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FUTURE ENERGY

Body Heat Powers Future Electronic Skins

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Introduction

The global market for smart electronic skins (E-skins), driven by the rise in the aging population and chronic patient care, is estimated to be >$1.7 billion.[1] It is exciting to witness the advancement in synthetic skins, which can mimic the sensory and self-healing functionalities of natural skin, monitor vital signs, and deliver diagnoses remotely. However, the lack of ultrathin, stretchable, and reliable power sources has dramatically hindered their commercial application to date. The continually released thermal energy from our body provides a plausible solution to power the miniaturized sensors and generic circuits in E-skins. This article presents the recent advances and challenges in E-skins and highlights the prospects of thermoelectric (TE) generators as the potential power supply. We also discuss the conceptual design of skin-conformal TE devices and provide a direction for self-powered integrated E-skin systems.

Recent Advances and Challenges in E-Skins

E-skins are artificial skin-type electronic devices, which hold great promise for applications in limb prostheses, soft robotics, and artificial intelligence (Figure 1). As the aging population is increasing, E-skin devices and chips are expected to be in high demand for establishing wireless health monitoring systems, and their global market is anticipated to reach $1.7 billion by 2025.[1]

To fulfill the requirements of such applications, skin-conformal, maintenance-free, and, ideally, self-powered generators are highly desired. Although flexible batteries and micro-supercapacitors can be integrated to power E-skins, these still require manual intervention for periodic re-charging or replacement,[2] which is not suitable for long-term unattended monitoring. Recently, high-efficiency solar cells and the emerging photosynthetic "green" devices have demonstrated their great potentials in such aspects.[3,4] However, the voltage generated by these devices largely depends on the received light intensity, and their applications will be restricted when there is no light exposure.

Nanogenerators such as piezoelectric generators can turn mechanical energy into electricity, but they work at a specific frequency only. In addition, triboelectric generators can harvest energy from body motion to self-power E-skins. However, the produced voltage is in the form of short transient pulses, which need to be accumulated by an energy storage device. Thus, it could only provide power periodically. This may satisfy

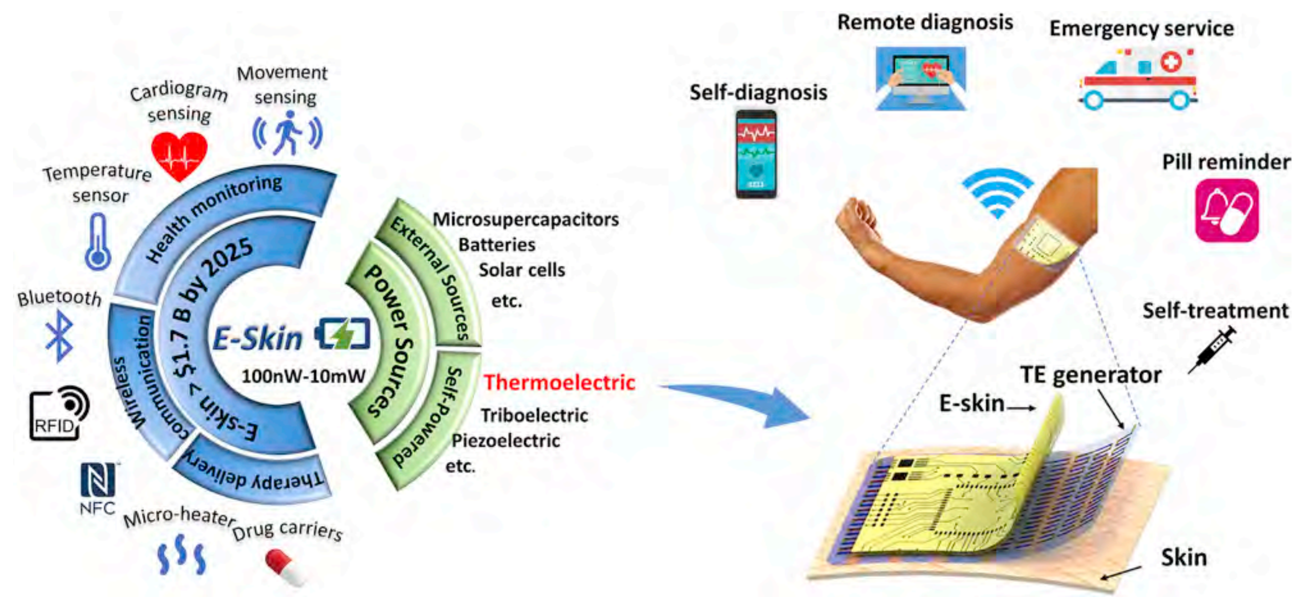

Figure 1. The Prospects of Future E-Skins Powered by Body Heat

Functional E-skins and power sources (left) and the schematic illustration of E-skins powered by body heat using an integrated thermoelectric (TE) generator for potential wireless health monitoring and diagnosis (right).

the requirements for certain micro-sensors, where standby and active modes are working alternately.[5]

Apart from mechanical motions, our body can continually provide a thermal energy up to 20 mW/cm^2,[6] which can be harvested via a TE device and generate a direct current. Such thermally driven generators are superior when a continuous working mode is preferred. If we assume that the figure of merit of a TE material can achieve 1 at room temperature, the thermal energy conversion efficiency[7] will reach 3% (equal to a maximum of 0.6 mW/cm^2) at a temperature gradient of 5 K. This provides a plausible solution to power most of the integrated circuits and sensors in E-skins systems, which generally have the energy consumption of 100 nW–10 mW.[8] A successful example is a commercialized MATRIX PowerWatch, in which a TE generator utilizes body heat to self-charge an internal battery and measure daily activities.

Despite these exciting achievements, it should be noted that most of the traditional TE generators are rigid, which is inefficient to harvest heat from non-planar surfaces. Alternatives, such as organic devices, are still at the proof-of-concept stage. Although several flexible prototype generators have been reported,[9,10] these have yet to meet the skin-conformal requirements. In this article, we will focus on the following aspects, which are crucial to the development of self-powered smart E-skin systems: (1) material selection—high power output, lightweight, flexible, and solution-processable; (2) ink formulation—adapted for various printing and scale-up fabrication methods; and (3) conceptual design of skin-conformal TE nanogenerator and smart integrated E-skin system.

Material Selection Criteria and Ink Formulation

Flexible, high-output, and ink-formulated materials are essential for fabricating skin-conformal TE devices. From the viewpoint of power generation, most of the developed inorganic TE materials will reach their peak performance at temperatures above 100°C and generally have relatively low power output at near room temperature. In addition, the brittle nature of these materials will restrict the overall device flexibility. From the perspective of device fabrication, solution-processable materials are desirable and preferable, as they can be formulated into inks and adapted for scale-up production.

Typical TE generators require both *p*- and *n*-type semiconducting materials connected in series to provide sufficient voltage and current for smart electronics. Among the *p*-type organic materials, poly(3,4-ethylenedioxythiophene)-tosylate, carbon nanotubes, and their hybrid composites have demonstrated excellent TE performance (power factor > 1,000 μW/mK^2).[10] However, the commercial implementation of flexible TE generators is impeded by the lack of high-efficiency and air-stable *n*-type organic semiconductors.[9] Recently, new dopants and solvents aimed at overcoming this bottleneck for stable *n*-type polymers have been reported.[9,11] In addition, *n*-type 2D materials, such as transition metal dichalcogenides, have demonstrated extraordinary TE performance resulting from enhanced quantum confinement

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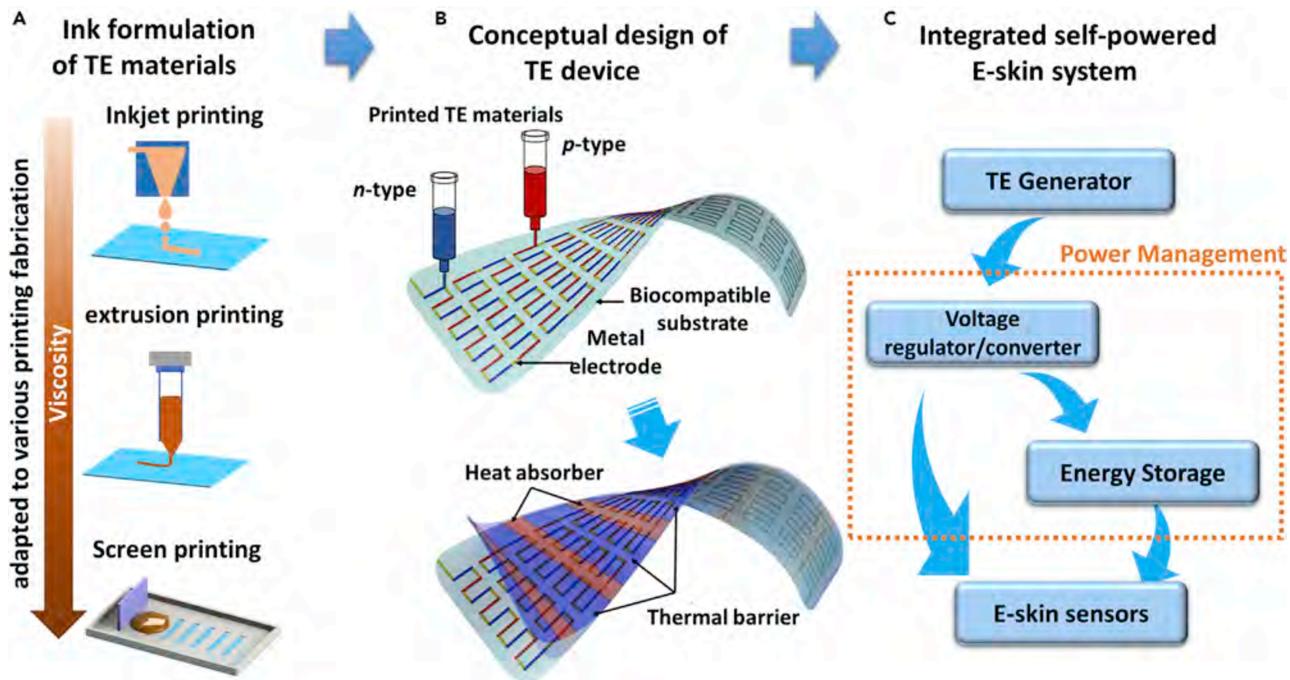

Figure 2. Conceptual Design of a TE Generator and Integrated Self-Powered E-Skin System

(A) Functional inks of TE materials adapted to various printing methods.

(B) Conceptual design of skin-conformal TE device.

(C) Schematic illustration of integrated self-powered E-skin system.

effects. The intercalation of organic cations and molecules into van der Waals gaps of these 2D materials can further increase material flexibility and reduce thermal conductivity of these materials.[12] Moreover, it is expected that their power output can be enhanced by tuning the interplay between inorganic and organic layers. This will enable 2D TE materials to generate a decent power for the micro- to milliwatt sensors at a small temperature gradient.

The solution processability of the above-discussed materials allows for the ink parameters such as active material loading, exfoliated particle dimensions, shear viscosity, and surface tension to be carefully controlled (Figure 2A). This protocol will allow for functional inks to be tailored and customized, which potentially enables seamless integration of TE generators based on these materials into existing E-skin systems at a more affordable price.

Conceptual Design of Skin-Conformal TE Generator

Figure 2B depicts the conceptual design of a prototype skin-conformal TE device, where both *p* and *n*-type inks will be directly printed onto a soft biocompatible substrate with pre-patterned electrodes. In contrast to the rigid-type traditional generators, this proposed device will have a planar shape and ultrathin thickness, which can conform well to the skin and capture the heat more efficiently. As indicated in Figure 2B, the induced thermal barrier and heat absorber will enable the generation of temperature gradients along each TE leg during operation, and the heat will be converted into electricity.

It should be noted that the conversion efficiency of a TE device depends on not only the power generated but also the heat absorbed on the hot side. To improve the overall power output, there are two competing factors to consider. First, it is vital to minimize the internal resistance (i.e., shorter TE legs are favorable) to reduce the energy consumed by joule heating while maintaining sufficiently large temperature gradients (i.e., longer legs are preferred). Second, it is essential to take account of the heat release on the cold side, and this requires a rational device design with a trade-off between these parameters.

Future Integrated E-Skin Systems

Figure 2C presents a conceptual integrated self-powered E-skin system, where the TE generator has two working modes. It can directly drive the low-power sensors in a continuous way. Alternatively, the generated voltage can be accumulated by an energy storage unit and then used to power the sensors with higher energy consumption. In addition to the power-generation capability, there is a strong need to develop highly stretchable and biocompatible devices for seamless integration to the skin. While most E-skin prototype devices are bendable, they are not as stretchable as natural skin. For future device fabrication, both nanogenerators and sensors are preferentially printed onto elastic substrates with low Young modulus, with the whole device being only several micrometers thick. This will enable intimate contact between the device and epidermis with maximum flexibility. Air permeability (or breathability) also needs to be considered to minimize the discomfort associated with long-term wear. Another challenge to address is the material degradation over time, which can arise from various sources including deformation, environmental conditions, or external damage. It is very difficult to detect the microscale cracks at an early stage and is costly to have periodic inspections and manual repairs. Therefore, it is essential that the materials either have the built-in capability to self-repair damage or are encapsulated by self-healing coatings to protect the active components from environmental exposure. Lastly, to further reduce the fabrication cost, ink-formulated materials are highly desired, which will enable the integration of power supply, energy storage unit, and multiple sensors in a cost-effective and straightforward way.

As the Internet of Things makes home care a possibility, the development of self-powered epidermal electronics will increase the likelihood of breakthroughs in the field of wireless health monitoring and diagnosis. One day, the tattoo-like devices will no longer be science fiction and they will unlock the new potential for human-machine synergy and provide better solutions for achieving the long-standing goals of living longer and healthier.

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AUTHOR CONTRIBUTIONS

R.T., Y.L., K.K., and J.C. conceived and designed the project. R.T., Y.L., and J.C. wrote the manuscript. All authors discussed the results and commented on the manuscript.

1. Kumar, R., and Mutreja, S. (2018). https://www.alliedmarketresearch.com/electronic-skin-market.
2. Kim, D., Kim, D., Lee, H., Jeong, Y.R., Lee, S.J., Yang, G., Kim, H., Lee, G., Jeon, S., Zi, G., et al. (2016). Body-attachable and stretchable multisensors integrated with wirelessly rechargeable energy storage devices. Adv. Mater. *28*, 748–756.
3. Kaltenbrunner, M., Adam, G., Głowacki, E.D., Drack, M., Schwödiauer, R., Leonat, L., Apaydin, D.H., Groiss, H., Scharber, M.C., White, M.S., et al. (2015). Flexible high power-per-weight perovskite solar cells with chromium oxide–metal contacts for improved stability in air. Nat. Mater. *14*, 1032–1039.
4. Ravi, S.K., Wu, T., Udayagiri, V.S., Vu, X.M., Wang, Y., Jones, M.R., and Tan, S.C. (2018). Photosynthetic bioelectronic sensors for touch perception, UV-detection, and nanopower generation: toward self-powered E-skins. Adv. Mater. *30*, e1802290.
5. Wang, Z.L. (2012). Self-powered nanosensors and nanosystems. Adv. Mater. *24*, 280–285.
6. Vullers, R.J.M., van Schaijk, R., Doms, I., Van Hoof, C., and Mertens, R. (2009). Micropower energy harvesting. Solid-State Electron. *53*, 684–693.
7. Snyder, G.J., and Toberer, E.S. (2008). Complex thermoelectric materials. Nat. Mater. *7*, 105–114.
8. Proto, A., Penhaker, M., Conforto, S., and Schmid, M. (2017). Nanogenerators for human body energy harvesting. Trends Biotechnol. *35*, 610–624.
9. Russ, B., Glaudell, A., Urban, J.J., Chabinyc, M.L., and Segalman, R.A. (2016). Organic thermoelectric materials for energy harvesting and temperature control. Nat. Rev. Mater. *1*, 16050.
10. Wang, H., and Yu, C. (2019). Organic thermoelectrics: materials preparation, performance optimization, and device integration. Joule *3*, 53–80.
11. Tian, R., Wan, C., Hayashi, N., Aoai, T., and Koumoto, K. (2018). Wearable and flexible thermoelectrics for energy harvesting. MRS Bull. *43*, 193–198.
12. Wan, C., Tian, R., Kondou, M., Yang, R., Zong, P., and Koumoto, K. (2017). Ultrahigh thermoelectric power factor in flexible hybrid inorganic-organic superlattice. Nat. Commun. *8*, 1024.

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