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Building the Nexus Between Electronics and the Human Body for Enhanced Health

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Sihong Wang

Over the past few decades information technology (IT) has suffused every corner of society and reshaped the way people live, communicate, work, and entertain themselves. The next 50 years are likely to yield another generational change in electronics, and corresponding changes in people's lives.

A major recent trend is the creation of electronics, including stretchable microchips, that can be integrated, even merged, with the human body (Chu et al. 2017; Kim et al. 2011; Wang et al. 2018a), expanding the role of IT from obtaining information for human use to obtaining information from the human body.

A nexus between electronics and the body, with its rich quantity and diversity of information, will significantly enrich technological approaches that can benefit people's life and health (figure 1). To achieve this, the conventional silicon electronics in planar and rigid form factors need to give way to a new generation that possesses multiaspect similarity and compatibility with the human body (Ray et al. 2019; Someya et al. 2016; Wang et al. 2018b).

Projected Benefits

The ability to easily obtain different types of information from the human body—from movements and vital signs to organ conditions and brain

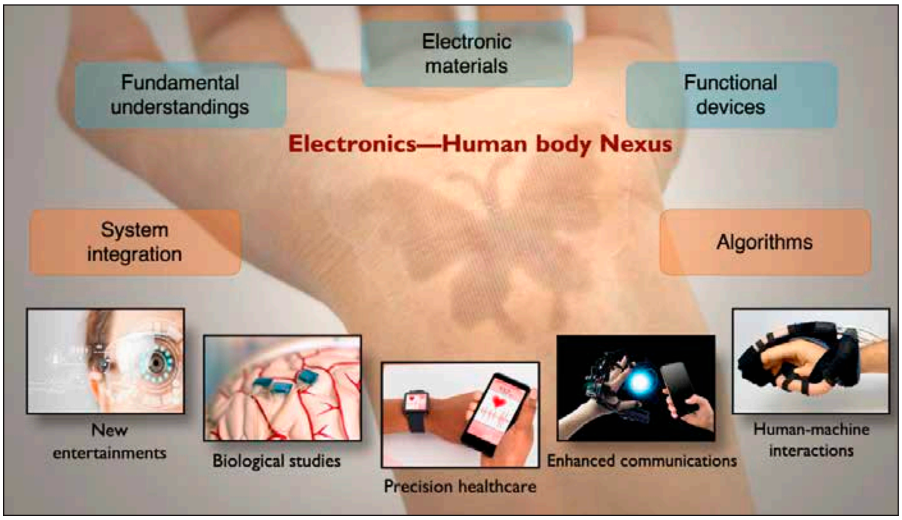

FIGURE 1 Building the nexus between electronics and the human body, as the technological basis for the future of information technology: areas of technological challenges and application impacts.

activity—could enable a number of improvements in people's life and health.

Ubiquitous and Precision Health Care

Continuous access to complex and rapidly changing health data (e.g., body temperature, blood pressure, breathing rate, perspiration composition) can enable constant monitoring of health conditions, early diagnosis of diseases, and preventive and point-of-care treatments. Moreover, the accumulated big data of an individual's health history can provide a record and understanding of health characteristics to support precision medicine.

Deeper Understanding of Human Biology

With the technological feasibility of high spatiotemporal resolutions, it will be possible to decipher mysterious biological mechanisms of the body in both healthy and diseased states. In particular, important discoveries can be made about pathogenic causes of complicated diseases to guide the development of more effective treatment methods.

Remote Physical Interactions

The major challenge in current remote communication approaches and face-to-face interactions is the lack of direct physical interaction. In the future, the development of electronics for collecting physical information in real time could add this missing piece to communication technology, so that a "handshake" can happen between two persons at different locations and physical therapies can be carried out remotely.

Technological Challenges

To achieve the collection of high-fidelity, stable, and multitype information about an individual's physical health over a long period, electronic devices need to have a suite of properties that enable conformable attachment, minimal side effects, and long-term function. Notwithstanding some groundbreaking efforts, significant research and development progress are needed in the following areas.

Fundamental Understanding of Material-Biology Interfaces

For the relatively simple scenario of interfacing electronics on the body (i.e., on the skin), it is generally understood that the matching of mechanical properties is the primary requirement for electronics. However, for the more complicated case of implanted electronics, systematic studies and knowledge are still largely lacking about the relationships between electronic materials' physicochemical properties and long-term biocompatibility.

Generation of New Electronic Materials

The large variety of electronic devices (e.g., transistors, light-emitting diodes, biosensors, actuators) are built on different functional properties of materials. Although some successes have been achieved for combining certain electronic functions (e.g., semiconducting and conducting properties) with biocompatible form factors (Kayser and Lipomi 2019; Xu et al. 2017), new material designs must be created for the effective integration of the rest of the functional properties.

Because biological tissues are primarily composed of biopolymers, polymers are the most favorable material family for achieving the desired biocompatibility. To realize advanced functions, polymers with biocompatible designs will have to provide functional properties on par with their rigid counterparts.

New Device Designs and Fabrication Methods

Operations on or in the human body and uses of new classes of materials may exclude the use of many existing device designs for certain applications. Thus, new device designs—and even new working principles—are needed to ensure desired performance with the simplest device and system architectures possible.

Devices need to be designed to perform reliably, undistorted by the body's mechanical and chemical conditions. And for the new class of electronic materials, fabrication methods (Kaltenbrunner et al. 2013; Wang et al. 2018a) need to move away from microfabrication for silicon electronics and to confer large-area scalability, low cost, and batch-to-batch uniformity.

Sustainable and Biocompatible Power Sources

As an integral part of electronic systems, power sources must have biocompatible properties. Batteries (Liu et al. 2017; Xu et al. 2013) need to be stretchable and made of nontoxic chemicals, while still providing enough energy density.

With the very limited options of recharging or replacing batteries, on-body generation of electricity through energy harvesting will be needed (Jiang et al. 2020). Efficiencies and power outputs need to satisfy power requirements by functional modules.

The possible impacts of energy harvesting on biological processes over the long term need to be carefully studied as well.

High-Throughput and Trainable Data Processing

To make full use of continuously produced, large-quantity health data from each individual, artificial intelligence (AI) needs to be built into data-processing algorithms. For faster speed and better reliability, such AI algorithms should be implemented by human-compatible computational chips, which require development based on emerging architectures (e.g., neuromorphics) that are especially efficient for AI (Burr et al. 2017; van de Burgt et al. 2018).

System-Level Integration Strategies

For different functional modules (e.g., sensing, data conditioning and computation, wireless communications) in fully integrated electronics for acquiring information from the body, application-specific requirements for the performance parameters (e.g., speed, bandwidth, energy consumption) must be clearly defined. In particular, notwithstanding substantial research progress in the use of both conventional inorganic materials and emerging functional polymers to build human-integrated electronics, their overall suitableness for different functions is still unclear.

Societal and Cultural Challenges

It won't be trivial to persuade people to accept the long-term attachment or implantation of electronics to or in their body to acquire information. It will be essential to clearly communicate the benefits of accessing the information.

> *Protocols for protecting the privacy and security of personal physical data will be critically important.*

In addition, the best approaches for using this previously unavailable health data need to be studied and guidelines established for the use of these data. Protocols for protecting the privacy and security of the data will be critically important. Not least, the public needs to be better informed about science and technology, to allay fears and misconceptions about technology.

Perspective for the Future

Human-integrated electronics are likely to become an important part of the electronics and health industries over the next 50 years. Wearable electronics alone are projected to have a market value of about $150 billion by 2026 (Hayward et al. 2016).

The successful commercialization of new types of electronics with novel applications for the human body can be expected to significantly enhance quality of life and increase lifespan. The path to get there requires deep collaborations between academia, industry, and government.

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