Malengier, T. Tesfaye, I. Ciesielska-Wrobel, A. B. Haji Musa, and L. Van Langenhove, "A review of contemporary techniques for measuring ergonomic wear comfort of protective and sport clothing," AUTEX Res. J., vol. 21, no. 1, pp. 32–44, 2021, doi: 10.2478/aut-2019-0076.
[10] Y. Shao, H. Hu, and Y. Visell, "A wearable tactile sensor array for large-area remote vibration sensing in the hand," IEEE Sens. J., vol. 20, no. 12, pp. 6612–6623, Jun. 2020.
[11] J. Wu, X. Teng, L. Liu, H. Cui, and X. Li, "Eutectogel-based self-powered wearable sensor for health monitoring in harsh environments," Nano Res., vol. 17, no. 6, pp. 5559–5568, Jun. 2024, doi: 10.1007/s12274-024-6425-8.
[12] Y. Gui, S. He, Y. Wang, and J. Yang, "MOF-derived porous Ni/C material for high-performance hybrid nanogenerator and self-powered wearable sensor," Compos. Part A, vol. 168, Art. no. 107492, May 2023, doi: 10.1016/j.compositesa.2023.107492.
[13] A. Babu, I. Aazem, R. Walden, S. Bairagi, D. M. Mulvihill, and S. C. Pillai, "Electrospun nanofiber-based TENGs for wearable electronics and self-powered sensing," Chem. Eng. J., vol. 452, Art. no. 139060, Jan. 2023, doi: 10.1016/j.cej.2022.139060.
[14] Y. Zhang et al., "Liquid metal enabled elastic conductive fibers for self-powered wearable sensors," Adv. Mater. Technol., vol. 8, no. 10, Art. no. 2202030, May 2023, doi: 10.1002/admt.202202030.
[15] M. Seong et al., "3D printable self-adhesive and self-healing ionotronic hydrogels for wearable healthcare devices," ACS Appl. Mater. Interfaces, vol. 15, no. 8, pp. 11042–11052, Mar. 2023, doi: 10.1021/acsami.2c21704.

Accepted Manuscript

[16] V. B. Juska, G. Maxwell, P. Estrela, M. E. Pemble, and A. O'Riordan, "Silicon microfabrication technologies for biology-integrated advanced devices and interfaces," Biosens. Bioelectron., vol. 237, Art. no. 115503, Oct. 2023, doi: 10.1016/j.bios.2023.115503.
[17] R. Vinoth, T. Nakagawa, J. Mathiyarasu, and A. M. V. Mohan, "Fully printed wearable microfluidic devices for high-throughput sweat sampling and multiplexed electrochemical analysis," ACS Sens., vol. 6, no. 3, pp. 1174–1186, Mar. 2021, doi: 10.1021/acssensors.0c02446.
[18] C. Huang, J. Wang, S. Wang, and Y. Zhang, "Internet of medical things: A systematic review," Neurocomputing, vol. 557, Art. no. 126719, Nov. 2023, doi: 10.1016/j.neucom.2023.126719.
[19] N. Dai, I. M. Lei, Z. Li, Y. Li, P. Fang, and J. Zhong, "Recent advances in wearable electromechanical sensors—Moving towards machine learning-assisted wearable sensing systems," Nano Energy, vol. 105, Art. no. 108041, Jan. 2023, doi: 10.1016/j.nanoen.2022.108041.
[20] G. Tse et al., "Healthcare big data in Hong Kong: Development and implementation of artificial intelligence-enhanced predictive models for risk stratification," Curr. Probl. Cardiol., Art. no. 102168, 2023.
[21] L. Wang et al., "A blockchain-based privacy-preserving healthcare data sharing scheme for incremental updates," Symmetry, vol. 16, no. 1, Art. no. 89, 2024, doi: 10.3390/sym16010089.
[22] A. A. Smith, R. Li, and Z. T. H. Tse, "Reshaping healthcare with wearable biosensors," Sci. Rep., vol. 13, no. 1, Art. no. 4998, Mar. 2023, doi: 10.1038/s41598-022-26951-z.

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Section 10: Scalability and Manufacturing Challenges

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Status

The transition of wearable and textile-based health technologies from laboratory prototypes to commercially viable products is significantly influenced by scalability and manufacturing considerations. While proof-of-concept demonstrations continue to showcase technological feasibility, mass production remains a major bottleneck. Key issues include the scalability of sensor integration processes, cost-effectiveness of advanced materials, and reliability of mass-manufactured devices [1,2].

Smart textiles, in particular, demand novel production workflows that can accommodate flexible substrates, conductive yarns, and embedded electronics without compromising fabric integrity or user comfort. Unlike traditional electronics, e-textile manufacturing must account for dynamic mechanical stresses, repeated washing, and body-conforming wear, necessitating new quality assurance frameworks and standardization protocols [3]. These manufacturing considerations—including production scalability, cost, quality control, and sustainability—are summarized in **Figure 35.**

Cost remains another limiting factor, especially in healthcare applications where affordability, reimbursement, and production scalability are critical. While the price of components such as microcontrollers and energy harvesters has declined, large-scale fabrication techniques for smart garments are still maturing. Moreover, the adoption of sustainable and ethically sourced materials is increasingly demanded by both consumers and regulators, adding complexity to the supply chain [4]. These challenges span production scalability and cost considerations, quality control and standardization, as well as environmental and ethical considerations, which collectively determine the feasibility of large-scale deployment.

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Figure 35. Key scalability and manufacturing challenges in wearable and textile-based healthcare technologies. The figure highlights four major factors: production scalability, cost considerations, quality control and standardization, and environmental and ethical concerns. Addressing these challenges is essential to transition from prototypes to mass-market, clinically validated solutions.

Current and Future Challenges

One of the foremost challenges is the lack of established, scalable manufacturing pipelines tailored to smart textiles. Conventional textile fabrication methods like weaving, knitting, and printing need to be reengineered to accommodate electronic functionalities without compromising comfort or durability. Additionally, the integration of multiple sensing modalities—e.g., ECG, motion, and temperature—often requires hybrid techniques that are not easily compatible with existing assembly lines [2].

Quality control and standardization present another pressing issue. Minor inconsistencies in conductive coatings, sensor positioning, or textile elasticity can lead to substantial variations in signal quality. Current testing methods are often manual or destructive, limiting their use in high-throughput environments. Developing robust, automated quality control and standardization systems is essential for commercial scalability [5].

Environmental and ethical considerations, including responsible material sourcing and labor practices, are increasingly shaping manufacturing choices. The disposal of wearable electronics raises concerns about electronic waste and microplastic pollution. Furthermore, the sourcing of raw materials, particularly rare earth elements and synthetic fibers, can have significant environmental footprints. Future manufacturing strategies must prioritize circular design principles, biodegradable materials, and energy-efficient production processes [4,6].

Advances in Science and Technology to Meet Challenges

Emerging additive manufacturing techniques such as inkjet printing, screen printing, and 3D printing are proving effective for embedding functional materials into textiles at scale. These methods enable precise deposition of conductive inks and polymers on flexible substrates, allowing for mass production of multilayered and multifunctional smart fabrics [1,3].

Efforts to standardize fabrication methods have led to the development of open-source platforms and modular textile circuits, which promote design interoperability and facilitate cross-industry

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adoption. Additionally, machine vision and AI-powered inspection systems are being explored for real-time defect detection during textile production, thereby enhancing yield and consistency [5].

To address environmental concerns, researchers are exploring biodegradable conductors, organic semiconductors, and natural fiber composites. Green chemistry approaches are being integrated into fabrication workflows to reduce the use of toxic solvents and heavy metals. Furthermore, life cycle assessments (LCAs) are now routinely conducted during product development to evaluate environmental impact and guide sustainable design [4,6].

Concluding Remarks

Scalability and sustainable manufacturing remain key hurdles in the widespread adoption of wearable and textile-based healthcare technologies. Addressing these challenges requires not only technological innovation but also systemic changes in production, regulation, and design philosophy. As the field moves forward, collaborative efforts across academia, industry, and policy will be critical in building scalable, standardized, and environmentally responsible smart textile solutions.

Acknowledgements

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References

[1] M. R. Islam, S. Afroj, and N. Karim, “Scalable production of 2D material heterostructure textiles for high-performance wearable supercapacitors,” *ACS Nano*, vol. 17, no. 18, pp. 18481–18493, 2023.

[2] Y. Peng *et al.*, “Multimodal health monitoring via a hierarchical and ultrastretchable all-in-one electronic textile,” *Nano Energy*, vol. 110, Art. no. 108374, 2023.

[3] G. Chen *et al.*, “Electronic textiles for wearable point-of-care systems,” *Chem. Rev.*, vol. 122, no. 3, pp. 3259–3291, 2021.

[4] Y. Liu *et al.*, “Eco-friendly strategies for the material and fabrication of wearable sensors,” *Int. J. Precis. Eng. Manuf.-Green Technol.*, vol. 8, no. 4, pp. 1323–1346, 2021.

[5] M. Azeem *et al.*, “Design and development of textile-based wearable sensors for real-time biomedical monitoring: A review,” *J. Text. Inst.*, vol. 116, no. 1, pp. 80–95, 2025.

[6] M. Dulal *et al.*, “Toward sustainable wearable electronic textiles,” *ACS Nano*, vol. 16, no. 12, pp. 19755–19788, 2022.

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Section 11: Biodegradable Adhesives for Skin–Textile Interfaces and Sustainable E-Textiles

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Status

Biodegradable adhesives play a critical enabling role in textile-integrated wearables by mediating skin–textile interfaces and textile–device bonding. Key challenges include maintaining adhesion under sweat, motion, and repeated washing, while supporting durability, user comfort, and end-of-life recyclability of e-textile systems.

In parallel, biodegradable adhesives have long been explored in broader biomedical applications, including tissue reconstruction and wound closure, where strong yet transient adhesion is required. The earliest known adhesives, produced by dry distillation of birch bark and dating back roughly 200,000 years, exemplify early biodegradable adhesive technologies [1]. Insights from these biomedical developments provide valuable design principles for modern adhesive systems intended for textile-integrated wearable applications.

Modern biodegradable adhesives, whether synthetic (e.g., cyanoacrylates, polyurethanes, polyesters) or naturally derived (e.g., fibrin, polysaccharides), are designed to degrade safely without releasing harmful byproducts [2, 3]. Clinically, these materials have been used for tissue reconstruction, wound closure, vascular repair, and skin graft stabilization, where they can minimize inflammation and eliminate the need for removal surgery. Although sutures, metallic grafts, and skin closure strips remain the clinical gold standard for tissue reconstruction [4], these methods can trigger inflammation or discomfort upon removal, underscoring the need for degradable alternatives. Such applications highlight the capacity of biodegradable systems to meet mechanical and biological requirements simultaneously. Beyond reconstructive medicine, bioinspired and polymer-based adhesives are now being developed for wearable and bio-integrated technologies, where comfort, breathability, and environmental compatibility are equally critical. These aspects underpin ergonomic design and user acceptance, central to long-term wearability in continuous-use devices. In this context, biodegradable adhesives serve as a bridge between traditional surgical materials and emerging stimuli-responsive platforms capable of safe, on-demand detachment and potential integration with disease-monitoring electronics [5]. **Figure 36** summarizes the functional roles of biodegradable adhesives at skin–textile and textile–device interfaces, highlighting their dual requirements for mechanical robustness, biocompatibility, and controlled degradation in wearable healthcare systems.

Current and Future Challenges

Although biodegradable adhesives show great promise for future healthcare applications, several limitations remain. A significant concern with commercially available adhesives is the potential damage they may cause upon removal. Medical adhesive-related skin injuries (MARSI) are lesions

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that persist on the skin after adhesives are manually removed. This removal process can damage up to 40% of the delicate skin found on neonates, the elderly, and patients with specific conditions, such as those requiring vascular access, skin grafts, or treatments for burn wounds. The excessive force applied when peeling off an adhesive, ranging from 19 to 41 N m^{-1} for common adhesives, often tears the outer layer of these fragile tissues [6, 7]. Thus, the frontier of wearable adhesives is trending towards biodegradable alternatives that maintain strong adhesion properties, while still being easy to remove after use. This is a complex task, as materials with high adhesive strength, on the order of MPa, tend to resist removal, while those designed for easy removal often fail to provide adequate adhesion [8]. Specific challenges are associated with both internal and external body applications. For internal applications, the key challenges include limited effectiveness in wet environments, maintaining hemostasis in blood, and preventing cytotoxicity in deep tissue-interfaced applications. In contrast, external applications face challenges such as comfort, sensitivity and limited protection from weather and environmental factors. These challenges are not limited to wearable systems but also remain critical for internal biomedical uses such as tissue reconstruction, wound repair, and vascular sealing, where balancing strong adhesion with safe biodegradation is essential for clinical success. Additionally, comfort, durability, and irritation remain critical concerns for the development of new wearable adhesives that can potentially replace current gold standards for commercial acceptance. Comprehensive wearability testing, including prolonged skin-contact and motion studies, will be essential to ensure user comfort and compatibility across diverse skin types and activity levels. Finding solutions to these challenges is paramount for significantly improving healthcare quality, enhancing patient outcomes, and advancing the field of medical adhesives.

Advances in Science and Technology to Meet Challenges

Comfort and compatibility of adhesives is of paramount concern in the field. In this regard, focus is shifted towards artificial skin grafts, which can replace damaged or missing tissue to treat large burns and chronic wounds by mimicking natural tissue. Inspired by the multi-layered fibrous structure of skin, Hao et al. designed SPRABE-skin, a soft and stretchable material with high adhesion strength [9]. Innovations in stimuli-responsive and bioinspired adhesive design directly address these same demands across both reconstructive and wearable applications, aiming to achieve controlled degradation, tissue compatibility, and adaptability under physiological conditions. Bone fracture repair is another area where adhesives offer several advantages over traditional fixation methods, such as bone plates or screws. Adhering arbitrarily shaped bone fragments together can avoid the need for secondary surgery to remove them, reducing the risk of infection and pain. Li et al. developed a polyurethane-based adhesive with a unique molecular design, taking inspiration from catechol-decorated proteins in mussels, to address the need for a biocompatible, degradable, and osteogenic bone adhesive [10]. By incorporating disulfide bonds into the polyurethane backbone, these adhesive materials degrade over time in response to the reducing agent glutathione. Bioinspired catechol functionalization increases the material's performance in wet media through dynamic hydrogen bonding with various substrates. This modification also promotes osteogenesis, or new bone tissue formation, via mineralization by adsorbing free calcium ions.

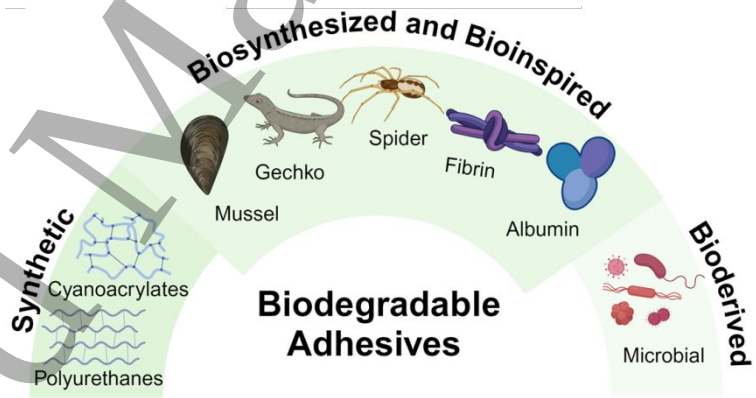


Figure 36: Overview diagram of biodegradable adhesives for healthcare applications.

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Stimuli-responsive adhesives have emerged as candidates to overcome advanced healthcare challenges. These materials utilize chemistries programmed to undergo modulation in their bulk mechanical properties upon exposure to specific signals from their surroundings. Such changes can rely on endogenous (e.g., pH, redox, enzyme, salts) or exogenous (e.g., light, mechanical, temperature, electrical, magnetic) stimuli [11]. These stimuli target specific molecular functionalities in the adhesives, triggering debonding and allowing for safe removal. Dynamic covalent bonds, for example, are molecular bonds which can actively break and reform with another chemical partner. Wang et al. applied this concept to synthesize reversible underwater adhesives inspired by marine organisms [12]. They incorporated tannic acid, a natural product with abundant catechol functionality, into a hydrogel of gelatin and hyaluronic acid. The result was a biocompatible and biodegradable adhesive which demonstrated adhesion strength over three times higher than fibrin glue, the current widely used tissue sealant. The hydrogel also responded to mechanical stress stimuli from the surrounding tissue, conforming to the surface and increasing tissue compatibility. Efficient underwater adhesion makes them desirable candidates for applications on human vasculature, such as sealants for ruptured vessels, embolizing agents for rediverting blood from varicose veins, and maintaining homeostasis during surgery. Lee et al. also turned to stimuli-responsive adhesives to address issues with dural sealants used during neurosurgery, where sutures and traditional sealants cannot create a watertight seal in 94% of cases [13]. To prevent the leakage of cerebrospinal fluid due to intracranial pressure and high suction during surgery, they prepared a photocurable hyaluronic acid-based sealant. In response to five seconds of low-energy light exposure, the photo sealant firmly adhered to the dura forming a watertight seal which retained stability for over four weeks, the relevant therapeutic timeline. It outperformed its commercial counterparts in measures of biocompatibility, showed no cell degeneration, and even promoted osteogenesis, all the while being safe and effective.

User Comfort and Wearability

Beyond clinical performance, ergonomic design and user acceptance are critical for wearable and bio-integrated adhesives. Recent studies emphasize that material comfort, breathability, and skin compatibility determine whether users tolerate extended wear. For true long-term wearability, materials should sustain continuous skin contact for 14–30 days with minimal edge-lift (< 5 %), low irritation scores (≤ grade 1 erythema), and perceived comfort rated below 3 on a 10-point pain/discomfort scale, as established in clinical adhesive-tolerance studies [14]. Maintaining a water-vapor transmission rate (MVTR) of 500–1000 g m^{-2} day^{-1} supports breathability and moisture balance [15], while substrate choice and mechanical softness directly affect how users perceive comfort during prolonged use. Soft, on-skin sensor platforms have also underscored the importance of adhesive interface design, skin–material interactions, and fatigue resistance under motion for maintaining mechanical and perceptual comfort [16]. Standardized testing can quantify these properties: ASTM D3330 (peel adhesion), ASTM D3654 (shear adhesion), and ISO 10993-1 (biocompatibility for skin contact) provide relevant benchmarks. Complementary in-vivo wear trials, following these standards and conducted over at least 21 days under realistic movement and perspiration conditions [15, 16], are recommended to assess comfort, adhesion stability, and long-term user compliance. Incorporating ergonomic geometries, breathable adhesives, and stimuli-responsive release mechanisms further supports safe removal and re-application, bridging the gap between short-term clinical adhesives and next-generation wearable platforms. Such quantitative evaluation ensures that biodegradable adhesives meet both mechanical and physiological criteria for next-generation wearable devices.

Concluding Remarks

Biodegradable adhesives with improved comfort and compatibility and new stimuli-responsive behaviour represent transformative advancements in healthcare that offer innovative solutions to ongoing challenges in tissue reconstruction and wearable technologies. This field has opened new

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pathways to developing dynamic, adaptable materials that cater to diverse healthcare needs, from skin grafts to vascular repair. Looking forward, biodegradable adhesives could be integrated with existing wearable electronics for disease monitoring [17]—where controlled adhesive biodegradation enables gentle removal from fragile tissues—creating multifunctional platforms that combine strong yet transient adhesion with real-time sensing on the body. The next steps involve improving material biocompatibility, functionality, and scalability to ensure their widespread usage in clinical settings. Future development should integrate ergonomic modeling, skin-mimetic mechanics, and longitudinal user studies to fully establish material comfort and long-term wearability.

Acknowledgements

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References

[1] P. R. B. Kozowyk, M. Soressi, D. Pomstra, and G. H. J. Langejans, "Experimental methods for the Palaeolithic dry distillation of birch bark: Implications for the origin and development of Neandertal adhesive technology," *Sci. Rep.*, vol. 7, no. 1, Art. no. 8033, Aug. 2017, doi: 10.1038/s41598-017-08106-7.

[2] A. Tzagiollari, H. O. McCarthy, T. J. Levingstone, and N. J. Dunne, "Biodegradable and biocompatible adhesives for the effective stabilisation, repair and regeneration of bone," *Bioengineering*, vol. 9, no. 6, Art. no. 250, 2022. [Online]. Available: https://www.mdpi.com/2306-5354/9/6/250

[3] V. Bhagat and M. L. Becker, "Degradable adhesives for surgery and tissue engineering," *Biomacromolecules*, vol. 18, no. 10, pp. 3009–3039, Oct. 2017, doi: 10.1021/acs.biomac.7b00969.

[4] K. Zheng, Q. Gu, D. Zhou, M. Zhou, and L. Zhang, "Recent progress in surgical adhesives for biomedical applications," *Smart Mater. Med.*, vol. 3, pp. 41–65, 2022, doi: 10.1016/j.smaim.2021.11.004.

[5] Y. L. Tan *et al.*, "Adhesion evolution: Designing smart polymeric adhesive systems with on-demand reversible switchability," *ACS Nano*, vol. 18, no. 36, pp. 24682–24704, Sep. 2024, doi: 10.1021/acsnano.4c05598.

[6] P. Jani *et al.*, "Global variation in skin injuries and skincare practices in extremely preterm infants," *World J. Pediatr.*, vol. 19, no. 2, pp. 139–157, Feb. 2023, doi: 10.1007/s12519-022-00625-2.

[7] F. Mbithi and P. R. Worsley, "Adhesives for medical application—Peel strength testing and evaluation of biophysical skin response," *J. Mech. Behav. Biomed. Mater.*, vol. 148, Art. no. 106168, Dec. 2023, doi: 10.1016/j.jmbbm.2023.106168.

[8] N. D. Blelloch, H. J. Yarbrough, and K. A. Mirica, "Stimuli-responsive temporary adhesives: Enabling debonding on demand through strategic molecular design," *Chem. Sci.*, vol. 12, no. 46, pp. 15183–15205, 2021, doi: 10.1039/D1SC03426J.

[9] Y. Hao *et al.*, "A stretchable, breathable, and self-adhesive electronic skin with multimodal sensing capabilities for human-centered healthcare," *Adv. Funct. Mater.*, vol. 33, no. 44, Art. no. 2303881, 2023, doi: 10.1002/adfm.202303881.

[10] Q. Li *et al.*, "Overcoming the dilemma of *in vivo* stable adhesion and sustained degradation by the molecular design of polyurethane adhesives for bone fracture repair," *Adv. Healthc. Mater.*, vol. 13, no. 5, Art. no. 2301870, 2024, doi: 10.1002/adhm.202301870.

[11] S. Bhattacharya, M. N. Ganivada, H. Dinda, J. D. Sarma, and R. Shunmugam, "Biodegradable copolymer for stimuli-responsive sustained release of doxorubicin," *ACS Omega*, vol. 1, no. 1, pp. 108–117, Jul. 2016, doi: 10.1021/acsomega.6b00018.

Accepted Manuscript

[12] H. Wang *et al.*, "Nature-inspired gelatin-based adhesive hydrogel: A rapid and user-friendly solution for hemostatic applications," *Adv. Healthc. Mater.*, vol. 13, no. 19, Art. no. e2304444, Jul. 2024, doi: 10.1002/adhm.202304444.
[13] H. Lee *et al.*, "Enhanced dural repair using biodegradable sealants based on photocurable hyaluronic acid," *Macromol. Biosci.*, vol. 24, no. 4, Art. no. 2300359, 2024, doi: 10.1002/mabi.202300359.
[14] R. G. Ferreira, A. P. Silva, and J. Nunes-Pereira, "Current on-skin flexible sensors, materials, manufacturing approaches, and study trends for health monitoring: A review," *ACS Sensors*, vol. 9, no. 3, pp. 1104–1133, Mar. 2024, doi: 10.1021/acssensors.3c02555.
[15] J. Dong *et al.*, "Breathable and stretchable epidermal electronics for health management: Recent advances and challenges," *Adv. Mater.*, vol. 36, no. 49, Art. no. 2409071, 2024, doi: 10.1002/adma.202409071.
[16] A. Barton *et al.*, "Medical adhesive–related skin injury at 10 years: An updated consensus," *J. Wound Ostomy Continence Nurs.*, vol. 51, no. 5S Suppl. 5, pp. S2–S8, Sep.–Oct. 2024, doi: 10.1097/WON.0000000000001116.
[17] Y. Deng *et al.*, "A soft thermal sensor for the continuous assessment of flow in vascular access," *Nat. Commun.*, vol. 16, no. 1, Art. no. 38, Jan. 2025, doi: 10.1038/s41467-024-54942-3.

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Section 12: Regulatory and Compliance Issues

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Status

As wearable and textile-based technologies advance from research prototypes to real-world healthcare applications, navigating the complex regulatory and compliance landscape has become increasingly critical. Regulatory frameworks govern the safety, effectiveness, interoperability, and privacy aspects of medical devices—and smart textiles are no exception. However, the multidisciplinary and hybrid nature of these systems challenges conventional classification and approval processes [1,2].

Current regulatory systems, such as those of the U.S. Food and Drug Administration (FDA), European Medicines Agency (EMA), and other national authorities, are primarily designed around traditional medical devices. Consequently, many wearable technologies fall into gray zones, particularly those that blend wellness monitoring with clinical-grade capabilities. For example, a smart shirt tracking ECG and respiration may require different regulatory routes depending on intended use, data processing, and claims made by the manufacturer [3].

Recent regulatory guidance, including the FDA's recommendations on Predetermined Change Control Plans (PCCP) for AI-enabled medical devices and the IMDRF Good Machine Learning Practice (GMLP) principles, provides an emerging framework for managing adaptive algorithms throughout the device lifecycle. These frameworks are directly relevant to textile-integrated wearables employing continuous learning, personalization, and software updates.

Additionally, most wearable systems incorporate AI algorithms for data analysis and personalized feedback. These algorithms, especially if adaptive, pose regulatory concerns regarding explainability, validation, and version control. The shift from static to dynamic software-based medical devices adds another layer of complexity to compliance [4].

In parallel, a growing set of international standards is emerging to guide the safe and effective deployment of wearable systems. Core requirements include IEC 60601 for electrical safety, ISO 10993 for biocompatibility of skin-contact materials, and ISO 13485 for quality management systems. For connected and wireless wearables, IEEE 2621 provides guidance on interoperability and reliability. AI-enabled wearable systems increasingly fall under Software as a Medical Device (SaMD) regulations, requiring compliance with medical software lifecycle standards and explicit validation of algorithm performance, robustness, and version control.

Current and Future Challenges

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One key challenge is the absence of harmonized international standards for wearable medical textiles. Developers must often navigate multiple, overlapping regulations depending on geography, intended application, and data handling practices. This fragmentation increases development timelines and market entry costs [2].

Compliance standards and certifications—such as ISO 13485 for medical devices, ISO 10993 for biocompatibility, IEC 60601 for electrical safety, and MDR (EU Medical Device Regulation)—are not always tailored to wearable systems that involve textiles, skin contact, and continuous data capture. As a result, companies frequently rely on consultants or ad hoc interpretations to achieve conformity [3,5].

Another rising concern is cybersecurity and data protection. With wearables collecting continuous, personal health data, regulators are now focusing on cybersecurity measures and compliance with frameworks like the GDPR (General Data Protection Regulation) and HIPAA (Health Insurance Portability and Accountability Act). Ensuring compliance while maintaining device usability and connectivity remains an ongoing balancing act [4].

Regulatory classification remains a major challenge for vital-sign monitoring wearables such as ECG, blood pressure, PPG, and EEG devices, as approval pathways depend strongly on intended use and clinical claims. Devices marketed for wellness purposes typically face lighter oversight, whereas medical-grade wearables must demonstrate clinical validation, accuracy benchmarks, and risk mitigation in line with FDA or EMA expectations. This distinction is particularly critical for AI-driven systems, which must comply with SaMD requirements related to dataset representativeness, algorithm stability, and post-market surveillance.

Advances in Science and Technology to Meet Challenges

Recent regulatory efforts have aimed to adapt to digital health innovation. For instance, the FDA's Digital Health Center of Excellence and the EU's Artificial Intelligence Act are developing guidance for AI-driven diagnostics and adaptive algorithms. These frameworks recognize the iterative nature of software-based systems and propose mechanisms for pre-certification and continuous learning models [1,6].

Regulatory alignment with clinical practice is evolving through initiatives such as the EU Medical Device Regulation (EU MDR), which mandates clinical evaluation, risk classification, and post-market surveillance for monitoring devices seeking CE marking. In the United States, the FDA's Good Machine Learning Practice (GMLP) framework provides guidance for AI-based medical devices across their lifecycle. Given the sensitive nature of continuously collected health data, compliance with GDPR and HIPAA has become integral to wearable system design, underscoring the need for harmonized global regulatory approaches.

Emerging industry standards, such as IEEE 2621 (standard for wireless wearable devices), are gaining traction as benchmarks for interoperability and safety. Collaborative efforts between industry groups, regulators, and academic institutions are driving consensus on best practices for testing, documentation, and risk mitigation.

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To address compliance with textile-specific challenges, researchers are creating testbeds and simulation platforms to evaluate material biocompatibility, durability, and washability under real-world conditions. Integration of digital twins, blockchain for traceability, and AI for regulatory intelligence are also being explored to streamline certification and auditing processes [5,6].

To address textile-integrated electronics, the International Electrotechnical Commission (IEC)—through IEC Technical Committee 124 (IEC TC 124)—is developing dedicated standards for electronic textiles. Key examples include IEC 63203-101-1 (test methods for smart garments), IEC 63203-201-3 (motion sensors and glove-type systems), and IEC 63203-204-1 (performance evaluation of fitness wearables). Importantly, regulatory pathways for medical e-textiles already exist, as demonstrated by FDA-approved wearable EEG systems for epilepsy, LiveMetric's FDA-cleared cuffless smartwatch-like blood pressure sensor, and 12-lead ECG remote monitoring garments developed by Mater Cousin and VivoMetrics.

Concluding Remarks

Wearables and smart textiles straddle the boundaries between medical devices, consumer electronics, and fashion. As such, regulatory clarity and flexible compliance pathways are essential to unlocking their full potential. Ongoing dialogue between stakeholders and continuous adaptation of regulatory frameworks will be vital in supporting the safe, ethical, and scalable deployment of wearable healthcare technologies.

References

[1] C. Wall, V. Hetherington, and A. Godfrey, "Beyond the clinic: The rise of wearables and smartphones in decentralising healthcare," *npj Digit. Med.*, vol. 6, no. 1, Art. no. 219, 2023.
[2] J. Kim *et al.*, "Wearable biosensors for healthcare monitoring," *Nat. Biotechnol.*, vol. 37, no. 4, pp. 389–406, 2019.
[3] M. Azeem *et al.*, "Design and development of textile-based wearable sensors for real-time biomedical monitoring: A review," *J. Text. Inst.*, vol. 116, no. 1, pp. 80–95, 2025.
[4] N. M. Thomasian and E. Y. Adashi, "Cybersecurity in the internet of medical things," *Health Policy Technol.*, vol. 10, no. 3, Art. no. 100549, 2021.
[5] G. Chen *et al.*, "Electronic textiles for wearable point-of-care systems," *Chem. Rev.*, vol. 122, no. 3, pp. 3259–3291, 2021.
[6] C. Mennella *et al.*, "Ethical and regulatory challenges of AI technologies in healthcare: A narrative review," *Heliyon*, vol. 10, no. 4, 2024.

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Section 13: System-Level Integration Challenges for Textile-Based Health Systems

Building on the material (Section 5) and system-level (Section 7) challenges discussed earlier, this section synthesizes cross-cutting integration issues.

13.1 – Technical and non-technical challenges

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Status

The integration of flexible and stretchable devices into everyday items like clothing, bedding, and medical gear which can sense, heat, and transmit data has led to the development of smart textiles [1]. The origins of 'smart textiles' (also referred as 'e-textiles') can be traced back to the 1850s when researchers began investigation the use of electricity in clothing, such as corsets and belts [2]. However, it wasn't until 1955, that wearable computing gained significant attention from the scientific community, following the success demonstrated by Edward Thorpe and Claude Shannon [3]. Since then, smart textiles have grown rapidly and are estimated to reach a valuation of $23.82 billion, reflecting a 25% growth from 2021 to 2031 [4].

Smart textiles are the result of interdisciplinary efforts combining art, computer science, design, electronics, electrical engineering and materials science [5]. While smart textiles have applications have diverse applications, they are particularly prominent in the areas of healthcare, fitness and fashion. The evolution of smart textiles can be divided into several phases, based on the methods used to integrate electronics onto textiles [6-8]. The first generation (1910-) smart textiles involved embedding electronic component onto textiles. The second generation (1990-) saw the knitting or weaving of conductive yarns onto the textile structure to create electronic functionality. The third generation (2010-) saw smart textiles become more durable, comfortable, and reliable with electronic systems and sensors fully integrated into garments, making these smart textiles more suitable for production than their predecessors. The fourth generation, also referred to as the future age of smart textiles, primarily exists in the concept or the prototype stage and involves state-of-art technology that seamlessly integrates electronic functionality into textiles.

Despite their potential, smart textiles are still in its early stages of development and requires significant advancements before they can achieve widespread acceptance. The multidisciplinary nature of smart textiles brings both challenges and opportunities. In this sub-section, we focus on the technical and non-technical barriers that current limit large-scale deployment and on the solutions that have already been demonstrated in prototypes, pilot studies, and early commercial products. **Figure 37** provides a system-level overview of these technical and non-technical challenges in smart textiles, mapping key concerns across materials, electronics, design, economic, and environmental domains alongside representative solution pathways.

Current and Future Challenges

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Challenges can be broadly categorized as technical and non-technical challenges.

Technical challenges:

These challenges fall into several recurring themes such as durability and washability, sensor integration and accuracy, energy storage and harvesting, user-centered design, and regulatory and sustainability constraints, each of which involves multiple disciplines.

1) **Material science-based challenges**: *Washability and durability:* Smart textiles incorporate electronic components such as cables, sensors, conductive threads, batteries, and circuits into fabrics, which must withstand repeated washing and high-humidity environments without losing their electronic performance [9]. Smart textiles, like the ICD+ textile coat developed by Philips and Levi, requires the removal of all electronic components before washing, highlighting the ongoing challenge of making these textiles durable and reusable [10]. *Comfort and Material compatibility:* The underlying choice of textiles is crucial and tricky. Metal-based yarns, while offering superior electrical conductivity, can be uncomfortable against the skin. Organic thin-film transistors, though flexible, present challenges when integrated with textile structures [5]. Recent developments with carbon nanotube (CNT) yarns provide a great alternative with its excellent electromechanical and thermal properties while providing structural flexibility that can easily be wrapped with traditional textile yarns. [11].

2) **Mechanical engineering-based challenges**: Currently, sensors are integrated into garments through sewing or embroidering, making it vulnerable to mechanical distortion. For example, flexible displays often rolled around cylinders have diameters of a few centimetres, whereas smart textile are exposed to much smaller bending radii and large tensile strains, which can compromise the fabric's flexibility and comfort [12].

3) **Electronics and electrical engineering-based challenges**: *Miniaturization of power sources:* Conventional batteries, though reliable, are large, bulky, and difficult to fully integrate into textile architecture. Alternative power sources, such as flexible or elastic batteries, supercapacitors, solar cells, and energy-harvesting devices, offer potential solutions but fall short of traditional batteries in terms of capacity and current output [13]. *Wiring for power and data transfer:* Wiring must be flexible and securely integrated into seams, which can impact sensor accuracy and precision. The need for reliable textile-compatible power supplies remains a significant challenge [1].

4) **Computer science-based challenges**: Sensor integration and accuracy are key challenges here. Incorporating embedded systems within sensors to process data in real-time and wirelessly communicate it to nearby devices increases power consumption and adds further complexity to powering smart textiles [14].

5) **Design-based challenges**: It is crucial to approach development of smart textiles from the end-user perspective. To achieve this, smart clothing must be designed and developed with consideration of technical, functional, aesthetics and cultural requirements [15].

Non-technical challenges:

These challenges refer to development philosophy, regulatory, economic, and environmental considerations around smart textiles. *Development philosophy:* The dominance of electronics over textile-related challenges in product development and research leads to incomplete integration in smart textiles. The imbalance between the two industries complicates successful development, as it hindered by differing jargon, high costs, and safety concerns [16]. *Compliance and standardization:* The lack of standard protocols and clear regulatory guidelines for the design, development, and commercialization of smart textiles poses a significant challenge. For example, in 2004, Eleksen

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created 109 textile keyboard prototypes but secured only three deals [13]. *Economic viability:* High R&D and manufacturing costs for integrating advanced electronics with textiles make smart textiles expensive, limiting their accessibility to average consumers. For example, smart jackets retailing about $3,000 whereas a simple sports shirt or sports bra cost upwards of $250 [13]. *Environmental considerations:* Concerns about the biodegradability of smart textiles have also emerged recently [17]. Popular smart-textile materials like synthetic polymer fibers (e.g., nylon and polyester), which, despite their flexibility and strength, have low biodegradation rates. The complexity and harmful ingredients involved in the synthesis of synthetic fibers also raise environmental concerns [18].

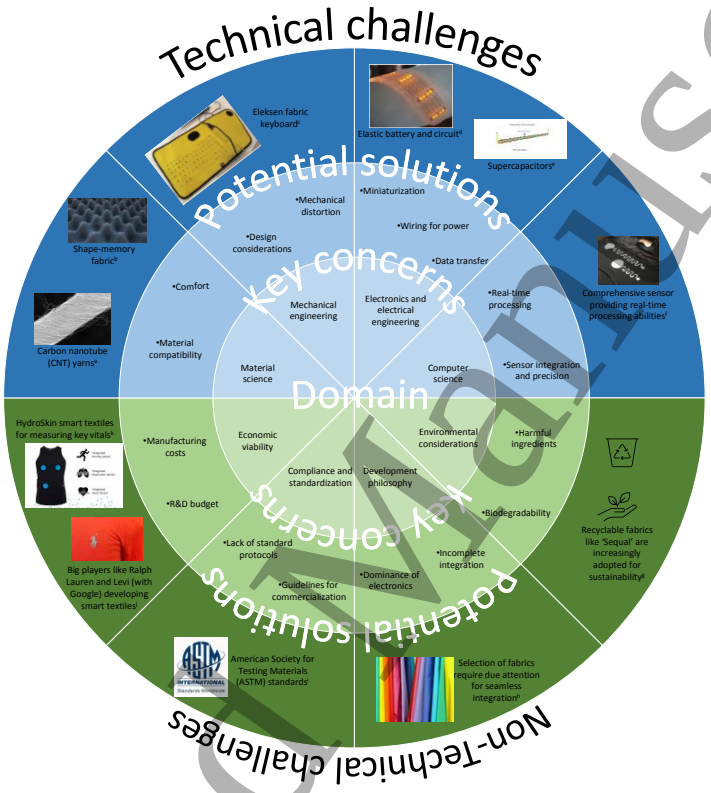


Figure 37. Smart textiles: Technical and non-technical challenges. a, e, g, h, i, j: Source: Wikimedia under Creative Commons License; **b:** Source Rawpixel under Creative Commons License **c, d:** From Cherenack et. al. under Creative Commons License; **f:** Source: Center for Advanced Self-Powered Systems of Integrated Sensors and Technologies (ASSIST), NC State University © 2024; **k:** Source Hydroskin © 2024

Current Solutions and Mitigation Strategies

The growing field and evolving research offer plenty of advancements to over the challenges surrounding smart textiles. Creating *hybrid fabrics* by combining materials that offer the desired properties from both textile and electronic perspectives can help overcome challenges related to comfort, durability, and mechanical distortion [19]. These hybrid fabrics aim to seamlessly integrate electronic components into textiles that can withstand distortion and twisting without compromising flexibility or comfort. More recent examples such as the Eleksen textile keyboard, rely on waterproof packaging to protect sensitive electronics during washing. *Alternative power sources* such as flexible or elastic batteries, supercapacitors, solar cells, and energy-harvesting devices like thermoelectric and piezoelectric generators are increasingly used as textile-compatible complements to conventional batteries [13, 20]. While these options do not yet match traditional

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batteries in terms of capacity, recent prototypes have shown that they can reliably power heart rate, motion, and temperature sensors over multiple wear and wash cycles. Printed interconnects and flexible wiring that can be securely integrated into seams without affecting sensor accuracy are likewise being demonstrated, improving the reliability and precision of smart sensor accuracy are likewise being demonstrated, improving the reliability and precision of smart textiles. Early 'system-on-fabric' approaches, in which circuits and sensors are directly printed or woven into the textile, further illustrate how complete sensing systems can be realized on cloth rather than only on rigid modules.

Enhancing standardization and regulatory development can make smart textiles more affordable and viable. There is a growing push for smart textiles to meet American Society for Testing and Materials (ASTM) standards, which would help improve design, innovation, marketing, and other services [1]. Standardization, in turn can lead to improved feedback, improving manufacturing processes further lowering the costs associated with smart textiles, making them more accessible to consumers [14]. *Sustainability initiatives:* Researchers are exploring more sustainable materials and processes for smart textile production, aiming to address environmental concerns related to biodegradability and the harmful ingredients used in synthetic fiber synthesis. These efforts include developing textiles that are both electronically functional and environmentally friendly. Recent updates on bacterial-cellulose-based conductive macrofibres used as biodegradable strain sensors, fully biodegradable conductive fibres that disintegrate in soil while supporting temperature and electromyography sensing, and Tencel-based e-textiles with inject-printed graphene and Poly (3,4-ethylenedioxythiphene) polystyrene sulfonate (PEDOT:PSS) for heart-rate monitoring [21, 22]. Such demonstrates show that sustainability can be addressed without sacrificing sensing performance, although large-scale deployment and end-of-life logistics remain open challenges.

Concluding Remarks

Despite numerous challenges, smart textiles have progressed from early conceptual designs to robust prototypes and initial commercial products that can withstand repeated laundering, integrate multiple sensors, and communicate wirelessly. Existing solutions such as hybrid fabrics, and encapsulated electronics for durability, textile-compatible batteries and energy harvesters, user-centered garment design processes and the first sustainability and standardization initiatives demonstrate that technically viable and user-acceptable systems are achievable today.

At the same time, important gaps remain. Long-term durability and washability across real-world use, reliable large-area sensor integration with lower power consumption, scalable manufacturing and repair, clear regulatory pathways, and circular-economy models for end-of-life management are still incompletely addressed. These current achievements and outstanding barriers provide the foundation for the emerging material, energy, and sustainability solutions that are explored in Section 13.2.

hold great potential for the future since clothing is the only wearable that adjusts to our daily lives over lifetime [5]. It represents a strong candidate to become the next interface between the real and the digital world, potentially replacing or extending smartphones and other portable connected device. By seamlessly capturing physiologic, kinematic, biochemical data etc., they could pave the way for new research and countless possibilities to enhance human lives. However, to realize this potential, several important aspects should be considered for the design and development of smart textiles, with usability being the most critical. Designing smart textiles that prioritize user comfort and needs will improve acceptance, ultimately helping to achieve the goals behind their creation.

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While these challenges present significant hurdles, ongoing innovations in materials, power sources, and design are rapidly addressing these limitations. The following section (13.2) outlines emerging solutions aimed at bridging current technological gaps and accelerating the adoption of smart textiles.

References

[1] J. S. Meena, S. B. Choi, S.-B. Jung, and J.-W. Kim, "Electronic textiles: New age of wearable technology for healthcare and fitness solutions," *Mater. Today Bio*, vol. 19, p. 100565, 2023.
[2] J. Zhang *et al.*, "The continuous fabrication of mechanochromic fibers," *J. Mater. Chem. C*, vol. 4, no. 11, pp. 2127–2133, 2016.
[3] E. O. Thorp, "The invention of the first wearable computer," in *Proc. 2nd Int. Symp. Wearable Comput.* (ISWC), Pittsburgh, PA, USA, 1998, pp. 4–8.
[4] H. L. O. Júnior, R. M. Neves, F. M. Monticeli, and L. Dall Agnol, "Smart fabric textiles: Recent advances and challenges," *Textiles*, vol. 2, no. 4, pp. 582–605, 2022.
[5] E. Ismar, S. Kurşun Bahadir, F. Kalaoglu, and V. Koncar, "Futuristic clothes: Electronic textiles and wearable technologies," *Global Challenges*, vol. 4, no. 7, Art. no. 1900092, 2020.
[6] T. Hughes-Riley, T. Dias, and C. Cork, "A historical review of the development of electronic textiles," *Fibers*, vol. 6, no. 2, Art. no. 34, 2018.
[7] X. Shi *et al.*, "Large-area display textiles integrated with functional systems," *Nature*, vol. 591, no. 7849, pp. 240–245, 2021.
[8] J. X. Wu and L. Li, "An introduction to wearable technology and smart textiles and apparel: Terminology, statistics, evolution, and challenges," in *Smart and Functional Soft Materials*. London, U.K.: IntechOpen, 2019.
[9] S. Rotzler, C. Kallmayer, C. Dils, M. von Krshiwoblozki, U. Bauer, and M. Schneider-Ramelow, "Improving the washability of smart textiles: Influence of different washing conditions on textile-integrated conductor tracks," *J. Text. Inst.*, vol. 111, no. 12, pp. 1766–1777, 2020.
[10] X. Tao, V. Koncar, T.-H. Huang, C.-L. Shen, Y.-C. Ko, and G.-T. Jou, "How to make reliable, washable, and wearable textronic devices," *Sensors*, vol. 17, no. 4, Art. no. 673, 2017.
[11] M. M. Hossain, M. M. Lubna, and P. D. Bradford, "Multifunctional and washable carbon nanotube-wrapped textile yarns for wearable e-textiles," *ACS Appl. Mater. Interfaces*, vol. 15, no. 2, pp. 3365–3376, 2023.
[12] K. Cherenack, C. Zysset, T. Kinkeldei, N. Münzenrieder, and G. Tröster, "Woven electronic fibers with sensing and display functions for smart textiles," *Adv. Mater.*, vol. 22, no. 45, pp. 5178–5182, 2010.
[13] K. Cherenack and L. Van Pieterson, "Smart textiles: Challenges and opportunities," *J. Appl. Phys.*, vol. 112, no. 9, Art. no. 091301, 2012.
[14] M. R. Hossain, M. R. Ahmed, and M. S. Alam, "Smart textiles," *Text. Prog.*, vol. 55, no. 2, pp. 47–108, 2023.
[15] J. McCann, R. Hurford, and A. Martin, "A design process for the development of innovative smart clothing that addresses end-user needs from technical, functional, aesthetic and cultural viewpoints," in *Proc. 9th IEEE Int. Symp. Wearable Comput.* (ISWC), Osaka, Japan, 2005, pp. 70–77.
[16] B. Ariyatum and R. Holland, "A strategic approach to new product development in smart clothing," in *Proc. 6th Asian Design Conf.*, Tsukuba, Japan, 2003, pp. 14–17.
[17] C. Wang, K. Xia, Y. Zhang, and D. L. Kaplan, "Silk-based advanced materials for soft electronics," *Acc. Chem. Res.*, vol. 52, no. 10, pp. 2916–2927, 2019.

Accepted Manuscript

[18] J. Li *et al.*, "Spider silk-inspired artificial fibers," *Adv. Sci.*, vol. 9, no. 5, Art. no. 2103965, 2022.
[19] N. Matsuhisa *et al.*, "Printable elastic conductors with high conductivity for electronic textile applications," *Nat. Commun.*, vol. 6, Art. no. 7461, 2015.
[20] F. Mokhtari, Z. Cheng, R. Raad, J. Xi, and J. Foroughi, "Piezofibers to smart textiles: A review on recent advances and future outlook for wearable technology," *J. Mater. Chem. A*, vol. 8, no. 19, pp. 9496–9522, 2020.
[21] Y.-W. Kim, K.-S. Kim, J.-H. Park, W.-J. Lee, J.-Y. Bae, and S.-K. Kang, "Fully biodegradable and mass-producible conductive fiber based on tungsten–poly(butylene adipate-co-terephthalate) composite," *npj Flexible Electron.*, vol. 9, no. 1, Art. no. 62, 2025.
[22] Z. Yuan *et al.*, "Biodegradable, robust, and conductive bacterial cellulose@PPy-P macrofibers as resistive strain sensors for smart textiles," *Carbohydr. Polym.*, vol. 349, Art. no. 122963, 2025.

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13.2 – Emerging Solutions for Smart Textiles and Wearables

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Status

The continued evolution of smart textiles and wearable technologies faces a range of technical and non-technical challenges, as detailed in the previous Section 13.1. However, innovation is rapidly advancing, offering new pathways to address these obstacles. This subsection focuses on emerging solutions and future-oriented solutions that aim to enhance the durability, energy efficiency, and sustainability of smart textiles, while also driving improvements in sensor integration, circular-economy practices, and regulatory frameworks.

1. Advanced Materials: Biohybrid, Adaptive, and Self-Healing Textiles

As highlighted in Section 13.1, ensuring washability and durability without compromising electronic functionality remains a central hurdle. Building on the hybrid fabrics and encapsulation strategies already deployed today, emerging material platforms move towards biohybrid, adaptive and self-healing textiles that can actively respond to their environment and repair damage.

A significant hurdle in smart textile development remains ensuring washability and durability without compromising electronic functionality. Emerging material solutions directly address this:

- **Hybrid and Biohybrid Fabrics:** Building on the conductive hybrid textiles described in Section 13.1, recent work combines conventional fibres with living or bio-derived components such as bacterial cellulose or engineering microbial biofilms to create fabrics that can self-heal micro-damage, respond to humidity or pH, and potentially host biosensing functions [1-3].

- **Adaptive and Self-Healing Polymers:** Self-healing coatings and adaptive polymer networks, originally developed for soft robotics, are being translated to textiles, enabling fabrics that can recover conductivity after cuts or abrasions and change stiffness or shape in response to temperature or electric fields [4, 5].

- **Next-Generation Conductive Fibres:** Fully biodegradable and conductive fibres such as those based on bio-derived polymers or transient electronic composites aim to combine high flexibility and conductivity with controlled degradation at end-of-life. These fibres can support sustainable e-textile design beyond the synthetic-fibre systems used today [6].

The progression of material durability in smart textiles over the past decade is illustrated in **Figure 38**. The figure demonstrates the steady improvements driven by innovations in carbon nanotube-

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based yarns and encapsulation technologies, with data sourced from Hossain et al. (2023)[7] and Tao et al. (2017)[8]. This upward trend reflects advancements in hybrid materials and structural resilience, which are critical for enhancing the longevity and reliability of smart textiles in real-world applications. These improvements are pivotal to overcoming one of the core limitations of early smart textiles—ensuring durability during repeated wash cycles and mechanical stress.

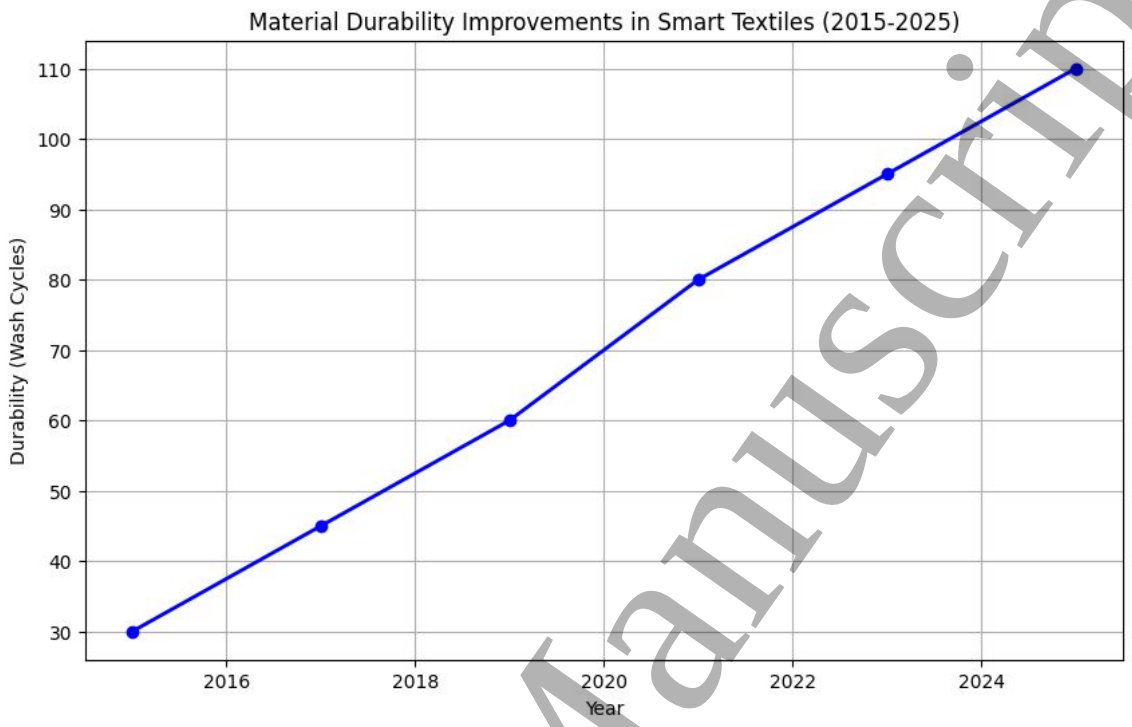


Figure 38: Material Durability Improvements in Smart Textiles (2015-2025). This figure highlights the steady progression in material durability of smart textiles over the past decade, driven by innovations in carbon nanotube-based yarns and encapsulation technologies. Data was adapted from the studies by Hossain et al.[7] and Tao et al.[8], which demonstrated enhanced durability metrics in repeated wash cycles and mechanical stress tests. The increase in durability is indicative of ongoing improvements in hybrid materials and structural resilience, pivotal to the commercialization and adoption of smart textiles in daily use.

2. Energy and Self-Powered Self-Textile Systems

Energy storage and management remain pivotal for smart textile reliability and user comfort. The following innovations are helping to overcome the limitations of conventional batteries:

- **Flexible and Printed Batteries:** Lightweight, printable batteries that conform to the shape of textile fibers are being developed, ensuring seamless integration without compromising aesthetics or flexibility[9].
- **Energy Harvesting Technologies:** Thermoelectric generators (TEGs), piezoelectric materials, and flexible solar textiles harness body heat, movement, and ambient light to generate energy, promoting sustainability by reducing the reliance on traditional power sources[10].
- **Micro-Supercapacitors:** Recent advances in micro-supercapacitor technology offer high energy density and fast charging, allowing smart textiles to store harvested energy more efficiently[11].

The comparative efficiency of key energy harvesting technologies is presented in **Figure 39**. The figure highlights into electricity, and while slightly less efficient than TEGs, they excel in applications involving high-motion activities, such as athletic gear and fitness trackers. Flexible solar textiles outperform both TEGs and piezoelectric materials, providing up to 50% efficiency by harnessing

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ambient light, making them suitable for outdoor and adventure wearables. Data compiled from Mokhtari et al. (2020)[10], Matsuhisa et al. (2015)[11] and Chen et al. (2020)[12] emphasize the increasing efficiency of these technologies, underscoring the transition toward self-powered and battery-independent wearable systems. This shift reduces reliance on conventional power sources and accelerates the adoption of more sustainable and eco-friendly smart textiles.

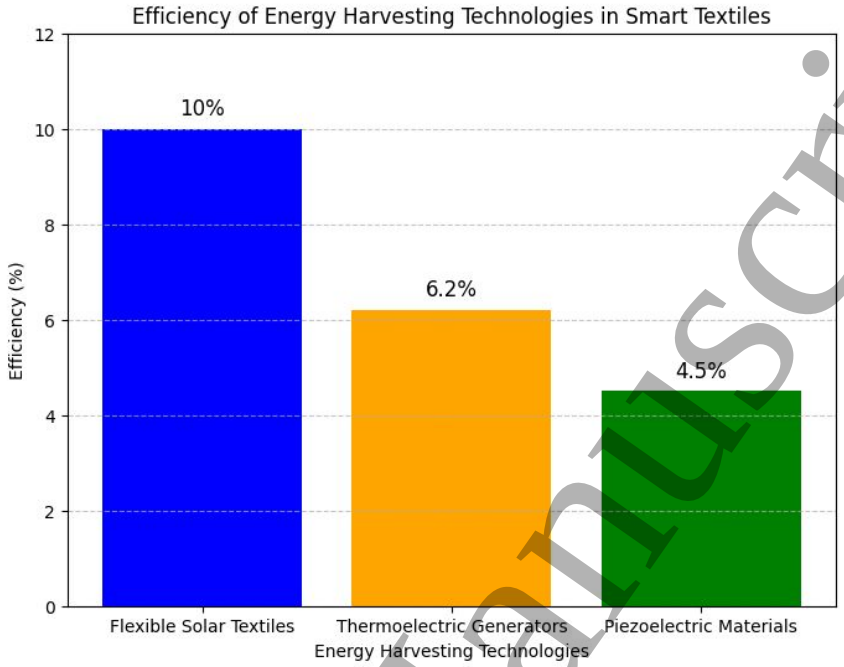


Figure 39: Efficiency of Energy Harvesting Technologies. This bar chart compares the efficiency of key energy harvesting technologies currently being integrated into smart textiles. Data has been compiled from Mokhtari et al.[10], Matsuhisa et al.[11], and Chen et al.[12] emphasizing the efficiency of thermoelectric generators (TEGs), piezoelectric materials, and flexible solar textiles. The rapid improvement in energy harvesting efficiency underscores the transition toward more sustainable and self-powered wearable technologies, reducing the dependency on conventional battery systems.

Beyond these individual technologies, recent roadmaps emphasize self-powered smart textiles in which energy harvesting and storage are distributed across the garment and managed by integrated power-management circuits [13]. Multi-source harvesters that combine body-heat, motion and ambient light, along with fibre-shaped batteries and textile micro-supercapacitors, point toward garments that can operate for long periods without conventional battery replacement, particularly in healthcare, industrial safety, and defense applications.

3. Sensor Integration and Data Accuracy

Reliable and accurate sensor data is crucial for the adoption of smart textiles. Where section 13.1 outlined how fabric deformation, wiring, and motion artefacts degrade signal quality, emerging solutions increasingly rely on material design and algorithms to compensate for these effects. New solutions enhance integration while maintaining comfort and minimizing interference:

- **Printed Sensors and Circuits:** Direct printing of sensors and circuits onto textiles eliminates the need for bulky attachments, significantly reducing overall weight and enhancing wearability [14].
- **AI-Driven Calibration:** Real-time data calibration through machine learning mitigates inaccuracies caused by fabric deformation, ensuring continuous and accurate monitoring [15].

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- **Stretchable Sensors:** Innovations in stretchable electronics enable the creation of sensors that expand and contract with the fabric, maintaining performance during motion or stretching [16].

4. Circular Economy and Sustainable Development

Addressing environmental concerns remains paramount in the evolution of smart textiles. Sustainability efforts focus on material development and recycling:

- **Biodegradable Conductive Materials:** Research into organic conductive polymers and silk-based fibers supports the creation of fully biodegradable smart textiles, minimizing environmental impact [17].
- **Closed-Loop Recycling Systems:** Developing systems that allow for the extraction and reuse of embedded electronic components facilitates the recycling of smart textiles, promoting circular economy principles [18].
- **Sustainable Manufacturing:** Processes such as waterless dyeing, 3D knitting, and low-energy manufacturing reduce the overall carbon footprint associated with smart textile production [19].

Recent reviews on sustainable e-textiles and flexible electronics highlight design frameworks such as the '4R' paradigm (repair, recycle, replace, reduce) and emphasize modular architectures and design-for-disassemble as key enablers of circularity in smart textiles [20-23]. Emerging recycling technologies including enzymatic depolymerization of synthetic fibres and bio-based fibre spinning platforms suggest that future systems may be able to recover both textile substrates and embedded electronics with significantly lower environmental impact than today's linear 'take-make-waste' models.

5. Regulatory and Standardization Efforts

Regulatory frameworks are evolving alongside technological advancements to ensure the safe and standardized development of smart textiles:

- **ASTM and ISO Standards:** Collaborative efforts between industry leaders and regulatory bodies are accelerating the development of international standards for smart textiles, facilitating market entry and ensuring consumer safety [24].
- **Interdisciplinary Consortia:** Partnerships between textile manufacturers, electronics companies, and regulatory agencies are fostering a harmonized approach to product development and compliance [25].

Looking ahead, smart textiles will be likely need to comply not only with safety and performance standards but also with emerging 'safe and sustainable by design' and digital product password frameworks, which are beginning to be proposed for nanotechnology enabled textiles and flexible electronics [23, 26].

6. Future Applications

As materials, energy systems, and circular-economy practices evolve, smart textiles are expected to expand into increasingly demanding applications. For example, in healthcare, biohybrid and self-powered garments could enable continuous monitoring of cardiovascular, metabolic, or dermatologic signals in outpatient settings, linked to AI-based triage systems [3, 13]. In sports and

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occupational performance, adaptive compression and temperature-regulating textiles may dynamically respond to exertion levels and environmental conditions [5, 27]. For environmental monitoring, self-powered textiles integrated into workwear, tents, or infrastructure could track air quality, noise, or structural health in a distributed manner, leveraging both local sensing and networked data fusion.

Concluding Remarks

The rapid advancements outlined in this subsection complement the challenges detailed in Section 13.1, offering actionable solutions that bridge current gaps in smart textile development. By integrating cutting-edge material science, sustainable practices, and interdisciplinary collaboration, the industry is poised to unlock new possibilities for healthcare, fitness, and everyday applications.

As these solutions mature, smart textiles will continue to redefine the intersection of technology and fashion, becoming a seamless part of daily life. Beyond enhancing personal health monitoring and convenience, these innovations will play a crucial role in fields such as remote patient care, sports performance optimization, and environmental sensing. The convergence of artificial intelligence, flexible electronics, and advanced energy systems will further drive the transition from prototype to large-scale commercialization, addressing key consumer needs for reliability, comfort, and sustainability.

Moving forward, fostering collaboration between academia, industry, and regulatory bodies will be essential to overcoming remaining barriers and accelerating the path to market-ready products. With continued investment and research, smart textiles are set to reshape how we interact with technology, offering transformative benefits across diverse sectors.

Acknowledgments

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References

[1] A. Cai, Z. Abdali, D. J. Saldanha, M. Aminzare, and N.-M. Dorval Courchesne, “Endowing textiles with self-repairing ability through the fabrication of composites with a bacterial biofilm,” *Sci. Rep.*, vol. 13, no. 1, Art. no. 11389, 2023.
[2] M. Shin, J. Lim, J. An, J. Yoon, and J.-W. Choi, “Nanomaterial-based biohybrid hydrogel in bioelectronics,” *Nano Converg.*, vol. 10, no. 1, Art. no. 8, 2023.
[3] H. Wu *et al.*, “Smart textiles with living interfaces: Microbiome–electronics integration for advanced skin health management,” *Adv. Fiber Mater.*, pp. 1–39, 2025.
[4] M. A. Islam *et al.*, “A review on self-healing featured soft robotics,” *Front. Robot. AI*, vol. 10, Art. no. 1202584, 2023.
[5] M. A. Sarwar, N. Stampone, and M. Usman, “From static to adaptive: A systematic review of smart materials and 3D/4D printing in the evolution of assistive devices,” *Actuators*, vol. 14, no. 10, Art. no. 483, 2025.
[6] Z. Yuan *et al.*, “Biodegradable, robust, and conductive bacterial cellulose@PPy-P macrofibers as resistive strain sensors for smart textiles,” *Carbohydr. Polym.*, vol. 349, Art. no. 122963, 2025.
[7] M. M. Hossain, M. M. Lubna, and P. D. Bradford, “Multifunctional and washable carbon nanotube-wrapped textile yarns for wearable e-textiles,” *ACS Appl. Mater. Interfaces*, vol. 15, no. 2, pp. 3365–3376, 2023.

Accepted Manuscript

[8] X. Tao, V. Koncar, T.-H. Huang, C.-L. Shen, Y.-C. Ko, and G.-T. Jou, "How to make reliable, washable, and wearable textronic devices," *Sensors*, vol. 17, no. 4, Art. no. 673, 2017.
[9] K. Cherenack and L. Van Pieterson, "Smart textiles: Challenges and opportunities," *J. Appl. Phys.*, vol. 112, no. 9, Art. no. 091301, 2012.
[10] F. Mokhtari, Z. Cheng, R. Raad, J. Xi, and J. Foroughi, "Piezofibers to smart textiles: A review on recent advances and future outlook for wearable technology," *J. Mater. Chem. A*, vol. 8, no. 19, pp. 9496–9522, 2020.
[11] N. Matsuhisa *et al.*, "Printable elastic conductors with high conductivity for electronic textile applications," *Nat. Commun.*, vol. 6, Art. no. 7461, 2015.
[12] G. Chen, Y. Li, M. Bick, and J. Chen, "Smart textiles for electricity generation," *Chem. Rev.*, vol. 120, no. 8, pp. 3668–3720, 2020.
[13] B. K. Dejene, "The future of fabric: A comprehensive review of self-powered smart textiles and their emerging applications," *Energy Rep.*, vol. 14, pp. 898–943, 2025.
[14] S. de Mulatier, M. Nasreldin, R. Delattre, M. Ramuz, and T. Djenizian, "Electronic circuits integration in textiles for data processing in wearable technologies," *Adv. Mater. Technol.*, vol. 3, no. 10, Art. no. 1700320, 2018.
[15] Z. Jin, Z. Zhang, and G. X. Gu, "Automated real-time detection and prediction of interlayer imperfections in additive manufacturing processes using artificial intelligence," *Adv. Intell. Syst.*, vol. 2, no. 1, Art. no. 1900130, 2020.
[16] A. Jafari, "Stretchable electronics: Advances in elastic conductive fibers for multifunctional applications," *Org. Electron.*, Art. no. 107145, 2024.
[17] X.-C. Yang *et al.*, "Silk-based intelligent fibers and textiles: Structures, properties, and applications," *Chem. Commun.*, vol. 60, no. 61, pp. 7801–7823, 2024.
[18] M. M. Sarkhoshkalat, A. Afkham, M. Bonyadi Manesh, and M. Sarkhosh, "Circular economy and the recycling of e-waste," in *New Technologies for Energy Transition Based on Sustainable Development Goals*. Cham, Switzerland: Springer, 2024, pp. 319–354.
[19] M. T. Rahaman, A. D. Pranta, M. R. Repon, M. S. Ahmed, and T. Islam, "Green production and consumption of textiles and apparel: Importance, fabrication, challenges and future prospects," *J. Open Innov. Technol. Mark. Complex.*, Art. no. 100280, 2024.
[20] N. Perera *et al.*, "Exploring sustainable approaches for electronic textile products and prototypes," *Sensors*, vol. 24, no. 17, Art. no. 5472, 2024.
[21] H. H. Shi *et al.*, "Sustainable electronic textiles towards scalable commercialization," *Nat. Mater.*, vol. 22, no. 11, pp. 1294–1303, 2023.
[22] E. Skrzetuska and P. Rzeźniczak, "Circularity of smart products and textiles containing flexible electronics: Challenges, opportunities, and future directions," *Sensors*, vol. 25, no. 6, Art. no. 1787, 2025.
[23] M. G. Tadesse, M. T. Abate, J. F. Lübben, and M. Rauch, "Recycling and sustainable design for smart textiles—A review," *Adv. Sustain. Syst.*, Art. no. 2401072, 2025.
[24] I. Furxhi *et al.*, "A roadmap towards safe and sustainable by design nanotechnology: Implementation for nano-silver-based antimicrobial textile coatings production by ASINA project," *Comput. Struct. Biotechnol. J.*, 2024.
[25] N. P. Dalbanjan *et al.*, "Descriptive review on conversion of waste residues into valuable bionanocomposites for a circular bioeconomy," *Nano-Struct. Nano-Objects*, vol. 39, Art. no. 101265, 2024.
[26] M. Dulal *et al.*, "Toward sustainable wearable electronic textiles," *ACS Nano*, vol. 16, no. 12, pp.

Accepted Manuscript

19755–19788, 2022.
[27] S. Xu, X. Fan, S. Chen, F. Manshaii, J. Yin, and J. Chen, “Advances in luminescent fibers for interactive smart textiles,” *cMat*, vol. 1, no. 3, Art. no. e33, 2024.

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Section 14: Roadmap Priorities and Time-Horizon Actions

Rather than reiterating previously discussed challenges, this section outlines prioritized roadmap actions across short- (3–5 year) and mid- to long-term (5–10 year) horizons, focusing on translational milestones, regulatory readiness, and large-scale deployment of textile-integrated health technologies.

14.1 – Future Directions and Emerging Trends in E-Textiles

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Status

Advances in materials have anticipated a new era where purely textile devices can sense, transmit information, and power themselves in comfortable packages indistinguishable from ordinary clothing. Printing of conductive traces and functional layers is a standard technique for flexible circuits. However, a shift to textile-based substrates often precludes existing printing techniques to be used for creation of devices in fabric. Cloth is non-homogeneous and is made of myriad individual fibres, each flexible and often also stretchable. This fact makes the application of rigid components and materials in textile undesirable; this includes use of traditional conductive inks required for construction of sensors and interconnects. The repeating and hierarchical structure of fabric can be cleverly utilized to overcome this problem. Simple electronic devices like resistors, capacitors, and inductors can be produced as fibres and further permuted into complex patterns using textile processes to unlock sophisticated functions while maintaining the ease of mass production. Recent advances use weaving to produce complete integrated circuits made fully in textiles [1]. Methods to produce printed circuit board (PCB)-like traces and interconnects on woven and knitted fabrics show high promise in wearable sensing [2]. Photolithography, a process that was previously mostly reserved for rigid substrates, has now been adapted for textiles and enables unprecedented resolution for production of electronic patterns and miniaturized electrochemical sensors [3].

More advanced electronic components have been developed in form of fabrics and textiles: antennas, power generators, diodes, and more. Whereas conventional batteries contrast with the goals of lightweight, unobtrusive fabric electronic devices, wireless power transmission and energy harvesting are promising candidates to eliminate rigid batteries and their associated connections. Harvesting sustainable electrical energy from wasted mechanical energy, electromagnetic energy, or thermal energy to power highly efficient textile electronics has recently become an area of intensive research.

In this roadmap, we focus on sensing, wireless transmission of data and power, self-powered textile devices, and applications of these in sports and health. For each, we identify the main challenges with developing the technology. We identify some recent advances in materials and processes which

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have promise to address these challenges and further the progress of wearable all-textile electronic systems. **Figure 40** summarizes these core technology pillars—strain sensing, wireless readout, and energy harvesting—and illustrates their convergence toward fully integrated, self-powered e-textile systems.

Current and Future Challenges

Sensing

Two major applications of sensing in textile devices are that of mechanically transduced signals and those measured electrochemically. Using textile strain sensors placed along joints is well established for human kinematics measurements. To approach the accuracy of inertial measurement units and optical motion capture, clusters of sensors are often required, which bring challenges with connecting and interfacing large textile sensor arrays. Resulting data must be processed by models to yield kinematics estimations. Despite the progress in machine learning, model performance degrades sharply when generalizing between individuals. Electrochemical sensors produced on textiles are most often utilized to analyse sweat, as this biofluid is probably the most readily available analytical medium that contacts garments [4]. The micro-scale pores formed by intersection of textile fibres can have a microfluidic effect that aids in sweat collection and flow-through analysis [5]. Textile electrochemical cells have been produced with embroidery techniques [6], but challenges persist especially for sweat sensing, where corrosion, degradation during washing, and resilience of the device are obstacles to practical use.

Wireless Transmission of Data and Power

As sensing solutions using textiles become denser and more integrated, the need for reliable, high-bandwidth data transmission increases. Wireless transmission of data is favourable because the wearable device can receive power and transmit information to a receiver placed in a pocket, decoupled from the garment for easy washing. Many current solutions require integrated circuits on the garment side that use digital communication protocols such as radio frequency identification (RFID) [7]. Passive resonators using inductive coupling eliminate rigid electronics on the garment [8]. However, passive methods currently have poor spectrum efficiency and require expensive and bulky readout devices [9]. There is a need for a wireless readout system that maximally avoids rigid devices yet allows efficient transmission of data and power.

Self-Powered Textile Devices

Due to the varying availability of different types of energy in environments, it is necessary to develop diverse energy harvesters. Designing textile circuits that are compatible with fabric characteristics and can rectify AC signals to power subsequent devices presents a significant challenge.

Applications and Adoption

The long-term monitoring of bio-signals throughout daily life provides great value in healthcare. In this area, the use of conductive textile as soft electrodes for the acquisition of ECG and EMG is of great interest [10]. The requirement for low electrical impedance between the skin and the textile electrodes is a challenge in the presence of dynamic movements of daily life. There have been recent

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efforts to address this challenge by improving the adherence of dry electrodes to the skin, but these still require tight fitting garments.

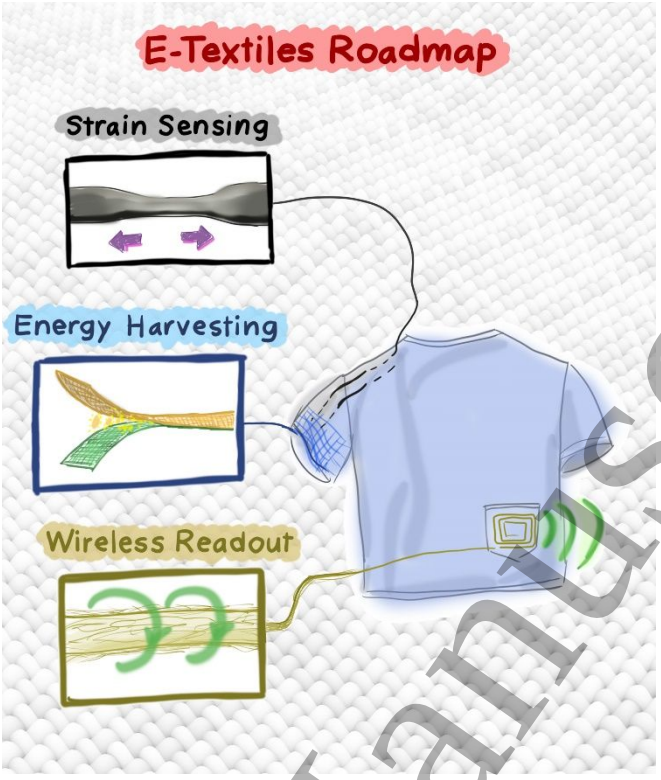


Figure 40. Key technologies for the development of e-textiles.

Advances in Science and Technology to Meet Challenges

Sensing

The development of soft strain and pressure sensor materials is reasonably mature, with the realization of highly sensitive fibres with excellent linearity possible using many techniques. The challenge of increasing sensor array density and processing the data is less addressed. Distributed arrays promise to both reduce the need for connections to many sensing elements [11] and increase the amount of information acquired from sensors. For example, a 2D strain map can be estimated from a resistive mesh sensor network with perimeter connections [12]. Another recent work uses sensing films directly printed on the skin to infer hand gesture and even classify the shape of an object being manipulated [13]. The authors use few-shot learning to rapidly calibrate the prediction model to new tasks or subjects, which is a step towards solving the problem of generalizing between subjects. The fibre structure in textiles enables distributed arrays of multiplexed electrochemical sensors, where a single thread comprises a functional electrode for detection of multiple analytes [14].

Wireless Transmission of Data and Power

Current approaches to improve the practicality of all-textile wireless readout include fine tuning the operating frequency of passive resonators by manipulating their dielectric materials [15]. Recent advances include human body coupling of textile based electronic fibres [16]. Other solutions use passive and chip-less textile RFID tags changing their property based on stimuli like bending, stretching, or temperature. However, signals from these RFID antennas can be corrupted by perturbations both from folds in the garments or external electromagnetic fields [17]. These

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approaches combined with improved RF modelling of the entire textile system are of interest for the coming years.

Self-Powered Textile Devices

Currently, researchers have begun to fabricate transducer devices on fabrics and have achieved environmental energy harvesting. For example, semiconducting materials have been embedded onto fabrics to convert energy dissipated by friction into rectified electrical energy [18]. These textile devices exhibit excellent flexibility, stability, and comfort. Additionally, others have integrated radio frequency energy and solar energy harvesting devices to power wearable electronics [19]. The direction of progress in self-powered devices is toward flexible energy harvesting from a variety of sources to improve power density and conversion efficiency.

Applications and Adoption

The sports market is growing application of textile electronics evidenced by products such as smart socks, smart shirts, and smart insoles used for the monitoring of movement and heart rate in recreational and professional sports. Particularly for monitoring electrical bio-signals, developments in dry adhesives based on hierarchical structures may address the difficulties of obtaining reliable conductivity with textile electrodes [20].

Concluding Remarks

Despite recent advancements in advanced functional textiles, their adoption in daily life remains limited. Smart clothing needs to be washable, mechanically robust, and sustainably manufacturable at high scale and low price. Many of these needs are more easily met with maximally textile devices. The increased availability of novel materials in fibre and fabric form and advances in manufacturing could enable further solutions in self-powered, and passive sensing systems with wireless data communication.

- Electrochemical and strain sensing stand to benefit from high-density arrays of sensors with their data processed by improved models.
- Wireless transmission of data, ideally avoiding rigid circuits, improves washability and makes e-textile garments feel like their non-functionalized counterparts.
- The application of new materials to enable rectifying electrical junctions in soft substrates allows energy harvesting from sliding motion, electromagnetic fields, and temperature gradients to power the textile system.

Together, these developments driven by materials advances set the direction of e-textile research toward intelligent, fully textile devices that are nearly indistinguishable from ordinary clothing.

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References

[1] Y. Yang et al., “A non-printed integrated-circuit textile for wireless theranostics,” Nat. Commun., vol. 12, no. 1, pp. 1–10, 2021, doi: 10.1038/s41467-021-25075-8.

[2] X. Ma et al., “A monolithically integrated in-textile wristband for wireless epidermal biosensing,” Sci. Adv., vol. 9, no. 45, pp. 1–10, 2023, doi: 10.1126/sciadv.adj2763.

Accepted Manuscript

[3] P. Wang et al., "Well-defined in-textile photolithography towards permeable textile electronics," Nat. Commun., vol. 15, no. 1, p. 887, 2024, doi: 10.1038/s41467-024-45287-y.

[4] D. Luo, H. Sun, Q. Li, X. Niu, Y. He, and H. Liu, "Flexible Sweat Sensors: From Films to Textiles," ACS Sensors, vol. 8, no. 2, pp. 465–481, 2023, doi: 10.1021/acssensors.2c02642.

[5] H. Zhao, L. Zhang, T. Deng, and C. Li, "Microfluidic Sensing Textile for Continuous Monitoring of Sweat Glucose at Rest," ACS Appl. Mater. Interfaces, vol. 16, no. 15, pp. 19605–19614, 2024, doi: 10.1021/acsami.4c01912.

[6] X. Liu and P. B. Lillehoj, "Embroidered electrochemical sensors for biomolecular detection," Lab Chip, vol. 16, no. 11, pp. 2093–2098, 2016, doi: 10.1039/c6lc00307a.

[7] X. Tian et al., "Wireless body sensor networks based on metamaterial textiles," Nat. Electron., vol. 2, no. 1, pp. 243–251, 2019, doi: 10.1038/s41928-019-0257-7.

[8] V. Galli, S. K. Sailapu, T. J. Cuthbert, C. Ahmadizadeh, B. C. Hannigan, and C. Menon, "Passive and Wireless All-Textile Wearable Sensor System," Adv. Sci., vol. 10, no. 22, pp. 1–13, 2023, doi: 10.1002/advs.202206665.

[9] A. Hajiaghajani and P. Tseng, "Microelectronics-Free, Augmented Telemetry from Body-Worn Passive Wireless Sensors," Adv. Mater. Technol., vol. 6, no. 4, pp. 1–9, 2021, doi: 10.1002/admt.202001127.

[10] D. Pani, A. Dessi, J. F. Saenz-Cogollo, G. Barabino, B. Fraboni, and A. Bonfiglio, "Fully Textile, PEDOT:PSS Based Electrodes for Wearable ECG Monitoring Systems," IEEE Trans. Biomed. Eng., vol. 63, no. 3, pp. 540–549, 2016, doi: 10.1109/TBME.2015.2465936.

[11] B. C. Hannigan, T. J. Cuthbert, C. Ahmadizadeh, and C. Menon, "Distributed sensing along fibers for smart clothing," Sci. Adv., vol. 10, no. 12, pp. 1–12, 2024, doi: 10.1126/sciadv.adj9708.

[12] Y. A. Lin et al., "Graphene K-Tape Meshes for Densely Distributed Human Motion Monitoring," Adv. Mater. Technol., vol. 6, no. 2000861, 2021, doi: 10.1002/admt.202000861.

[13] K. K. Kim et al., "A substrate-less nanomesh receptor with meta-learning for rapid hand task recognition," Nat. Electron., vol. 6, no. 1, pp. 64–75, 2022, doi: 10.1038/s41928-022-00888-7.

[14] E. Jacquet, J. Chambert, J. Pauchot, and P. Sandoz, "Intra- and inter-individual variability in the mechanical properties of the human skin from in vivo measurements on 20 volunteers," Ski. Res. Technol., vol. 23, no. 4, pp. 491–499, 2017, doi: 10.1111/srt.12361.

[15] P. Tseng, B. Napier, L. Garbarini, D. L. Kaplan, and F. G. Omenetto, "Functional, RF-Trilayer Sensors for Tooth-Mounted, Wireless Monitoring of the Oral Cavity and Food Consumption," Adv. Mater., vol. 30, no. 18, pp. 1–7, 2018, doi: 10.1002/adma.201703257.

[16] W. Yang et al., "Single body-coupled fiber enables chipless textile electronics," Science (80-.)., vol. 384, no. 6691, pp. 74–81, 2024, doi: 10.1126/science.adk3755.

[17] S. K. Behera, "Chipless RFID Sensors for Wearable Applications: A Review," IEEE Sens. J., vol. 22, no. 2, pp. 1105–1120, 2022, doi: 10.1109/JSEN.2021.3126487.

[18] J. Meng et al., "Flexible Textile Direct-Current Generator Based on the Tribovoltaic Effect at Dynamic Metal-Semiconducting Polymer Interfaces," ACS Energy Lett., vol. 6, no. 7, pp. 2442–2450, 2021, doi: 10.1021/acsenergylett.1c00288.

[19] B. Naresh, V. K. Singh, and V. K. Sharma, "Integration of RF rectenna with thin film solar cell to power wearable electronics," Int. J. Microw. Wirel. Technol., vol. 13, no. 1, pp. 46–57, 2021, doi: 10.1017/S1759078720000410.

[20] M. P. Murphy, S. Kim, and M. Sitti, "Enhanced adhesion by gecko-inspired hierarchical fibrillar adhesives," ACS Appl. Mater. Interfaces, vol. 1, no. 4, pp. 849–855, 2009, doi: 10.1021/am8002439.

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14.2 – Biohybrid and Sustainable Smart Textiles: Pioneering the Next Generation

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Status

The evolving landscape of intelligent textiles is expanding beyond traditional electronic integration, steering towards biohybrid materials, environmentally responsive fabrics, and sustainable designs that dynamically react to environmental and physiological stimuli [1]. As global priorities shift towards eco-conscious development and circular economy models, the textile industry is increasingly adopting biodegradable, self-healing, and bioengineered solutions that minimize environmental impact while enhancing functionality [2]. This section highlights these transformative trends, paving the way for the future of wearables that seamlessly merge biological processes with advanced materials for enhanced adaptability and user experience.

1. Biohybrid and Living Materials: Blending Biology with Textiles

One of the most radical advancements in textiles involves biohybrid materials—that is, integrating living cells, bacteria, and proteins into fabric matrices [3]. Such materials hold promise for providing dynamic functionality such as wound healing, chemical detection, and moisture regulation, making them ideal for healthcare, sports, and environmental monitoring.

- **Living Textile Sensors:** Biohybrid fibers embedded with microbial sensors can detect harmful pathogens or pollutants in the air, offering a proactive approach to health monitoring. For example, fabrics infused with genetically modified bacteria fluoresce in the presence of toxins or allergens [4].
- **Self-Regenerating Textiles:** Inspired by natural processes, researchers are developing materials that mimic skin regeneration. Textiles integrated with fibroblast cells can repair small tears or abrasions autonomously, significantly extending product lifespan and reducing waste [5].
- **Moisture-Responsive Garments:** Hydrogels or protein-based fibers embedded in garments enable fabrics to absorb or release moisture based on humidity levels, improving comfort and preventing overheating during physical activity [6].

2. Shape-Memory and Adaptive Textiles: Responsive to External Stimuli

Adaptive textiles represent the convergence of materials science and engineering, allowing garments to change shape, stiffness, or permeability in response to environmental factors.

- **Thermoresponsive Polymers:** These polymers expand or contract at different temperatures, enabling garments to adjust ventilation or insulation based on weather conditions [7].
- **Shape-Memory Alloys:** Integrated into compression garments or orthopedic wearables, these alloys allow textiles to dynamically tighten or loosen depending on muscle movement or body position [8].

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- **Mechanical Actuation in Textiles:** By embedding soft actuators into fabric, designers can create garments that adjust posture, provide muscle support, or deliver targeted compression without external power sources [9].

3. Circular Economy and Fully Recyclable Textiles

A significant shift in the textile industry revolves around achieving a closed-loop system—producing textiles that are not only recyclable but capable of being fully disassembled and repurposed.

- **Modular Textile Sensors:** Unlike single-use smart garments, modular sensors and detachable circuits are designed to be removed and reused in new garments, aligning with sustainable product lifecycle [10].
- **Biodegradable Conductors:** Researchers are developing conductors made from plant-based polymers and silk-derived threads that decompose naturally, leaving minimal environmental impact [11].
- **Textile Upcycling Programs:** Manufacturers are investing in initiatives that allow users to return worn smart garments for disassembly and reprocessing, contributing to a more sustainable consumer model [12].

4. Smart Textiles for Environmental Interaction

Smart textiles are increasingly being developed to interact with environmental conditions and provide insights into wearers' surroundings. Textiles can serve purposes beyond personal health, such as climate-resilient fabrics and pollution-detecting garments.

- **Air Quality Monitoring Textiles:** Embedded with electrochemical threads, these fabrics can track pollutants, greenhouse gases, and particulate matter, providing real-time feedback to users and researchers [13].
- **Solar-Powered Textiles:** Advanced lightweight photovoltaic fibers allow garments to collect solar energy, enabling long-term outdoor wearables without reliance on external power [14].
- **Erosion-Detecting Fabrics:** Specialized textile membranes embedded in soil or infrastructure monitor erosion, water flow, and material stress, expanding the role of textiles in environmental preservation [15].

5. Future Directions in Sustainable Textiles

The next phase of textile innovation is driven by cross-disciplinary collaboration between biologists, materials scientists, and engineers, exploring textile technologies that harmonize with nature rather than disrupt it.

- **Probiotic-Infused Garments:** Researchers are investigating textiles that release probiotics beneficial to skin health or antimicrobial treatments that maintain hygiene without chemical additives [16].
- **Enzyme-Embedded Fibers:** Textiles integrated with enzymes that break down pollutants or stains provide self-cleaning garments, reducing the need for frequent washing and conserving water [17].
- **Fungal-Based Fabrics:** Mycelium, the root structure of fungi, is emerging as a sustainable material capable of forming flexible, durable, and fully biodegradable garments [18].

Conclusion

Biodegradable, biohybrid, and shape-adaptive textiles are promising for the next generation of

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wearable technology. By integrating living cells, renewable materials, and modular designs, the future of textiles offers not only enhanced functionality but also minimal environmental impact and greater alignment with sustainable goals. This evolution reflects a holistic approach to textile innovation, where the boundaries between technology, biology, and materials science continue to blur.

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References

[1] A. Ighodaro, J. A. Osarobo, I. C. Onuguh, O. K. Ogbeide, and I. H. Ifijen, “Title not specified,” in Proc. TMS Annu. Meeting & Exhibition, Springer, pp. 877–896.
[2] C. Popescu, H. Dissanayake, E. Mansi, and A. Stancu, “Eco breakthroughs: Sustainable materials transforming the future of our planet,” Sustainability, vol. 16, Art. no. 10790, 2024.
[3] X. Hu, B. Lei, S. S. Li, L. J. Chen, and Q. Li, “Living cell-laden hydrogels: Unleashing the future of responsive biohybrid systems,” Responsive Materials, vol. 1, Art. no. e20230009, 2023.
[4] A. Rodrigo-Navarro, S. Sankaran, M. J. Dalby, A. del Campo, and M. Salmeron-Sanchez, “Engineered living biomaterials,” Nat. Rev. Mater., vol. 6, pp. 1175–1190, 2021.
[5] H. Zhang et al., “Skin-inspired, fully autonomous self-warning and self-repairing polymeric material under damaging events,” Chem. Mater., vol. 31, pp. 2611–2618, 2019.
[6] S. An et al., “Biological and bioinspired thermal energy regulation and utilization,” Chem. Rev., vol. 123, pp. 7081–7118, 2023.
[7] R. Liu et al., “Adaptive dynamic smart textiles for personal thermal–moisture management,” Eur. Polym. J., Art. no. 112777, 2024.
[8] R. Srivastava, S. H. Alsamhi, N. Murray, and D. Devine, “Shape memory alloy-based wearables: A review and conceptual frameworks on HCI and HRI in Industry 4.0,” Sensors, vol. 22, Art. no. 6802, 2022.
[9] A. Golgouneh and L. E. Dunne, “A review of on-body compression using soft actuators and sensors: Applications, mechanisms, and challenges,” IEEE Rev. Biomed. Eng., vol. 17, pp. 166–179, 2022.
[10] H. H. Shi et al., “Sustainable electronic textiles towards scalable commercialization,” Nat. Mater., vol. 22, pp. 1294–1303, 2023.
[11] K. Dušek, D. Koc, P. Veselý, D. Froš, and A. Géczy, “Biodegradable substrates for rigid and flexible circuit boards: A review,” Adv. Sustain. Syst., Art. no. 2400518, 2024.
[12] M. Saif et al., “Navigating legislative interventions, challenges, and opportunities in revolutionizing textile upcycling/recycling processes for a circular economy,” ACS Sustain. Resour. Manag., 2024.
[13] S. Hooshmand et al., “Wearable nano-based gas sensors for environmental monitoring and challenges in optimization,” Sensors, vol. 23, Art. no. 8648, 2023.
[14] I. Ali et al., “Advances in smart photovoltaic textiles,” ACS Nano, vol. 18, pp. 3871–3915, 2024.
[15] A. Aldalbahi et al., “Effects of technical textiles and synthetic nanofibers on environmental pollution,” Polymers, vol. 13, Art. no. 155, 2021.
[16] R. Broadhead, L. Craeye, and C. Callewaert, “The future of functional clothing for an improved skin and textile microbiome relationship,” Microorganisms, vol. 9, Art. no. 1192, 2021.

Accepted Manuscript

[17] S. Afroz et al., “Title not specified,” in Fundamentals of Natural Fibres and Textiles, Elsevier, pp. 557–597, 2021.
[18] C. Madusanka et al., “A review of recent advances in fungal mycelium-based composites,” Discover Materials, vol. 4, Art. no. 13, 2024.

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Section 15: Conclusion

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Summary of Key Findings

The roadmap on wearable and textile innovations outlines the rapid evolution and growing maturity of technologies that merge flexible electronics with fabrics to enable personalized, non-invasive, and continuous health monitoring. Across multiple sections, the paper identifies significant advancements in sensing technologies, energy harvesting, data analytics, and AI integration. Applications span diverse fields—from chronic disease management and mental health monitoring to functional rehabilitation and remote diagnostics—underscoring the versatility and transformative potential of smart textiles.

Implications for the Future

The convergence of biotechnology, materials science, and machine learning in wearable systems offers a clear trajectory toward decentralized, real-time healthcare. However, critical barriers persist: scalability, long-term biocompatibility, regulatory clarity, and affordability. Future developments must focus not only on performance but also on inclusivity, sustainability, and ethical deployment. Clinical-grade validation, AI fairness, and cross-platform interoperability will be central to securing trust and adoption across both high-resource and underserved settings.

Final Thoughts and Recommendations

To fully unlock the potential of wearable and textile innovations, we recommend:

1. Interdisciplinary collaboration between academia, industry, and regulatory bodies to accelerate translation from lab to clinic.
2. Standardization efforts to ensure consistency in sensor performance, data formats, and integration with healthcare IT systems.
3. Sustainable practices in materials sourcing and product lifecycle management, minimizing environmental footprint.
4. Proactive regulatory frameworks that evolve with technology and emphasize safety, data privacy, and inclusivity.
5. Investment in open-source platforms and scalable manufacturing to democratize access to next-generation health technologies.

Ultimately, wearable and textile systems stand at the forefront of personalized medicine and digital health. With responsible innovation, these technologies are poised to transform the global healthcare landscape, making it smarter, fairer, and more human-centered

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