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Editorial

Biomaterials innovations and challenges for wearable bioelectronic devices

The rapid convergence of biomaterials science, nanotechnology, and wearable electronics is redefining how we monitor, diagnose, and treat human diseases. Biomaterials have been widely investigated as injectable, implantable, and wearable systems for diagnostic, therapeutic, and theranostic applications. With rapid advances in nanobiotechnology, wearable bioelectronic devices have recently attracted particular attention due to patient compliance. This special issue highlights recent advances in four connected categories: (i) bio and nano materials innovations that provide the foundation for wearable bioelectronic devices, (ii) theranostic devices targeting diabetes management, sweat diagnostics, and wound healing, (iii) respiratory devices motivated by pandemic-driven needs, and (iv) platforms that extend wearables into textile-based motion recognition and physiologically relevant tissue models (Fig. 1). The articles together show how material design, device engineering, and biological integration advance the field of wearable bioelectronics, while also pointing to the translational challenges that remain.

1. Material foundations for reliable wearables

A robust framework for wearable devices begins with materials design. J. Koo and coworkers survey polymers, semiconductors, metals, and hybrids for organ-specific sensing, and emphasize multimodal integration, reliability in long-term use, and autonomy in power and communication [1]. Their organ-oriented view complements two biomaterials-focused reviews that analyze how the interface to skin and eye can be made both durable and comfortable.

C. H. Lee and coworkers highlight hydrogels, fibers, and hybrid materials as reliable interfaces for skin- and eye-mounted devices, focusing on stability, washability, and attachment methods that maintain performance under sweat, motion, and environmental variation [2]. T.–I. Kim and colleagues extend this perspective by detailing multifunctional hydrogel chemistry—stimuli-responsive, self-healing, conductive, and adhesive systems—that bridge soft tissues and electronic components and enable patterning and monolithic integration strategies that are compatible with bioelectronic fabrication [3]. Finally, T.–W. Lee and coworkers address sustainability and tissue compatibility by showing how natural polymers such as cellulose, silk fibroin, and chitosan can support neuromorphic and biodegradable devices, aligning bioelectronics with ecological goals while improving mechanical matching with soft tissues [4].

These foundational reviews emphasize that hydrogels and other soft composites are central to wearable bioelectronics because they provide tissue-like mechanics and support both ionic and electronic conduction. At the same time, they identify interface durability as a persistent challenge, since long-term adhesion and stability under physiological conditions remain difficult to achieve. Finally, they highlight the importance of scalable, batch-consistent manufacturing, which will ultimately determine which material platforms can progress beyond laboratory prototypes and achieve clinical translation.

2. Theranostic devices for diabetes, sweat analytics, and wound healing

2.1. Multifunctional nanomaterials for diabetes care

S. K. Hahn and coworkers review multifunctional nanomaterials for smart diabetic healthcare devices that integrate continuous glucose monitoring with targeted delivery for intervention [5]. Metal, carbon, polymeric, and hybrid nanomaterials enable selective sensing in tears, sweat, saliva, and interstitial fluid, and can be combined with on-demand drug release and wireless data links. Their review also articulates key translational questions that mirror those in our summary: relationships between blood glucose and other biofluids, lag times that can confound clinical interpretation, and the need for encapsulation and interface materials that resist friction and contamination in daily use. They also discuss photo-biomodulation as a noninvasive adjunct for glucose control, where near-infrared light penetration enables theranostic strategies with low systemic side effects.

2.2. Eliminating interference in sweat sensing

Reliable epidermal sensing depends on separating sweat from confounding secretions. Y. Lin and coworkers present a flexible biosensing patch that integrates a dual-layer hydrogel filtering membrane—poly (hydroxyethyl methacrylate) with nano-brush poly(sulfobetaine)—and Tesla-valve microfluidic channels for unidirectional flow [6]. This architecture removes serum and serum-soluble interferents, refreshes sweat at the sensing site, and improves accuracy for uric acid, pH, and sodium by up to 12 percent. The design demonstrates how hydrogel surface chemistry, antifouling brushes, and passive microfluidics can be combined to address a specific, real-world failure mode in on-body sensing.

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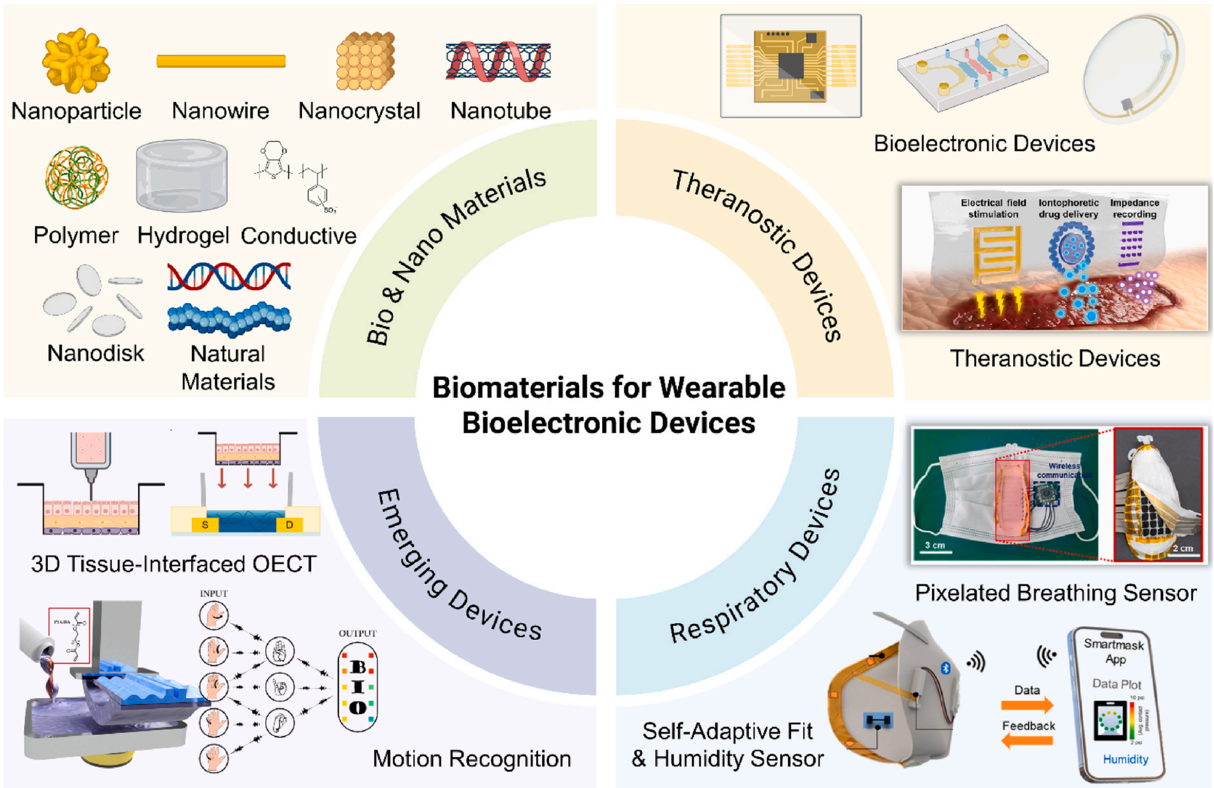

Fig. 1. Biomaterials for wearable bioelectronic devices. Adapted with permission from Refs. 7, 8, 9, 10, 11. Schematic illustration was created by Biorender.com.

2.3. *Hydrogel E-skin for wound therapy and monitoring*

Moving from diagnostics to therapy, D.–H. Kim and coworkers report a hydrogel electronic skin patch that accelerates wound healing and monitors tissue status in vivo [7]. The system integrates photolithography-compatible functional hydrogels: a PHEA substrate, Ag-flake hydrogel interconnects, PEDOT:PSS hydrogel electrodes, polydopamine adhesive, and PVA encapsulation. Electric field stimulation and iontophoretic delivery enhance fibroblast migration and proliferation, while impedance mapping provides real-time readouts of healing. The results exemplify how hydrogel chemistry and processability enable monolithic device assemblies that match tissue mechanics and operate under motion. These three contributions illustrate a consistent logic: start with a clear physiological barrier (biofluid lag, secretion contamination, or fragile wound tissue), select material functions that solve that barrier (selective transport, antifouling, adhesion, conductivity), and integrate them into devices that both sense and intervene.

3. Respiratory wearables prompted by pandemic needs

The pandemic accelerated innovation at the interface between protective equipment and sensing. W.–H. Yeo and coworkers introduce a smart filtering facepiece respirator that integrates a laser-induced graphene humidity sensor with an embedded heater for moisture reset, a capacitive pressure-sensor array based on a dielectric elastomer sponge for real-time fit mapping, and near-field communication for wireless power and data [8]. The system improves overall fit factor by about 10 percent compared with a commercial N95, across variations in face shape, size, gender, and presence of facial hair. This addresses two persistent needs: reliable sealing during long wear and continuous monitoring of the local microclimate inside the mask.

Complementing this, U. Jeong and coworkers present a wireless, breathable mask sensor that uses a pixelated piezoresistive array to create spatiotemporal two-dimensional maps of inhalation and exhalation [9]. Stretchable patterned electrodes on electrospun fibers and a CNT-based sensing layer provide strain-independent pressure readouts. The mask distinguishes oral versus nasal breathing, clogged nose, shortness of breath, coughing, and characteristic patterns consistent with rhinitis, sleep apnea, and pneumonia. Together, these studies shift masks from passive filtration to active diagnostic platforms, connecting materials choices to clinically relevant signal quality under real wear conditions.

4. Platforms for motion recognition and tissue-electronic models

Two research articles extend wearables toward human–machine interaction and disease modeling. G. G. Malliaras and coworkers develop 3D-printed PEDOT:PSS-based conducting eutectogel electrodes that combine a deep eutectic solvent (choline and lactic acid) with PEGDA for printability, conductivity, and mechanical stability [10]. By patterning flat, pyramidal, striped, and wavy geometries, they tune skin conformability, impedance, and signal-to-noise, then embed 20-electrode arrays into textiles to generate body surface potential maps of the forearm. The system records finger-specific muscle activation and achieves greater than 97 percent accuracy in recognizing three sign-language letters using logistic regression. The result connects electrode chemistry, mesoscale geometry, and wearable machine learning in a textile form factor.

In a complementary direction, S. Jung and coworkers integrate an inkjet-printed, large-area organic electrochemical transistor with a 3D-bioprinted, multilayer airway tissue to monitor barrier integrity in real time [11]. The platform tracks tissue formation in liquid–liquid and air–liquid interface cultures over 13 days, quantifies disruption following influenza A infection, and measures dose-dependent protection by oseltamivir. Because the readout is label-free and noninvasive, it maintains tissue viability while providing dynamic functional metrics. The study illustrates how organic bioelectronics can be coupled with engineered tissues to bridge the gap between static assays and in vivo behavior, with obvious implications for personalized medicine.

5. Cross-cutting themes

Three cross-cutting themes emerge in the studies presented in this Theme Issue.

Interfaces and durability. Skin and mucosa impose mechanical strain, sweat, serum, and microbial exposure. Antifouling hydrogels, soft encapsulation, and adhesive yet non-irritating interfaces are recurrent solutions [2,3,6,7]. Natural biomaterials add mechanical compliance and biodegradability and suggest routes to sustainable disposal [4]. Yet dehydration, environmental sensitivity, and batch variability remain obstacles that require chemistry, processing control, and packaging solutions.

Autonomy and integration. Long-term wear demands wireless communication, sustainable power, and minimal maintenance. The respirator systems exploit NFC for power and data and incorporate environmental reset features such as graphene heaters [8]. The mask array links two-dimensional sensing to real-time analytics [9]. Reviews call for integration of multimodal sensing with machine learning to raise diagnostic specificity [1,2].

Pathways to clinical translation. Many prototypes meet laboratory benchmarks but face hurdles in large-scale manufacturing, clinical validation, and regulatory compliance. Consistent material properties across batches, skin-safe adhesives, and proof of long-term biocompatibility are essential to clinical adoption [1–4]. Diabetes devices must address lag between blood and peripheral biofluids and establish calibration schemes that are reliable under daily life conditions [5]. Tissue–electronic models demonstrate how disease and therapy can be evaluated with dynamic metrics, which may shorten the path from bench to bedside [11].

6. Challenges and opportunities

Despite the pace of innovation, several challenges persist. Stable, irritation-free adhesion without compromising signal quality remains difficult during extended wear. Hydrogels and elastomers are soft and conductive but can lose function with dehydration, repeated strain, and temperature swings. Power autonomy for multi-day operation is not yet routine, and efficiency of energy harvesting approaches needs improvement. Translational steps such as biocompatibility, cost-effective manufacturing of functional biomaterials, and regulatory approval are rate-limiting for clinical adoption. Addressing these issues will require advances in biomaterials engineering and device packaging, alongside clinical studies that establish accuracy, safety, and usability in the intended populations.

The articles in this special issue present a connected set of advances, from material platforms to disease-focused devices and integrative tissue-electronic systems. They demonstrate how biomaterials can deliver both function and form in wearables, while identifying what still limits translation. We sincerely thank the authors for their excellent contributions, the reviewers for their constructive feedback, and the editorial staff of *Biomaterials* for their professional support. We hope this special issue will attract broad attention among scientists, researchers, and clinicians, and inspire further exploration of new science and engineering in biomaterials for wearable bioelectronic technologies.

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