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EDITORIAL

Advances in wearable and implantable bioelectronics for precision medicine

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The continuous pursuit for a better quality of life promotes continuous advancements in intelligent technology. Flexible wearable and implantable bioelectronics have emerged as an innovative complement to rigid material-based electronic devices [1–3]. Due to their distinct advantages in terms of ductile, ultrathin, and biocompatible features, these elastic and soft bioelectronic devices can be seamlessly mounted onto various real or artificial tissues and organs. They offer numerous applications in continuous health monitoring [4, 5], human–machine interfaces [6–8], and therapeutic interventions [9–11]. These devices can dynamically track their surroundings, effectively bridging the gap among humans, machines, and real or virtual spaces. Typically, these devices monitor physical, chemical, and electrophysiological information based on piezoresistive, capacitive, piezoelectric, or triboelectric principles. To construct these high-performance multifunctional bioelectronic devices, diverse processing methods combined with emerging versatile functional materials have been developed, enabling the formation of active components, interconnections, and hierarchical structures [12, 13].

Recent breakthroughs in the field of wearable and implantable bioelectronics not only open up new avenues for fundamental research but also suggest high impacts on human life. To present the advances in this multidisciplinary research field, we organized a special issue on the topic of "Wearable and Implantable Bioelectronics." The issue collects four review articles, seven research articles, and one letter, covering subjects from functional nanomaterials and advanced manufacturing to the working principles of wearable and implantable sensors, as well as therapeutic strategies (Fig. 1).

Functional nanomaterials serve as the building blocks for high-performance bioelectronics. For example, Liu et al. introduced a nacre-inspired MXene-based film for a piezoresistive pressure sensor with a broad detection range [14]. This sensor leverages the structural benefits of MXene nanosheets and cellulose fibers, mimicking the "brick and mortar" design of nacre. This contributes to its wide pressure range (up to 286.49 kPa) and short response/recovery time (8.58 ms/34.34 ms). The wearable pressure sensors have wide applications in monitoring robotic motion and various physiological signals.

Meanwhile, Zhang et al. proposed a graphene–metal nanofilm fabricated by an electron cyclotron resonance system for a high-precision touch-sensitive screen [15]. The working principle of the capacitive touch sensor is based on electron trapping and polarization effect among nanofilms. The screen maintains good performance after 3000 bending cycles, with a signal-to-noise ratio of 41.16 dB and a resolution of 650 dpi, achieving 94.82% accuracy in handwritten Chinese character recognition.

Furthermore, Tran et al. provided insights into the development of wearable bioelectronics focusing on conjugated polymers (CPs) [16]. These CPs, with delocalized π-electron systems, are composed of conjugated bond structures and repeating chemical units. The authors discussed their properties of conductivity, biocompatibility, mechanical stability, flexibility, stretchability, and solution-phase processability. To improve sensing performance, their development in nanostructures and hybridizations was also presented, including CP nanowires, nanofibers, nanotubes, and nanoporous CPs. Using CPs as a basic architecture, recent

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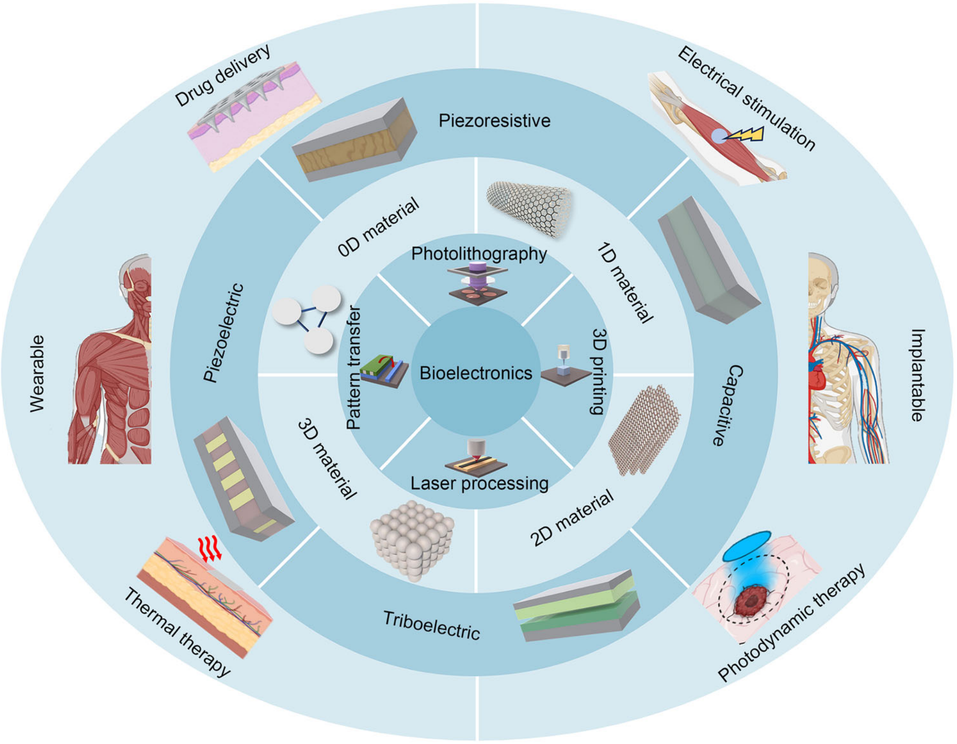
Fig. 1 Schematic of wearable and implantable bioelectronics



advances in self-powered, wearable, and implantable biosensors were overviewed.

Besides the functional nanomaterials, reliable processing methods should also be considered for versatile bioelectronic applications. Various fabrication approaches, such as photolithography, pattern transfer, additive manufacturing, solution printing strategies, and roll-to-roll methods, are essential. Typically, manufacturing multifunctional wearable and implantable devices involves several fabrication methods to realize sensitive units, structures, and interconnections. Fortunately, laser processing can accomplish these fabrication tasks due to its diverse mechanisms of laser and matter interactions [17, 18]. The modalities of laser processing primarily include subtractive, additive, and transformative categories [19–21]. Recently, Hong et al. discussed advances in laser-induced graphene, a typical transformative fabrication method [22]. Other processing techniques such as texturing, ablation, sintering, synthesis, and annealing were also summarized. Finally, they presented the applications of laser processing in various wearable and implantable devices, emphasizing chemical/physical sensors and energy devices.

Using hybrid manufacturing approaches and diverse functional nanomaterials, a variety of wearable physical, chemical, and electrophysiological sensors have been developed. In particular, electrochemical biosensors applied to analyze various biological fluids, such as sweat, saliva, and tears, have attracted extensive research and industry attention. These biofluids contain ions, proteins, and amino acids highly associated with human health. For instance, Wang et al. demonstrated a crosstalk-free dual-mode sweat microfluidic system for naked-eye sweat loss quantification with a resolution of 0.5 μL and a total volume of 11 μL [23]. The integration of this microfluidic system with a chloride sensor and a flexible printed circuit board allows real-time detection of sweat loss and ion concentration without crosstalk. This demonstrates the significance of noninvasive, precise sweat analysis in the growing field of bioelectronic health monitoring.

One of the advantages of wearable biosensors is their capability for point-of-care testing (POCT) in non-laboratory environments [24]. Such POCT strategies require no well-skilled technicians or sophisticated preparation procedures, making them highly desirable in resource-limited and remote regions. Recently, Ko et al. reviewed POCT techniques related to electrochemical biosensors from the perspectives of sensing mechanisms and fabrication methods [25]. They focused on the discussion of immobilizing various biorecognition elements such as enzymes, antibodies, and aptamers on electrode surfaces. The advantages and disadvantages of these enzyme immobilization approaches were critically analyzed. Additionally, most wearable bioelectronic devices are powered by batteries that require frequent charging or replacement for continuous monitoring. Fortunately, the emergence of triboelectric nanogenerators (TENGs) offers a potential solution for self-powered sensors by converting mechanical energy into electrical energy. Mao et al. comprehensively presented recent advances in stretchable TENGs for applications in wearable bioelectronic devices [26]. They first introduced the typical working principles, followed by descriptions of two solutions to achieve stretchable TENGs, i.e., the fabrication of intrinsically stretchable materials and the design of stretchable structures. Practical demonstrations include wearable and stretchable TENG-based devices for human health monitoring—such as pulse, body movements, and respiration detection—as well as human–machine interactions, including machine control, touch panels, and virtual reality.

Another vital category of flexible biosensors is implantable devices, which can be conformally attached to the heart, nerve, and brain tissue to probe electrophysiological signals and conduct disorder treatments. In particular, neuroscience research on brain activity recording has gained multidisciplinary attention due to its significance in developing brain–computer interfaces for disease treatment or communication. One major task is to design multichannel neural probes. For example, Liu et al. presented an implantable probe for in situ monitoring of action potentials and Ca^{2+} concentrations in the brain [27]. A sensitivity of 100.7 mV/decade for detecting Ca^{2+} is achieved with high selectivity. Twelve microelectrodes decorated with platinum black enable the tracking of neuron action potentials. The results indicate the probe's capability for concurrently tracking electrophysiological signals and ion concentrations.

Furthermore, Cai et al. designed and fabricated 16-channel microelectrode arrays (MEAs) modified with multiwalled carbon nanotube/poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) nanocomposites to rapidly and accurately locate and detect the subthalamic nucleus (STN) in rats with Parkinson's disease (PD) [28]. Results indicate that the STN in PD rats exhibits higher neural discharge compared to unlesioned rats. Additionally, the MEAs synchronously acquired neural signals from the STN and its upper or lower boundary nuclei, suggesting further investigation of deep brain nuclei.

To achieve high spatiotemporal resolution brain electrical signals, Feng et al. developed flexible ultrathin high-density electrode arrays using a laminated structure design, which overcomes the challenge of connecting many electrode wires within a limited space [29]. Eight hundred electrodes were fabricated with a minimum spacing of 15 µm. This size is similar to that of a single neuron, improving the positioning accuracy of epilepsy lesions from the centimeter to the submillimeter level. Such high-density electrode arrays provide pathways toward high-precision electroencephalogram acquisition.

Besides the diagnostic capabilities of wearable and implantable bioelectronic devices, therapeutic functionalities can also be integrated into such soft systems for continuous and on-demand treatments. Until now, typical strategies, including electrical stimulation, drug delivery, thermal therapy, and photodynamic therapy, have been developed for diabetes treatment, wound healing, neural stimulation, and cardiac therapy [30]. For example, Yu et al. demonstrated a kirigami-based wearable thermoelectric device (TED) with superior water vapor permeability (4.9 kg/(m^2·d)) and conformability [31]. Skin temperature can be increased by 3.8 °C or decreased by 3.5 °C by applying −0.50 A or 0.50 A of electricity to the device, respectively. Such wearable TEDs exhibit high potential in healthcare scenarios like thermal therapy and wound care.

In terms of implantable applications, one challenge is to circumvent bacterial invasion and inflammatory reactions when applying cortical electrodes for stimulation and/or recording of nervous system electrical activity. Huang and Li and their collaborators designed a bacterial cellulose-based hydrogel as substrates for cortical electrodes, which were encapsulated with specific drugs to inhibit the growth of Gram-negative and Gram-positive bacteria [32]. This significantly alleviates symptoms of bacterial infection when using therapeutic cortical electrodes for electrocorticographic recording.

In sum, we hope that this special issue of wearable and implantable bioelectronics will bring inspiration and insights to a wide community of researchers. Therefore, it is envisioned to call upon multidisciplinary researchers from material science, physics, chemistry, mechanical engineering, electrical engineering, optical engineering, biomedical engineering as well as computer engineering to involve in this rapidly growing field.

Declarations

Conflict of interest KCX is an academic editor and SHK is an associate editor for *Bio-Design and Manufacturing*, and they were not involved in the editorial review or the decision to publish this article. All the authors declare that they have no conflict of interest.

References

1. Tang HC, Yang YY, Liu Z et al (2024) Injectable ultrasonic sensor for wireless monitoring of intracranial signals. Nature 630(8015):84–90. https://doi.org/10.1038/s41586-024-07334-y
2. Wang WC, Jiang YW, Zhong DL et al (2023) Neuromorphic sensorimotor loop embodied by monolithically integrated, low-voltage, soft e-skin. Science 380(6646):735–742. https://doi.org/10.1126/science.ade0086
3. Yi JQ, Zou GJ, Huang JP et al (2023) Water-responsive supercontractile polymer films for bioelectronic interfaces. Nature 624(7991):295–302. https://doi.org/10.1038/s41586-023-06732-y
4. Lu YY, Yang G, Wang SQ et al (2024) Stretchable graphene–hydrogel interfaces for wearable and implantable bioelectronics. Nat Electron 7(1):51–65. https://doi.org/10.1038/s41928-023-01091-y

5. Libanori A, Chen GR, Zhao X et al (2022) Smart textiles for personalized healthcare. Nat Electron 5(3):142–156. https://doi.org/10.1038/s41928-022-00723-z
6. Kim KK, Kim M, Pyun K et al (2022) A substrate-less nanomesh receptor with meta-learning for rapid hand task recognition. Nat Electron 6(1):64–75. https://doi.org/10.1038/s41928-022-00888-7
7. Zhou YH, Zhao X, Xu J et al (2024) A multimodal magnetoelastic artificial skin for underwater haptic sensing. Sci Adv 10(1):eadj8567. https://doi.org/10.1126/sciadv.adj8567
8. Lu YY, Kong DP, Yang G et al (2023) Machine learning-enabled tactile sensor design for dynamic touch decoding. Adv Sci 10(32):e2303949. https://doi.org/10.1002/advs.202303949
9. Sani ES, Xu CH, Wang CR et al (2023) A stretchable wireless wearable bioelectronic system for multiplexed monitoring and combination treatment of infected chronic wounds. Sci Adv 9(12):eadf7388. https://doi.org/10.1126/sciadv.adf7388
10. Liu Z, Hu YR, Qu XC et al (2024) A self-powered intracardiac pacemaker in swine model. Nat Commun 15(1):507. https://doi.org/10.1038/s41467-023-44510-6
11. Qin XK, Zhong BW, Lv SX et al (2024) A zero-voltage-writing artificial nervous system based on biosensor integrated on ferroelectric tunnel junction. Adv Mater 2404026 (Early Access). https://doi.org/10.1002/adma.202404026
12. Gong S, Lu Y, Yin JL et al (2024) Materials-driven soft wearable bioelectronics for connected healthcare. Chem Rev 124(2):455–553. https://doi.org/10.1021/acs.chemrev.3c00502
13. Xu KC, Lu YY, Takei K (2021) Flexible hybrid sensor systems with feedback functions. Adv Funct Mater 31(39):2007436. https://doi.org/10.1002/adfm.202007436
14. Wang GF, Meng LX, Ji XY et al (2024) Nacre-inspired MXene-based film for highly sensitive piezoresistive sensing over a broad sensing range. Bio-Des Manuf (Early Access). https://doi.org/10.1007/s42242-024-00292-4
15. Zhang X, Ma JC, Deng HL et al (2024) A mixed-coordination electron trapping-enabled high-precision touch-sensitive screen for wearable devices. Bio-Des Manuf (Early Access). https://doi.org/10.1007/s42242-024-00293-3
16. Tran VV, Phung VD, Lee D (2024) Recent advances and innovations in the design and fabrication of wearable flexible biosensors and human health monitoring systems based on conjugated polymers. Bio-Des Manuf (Early Access). https://doi.org/10.1007/s42242-024-00297-z
17. Won D, Kim H, Kim J et al (2024) Laser-induced wet stability and adhesion of pure conducting polymer hydrogels. Nat Electron 7:475–486. https://doi.org/10.1038/s41928-024-01161-9
18. Choi SH, Kim JH, Ahn J et al (2024) Phase patterning of liquid crystal elastomers by laser-induced dynamic crosslinking. Nat Mater 23:834–843. https://doi.org/10.1038/s41563-024-01845-9
19. Cai ZM, Kuang C, Yang HY et al (2024) Hybrid laser manufacturing and applications in flexible micro-nano sensors. Chin J Lasers 51(4):0402403. https://doi.org/10.3788/CJL2313721
20. Sun MW, Cui SY, Wang ZZ et al (2024) A laser-engraved wearable gait recognition sensor system for exoskeleton robots. Microsyst Nanoeng 10(1):50. https://doi.org/10.1038/s41378-024-00680-x
21. Xu KC, Li QA, Lu YY et al (2023) Laser direct writing of flexible thermal flow sensors. Nano Lett 23(22):10317–10325. https://doi.org/10.1021/acs.nanolett.3c02891
22. Kim Y, Hwang E, Kai C et al (2024) Recent developments in selective laser processes for wearable devices. Bio-Des Manuf (Early Access). https://doi.org/10.1007/s42242-024-00300-7
23. Zhong BW, Xu H, Qin XK et al (2024) A crosstalk-free dual-mode sweat sensing system for naked-eye sweat loss quantification via changes in structural reflectance. Bio-Des Manuf (Early Access). https://doi.org/10.1007/s42242-024-00294-2
24. Xu KC, Zhou R, Takei K et al (2019) Toward flexible surface-enhanced raman scattering (SERS) sensors for point-of-care diagnostics. Adv Sci 6(16):1900925. https://doi.org/10.1002/advs.201900925
25. Kim J, Jeong J, Ko SH (2024) Electrochemical biosensors for point-of-care testing. Bio-Des Manuf (Early Access). https://doi.org/10.1007/s42242-024-00301-6
26. Wang YL, Zhu PC, Sun Y et al (2024) Recent advances in stretchable triboelectric nanogenerators for use in wearable bioelectronic devices. Bio-Des Manuf (Early Access). https://doi.org/10.1007/s42242-024-00284-4
27. Xiao JY, Xu MF, Wang LC et al (2024) Implantable probe with integrated reference electrode for in situ neural signal and calcium ion monitoring. Bio-Des Manuf (Early Access). https://doi.org/10.1007/s42242-024-00283-5
28. Jing LY, Xu ZJ, Fan PH et al (2024) Deep brain implantable microelectrode arrays for detection and functional localization of the subthalamic nucleus in rats with Parkinson's disease. Bio-Des Manuf (Early Access). https://doi.org/10.1007/s42242-023-00266-y
29. Liu YF, Wang ZH, Jiao Y et al (2024) Flexible, high-density, laminated ECoG electrode array for high spatiotemporal resolution foci diagnostic localization of refractory epilepsy. Bio-Des Manuf (Early Access). https://doi.org/10.1007/s42242-024-00278-2
30. Zhang ZM, Zhu ZT, Zhou PC et al (2023) Soft bioelectronics for therapeutics. ACS Nano 17(18):17634–17667. https://doi.org/10.1021/acsnano.3c02513
31. Chow L, Zhao GY, Wu PC et al (2024) Soft, body conformable electronics for thermoregulation enabled by kirigami. Bio-Des Manuf (Early Access). https://doi.org/10.1007/s42242-024-00290-6
32. Qin RR, Li T, Tan YF et al (2024) A drug-loaded flexible substrate improves the performance of conformal cortical electrodes. Bio-Des Manuf (Early Access). https://doi.org/10.1007/s42242-024-00299-x

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