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Editorial

Introduction: Wearable Devices

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Wearable devices, including smart watches, virtual reality glasses, skin patches, and smart garments, just to name a few, are becoming increasingly visible in human society. They track critical physiological parameters for health surveillance and athletic performance assessment; they continuously monitor biomarkers for chronic disease management; they also collect body information and deliver stimulation for seamless human−machine interaction. The global wearable technology market size was worth around USD 55.5 billion in 2022 and is predicted to grow to around USD 142.4 billion by 2030 with a compound annual growth rate (CAGR) of 12.5% (source: ZION Market Research). Optimistic analysis even forecasts a market size of USD 466 billion by 2032 with a CAGR of 31.2% from 2023 to 2032 (source: Market Research Future). Such explosive growth is, on the one hand, propelled by fast-evolving technologies in materials, electronics, telecommunication, and data science and, on the other hand, driven by mass digitalization and increasing healthcare needs from an aging population.

Traditional wearable devices, characterized by their bulkiness and rigidity, face challenges in establishing reliable, conformal contact with the soft and curvilinear human anatomy, crucial for high-quality biosignal acquisition and feedback stimulation. This limitation not only compromises the quality of the data collected but also detracts from user conformity during extended wear periods. In response, contemporary research endeavors are directed toward the development of devices that are thinner, smaller, softer, and more stretchable. Such advancement promises to unlock a number of previously unattainable applications. Research to this end starts from structural design, material processing and manufacture and then goes further for integrated devices with various functionalities and form factors. New applications are explored in simulated and real-life scenarios, with the help of information and communications technology. Wearable devices encompass a wide range of device components/types, including sensors, energy harvesters, energy storage devices, actuators, displays, communication modules, processors, memories, and more recently artificial neurons. Given the convergence of multiple disciplines and research domains required to advance this field, wearable device research is inherently multidisciplinary, interdisciplinary, and transdisciplinary. While it is impossible to cover all the topics, this virtual thematic issue brings together leaders in the field of diverse backgrounds to discuss recent advancements, trends, and future directions for wearable devices.

A few categories of materials are highlighted for their unique potential in wearable devices. Rogers and co-workers summarize recent progress in bioresorbable materials, materials that can be decomposed *in vivo* and absorbed by biological tissues. This property allows electronic devices to be implanted inside bodies, perform the function, and disintegrate at a desired time, without a retrieval procedure that may cause complications to the patients. The review looks at the fundamental chemistry enabling safe absorption of materials by tissues and gives examples of integrating bioresorbable materials in electronics for therapeutic functions. Meanwhile, liquid metal with high electronic conductivity, fluidity, and biocompatibility is one of the promising materials for soft and stretchable biointerfacing devices. Jiang and co-workers reviews the fabrication of liquid metal−polymer composite conductors for applications in sensing, restoration, and augmentation of the human body. Cheng and co-workers give a more panoramic overview of soft materials that enable applications in connected healthcare. They review the types and fabrication of soft materials and specifically highlight the challenge of energy supply. They also discuss how artificial intelligence, telecommunication, and software play roles in realizing connected healthcare. Two-dimensional (2D) materials with intrinsic mechanical flexibility and unique electrical and optical properties are one of the most studied materials for flexible electronics. Ahn and co-workers summarize the characteristics, fabrication, device integration, and applications of 2D materials in flexible electronics and highlight the challenges and prospects for further development. Current manufacturing of wearable devices mainly relies on microprocessing/fabrication technologies such as vacuum processes and photolithography, which are hardly compatible with soft and stretchable materials. Printing emerges as a promising alternative for fabricating soft and stretchable devices, with great customizability and compatibility with emerging materials. Aiming to guide researchers’ choice of printing techniques and formulation of inks, Dickey and co-workers put up a practical review discussing the principles underlying these critical issues.

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The form factor of wearable devices goes bold thanks to researchers' unbound imagination. Lu and co-workers introduce imperceptible electronic tattoos (e-tattoos) that resemble temporary tattoo stickers but boast advanced electrical, mechanical, optical, thermal, and chemical functionalities. Zheng and co-workers focus on porous conductive textiles to enable comfortable, durable, and diverse wearable applications. Park and co-workers discuss smart contact lenses to capture the rich physiological information around the eye for health monitoring and disease diagnosis. Gutruf and co-workers delve into wireless battery-free implantable devices to monitor various organs' conditions and perform medical interventions with minimal disruption to patients' lives. Zhang and co-workers discuss three-dimensional (3D) architected flexible electronics, which offer unmatched 3D interfacing with biology and structure-enabled functionalities. Specifically, they discuss how mechanics is used to guide the design and fabrication of 3D electronics. Bioadhesives have recently been engineered to expand from their traditional use of tissue repairing to a powerful biotic−abiotic interface. It not only reliably attaches soft or hard electronics on biological tissues but also allows multimodal communications between them. Zhao and co-workers thoroughly introduce the design principles of next-generation bioadhesives and provide exciting future prospects for this technology platform.

Although a few device types are the topic of discussion, sensors and energy devices are the most visited ones. J. Wang and co-workers put up a comprehensive review on electrochemical glucose sensors, covering sensing mechanisms, device evolution history, target biofluids, multiplexed sensing, commercial status, and prospects, leading to the idea of an artificial pancreas for closed-loop diabetes management. Gao and co-workers delve into sweat analysis and biosensing, as sweat is an easily accessible biofluid carrying rich biological information. They summarize the state-of-the-art technologies and critically analyze the challenges and prospects toward precision medicine. Power supply is a critical component for wearable devices. Within this topic, a panoramic review on self-powered sensors and systems is presented by Z. L. Wang and co-workers, whereas Kim and co-workers focus on bioresorbable triboelectric nanogenerators.

In addition, optoelectronic devices including light-emitting diodes and photodetectors are reviewed by Kim and co-workers, with a focus on materials, fabrication, and device design strategies to endow softness and stretchability to these devices. Such devices have the potential to be intimately integrated into the human body for physiological sensing, display, and optical stimulation or on robots for them to interact with humans more efficiently. S. H. Ko and co-workers highlight transparent devices that allow access to the optical information on biological surfaces and improve user compliance due to invisibility. H. Ko and co-workers focus on sensors and actuators for a haptic human−machine interface. They highlight design principles for desired sensor performance and envision applications in metaverse, robotics, and user-interactive devices. Chen and co-workers present a panoramic view on the underlying principles and advances in artificial neuron devices, which are believed to be the next frontier of bioinspired electronics.

We are deeply grateful to all the authors who have undertaken strenuous work to make this virtual thematic issue possible. We hope readers can find practical guidance in advancing their research on wearable devices from this diverse collection of topics. Additionally, we aim for the discussions presented to invoke deeper thinking and inspire cross-disciplinary innovations that can address the outstanding scientific and technological challenges associated with wearable devices. Our goal is to collaborate in developing reliable, comfortable, and intelligent wearable devices that improve users' health and quality of life.

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Notes

Views expressed in this editorial are those of the authors and not necessarily the views of the ACS.

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Dae-Hyeong Kim obtained his B.S. and M.S. degrees in Chemical Engineering from Seoul National University, Korea, in 2000 and 2002, respectively. He received his Ph.D. degree in Materials Science and Engineering from University of Illinois at Urbana−Champaign in 2009. From 2009 to 2011, he was a postdoctoral research associate at University of Illinois. He joined Seoul National University in 2011 and is currently a professor in School of Chemical and Biological Engineering of Seoul National University. He has been serving as an associate director of Center for Nanoparticle Research of Institute for Basic Science (IBS) since 2017. He has been focusing on the research of nanomaterials and deformable devices and their application to biointegrated and bioinspired electronics. He has been recognized with several awards including the George Smith Award (2009), TR 35 award (2011), Hong Jin-ki Creative Award (2015), SCEJ Award (2016), and Korea Young Scientist Award (2017). He was also selected as one of the highly cited researchers by Clarivate Analytics in 2018−2023.

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Rising Star. She has received an NSF CAREER Award, ONR and AFOSR Young Investigator Awards, a 3M nontenured faculty award, and the ASME Thomas J.R. Hughes Young Investigator Award.

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