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Paper: A promising material for human-friendly functional wearable electronics

Hao Liu[a,b], Huaibin Qing[b,c], Zedong Li[a,b], Yu Long Han[a,b], Min Lin[a,b], Hui Yang[d], Ang Li[e], Tian Jian Lu[b,f], Fei Li[b,g,*], Feng Xu[a,b,*]

[a] The Key Laboratory of Biomedical Information Engineering of Ministry of Education, School of Life Science and Technology, Xi'an Jiaotong University, Xi'an 710049, PR China
[b] Bioinspired Engineering and Biomechanics Center (BEBC), Xi'an Jiaotong University, Xi'an 710049, PR China
[c] State Key Laboratory for Mechanical Behavior of Materials, School of Materials Science and Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China
[d] School of Life Sciences, Northwestern Polytechnical University, Xi'an 710072, PR China
[e] Key Laboratory of Shaanxi Province for Craniofacial Precision Medicine Research, College of Stomatology, Xi'an Jiaotong University, Xi'an 710049, PR China
[f] State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi'an Jiaotong University, Xi'an 710049, PR China
[g] Department of Chemistry, School of Science, Xi'an Jiaotong University, Xi'an 710049, PR China

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ABSTRACT

The ever-growing overlap between electronics and wearable technology is driving the demand for utilizing novel materials that are cost-effective, light-weight, eco-friendly, mechanically deformable and can be conformably and comfortably worn on human body as substrate to support the reliable operation of wearable electronic functionalities. Paper materials comprised of bio-origin ingredients (*e.g.*, cellulose and carbon derivatives) have recently attracted remarkably increasing research and commercial interests for prototyping next-generation wearable electronics due to their superiorities including natural abundance, flyweight, mature manufacturing process, specific structural properties, favorable mechanical bendability, biocompatibility and nontoxicity over their counterparts. Feasibility of engaging paper materials has been proved by outstanding performances in body-worn healthcare sensing systems, electro-stimulated artificial muscles, on-site memory storage and wearable power supply on paper substrate. In this review, we present a state-of-the-art introduction of diverse paper substrate options and fabrication techniques employed for realizing paper electronics, and discuss both pros and cons of each manufacturing tactic. Additionally, we summarize developing trends of paper-based electronics in the emerging wearable applications. Based upon these, final conclusions, encountering challenges, accompanied with advancing outlooks are illustrated.

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* Corresponding authors at: Bioinspired Engineering and Biomechanics Center (BEBC), Xi'an Jiaotong University, Xi'an 710049, PR China.
E-mail addresses: feili@mail.xjtu.edu.cn (F. Li), fengxu@mail.xjtu.edu.cn (F. Xu).

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1. Introduction

Wearable electronics, encompassing a series of smart electronic accessories and systems that can be conformably and comfortably incorporated on human body, have recently attracted significant attention among labs and markets globally. Examples include flexible displays [1], electronic skins [2,3], healthcare monitoring systems [4–7], energy harvesting devices [8,9], *etc*. The captivating attribute of wearable electronics lies in their capability to fulfill the ever-growing demand for instant information interaction [10], real-time physiological function tracking [11,12] and comfortable user experience [13]. The target of enduring less discomfort caused by directly body-worn devices calls for flexible substrate materials. Therefore, the discovery of soft materials is playing a crucial part in the development of wearable technology.

Until now, various soft materials have been used as substrates for wearable electronics. Among these, plastics [14–18] and silicone elastomers [19–22] are the two most commonly employed categories. However, there are several challenges associated with these materials such as the costly production process and adverse impacts on the environment. These factors limit their further applications, particularly those oriented towards large market prospects in underdeveloped regions. For instance, despite the ultra-thin thickness and light weight, plastics, such as PET (polyethylene terephthalate), are hazardous for the environment [18] because plastic debris is a major source of marine pollution resulting in a rapid decline of global biodiversity [23]. For the silicon-based strategies, such as PDMS (polydimethylsiloxane), apart from the intrinsic non-ecofriendly nature of the material [24], the complex fabrication process that usually requires a time-consuming molding technique [25,26] shows a mismatch with the

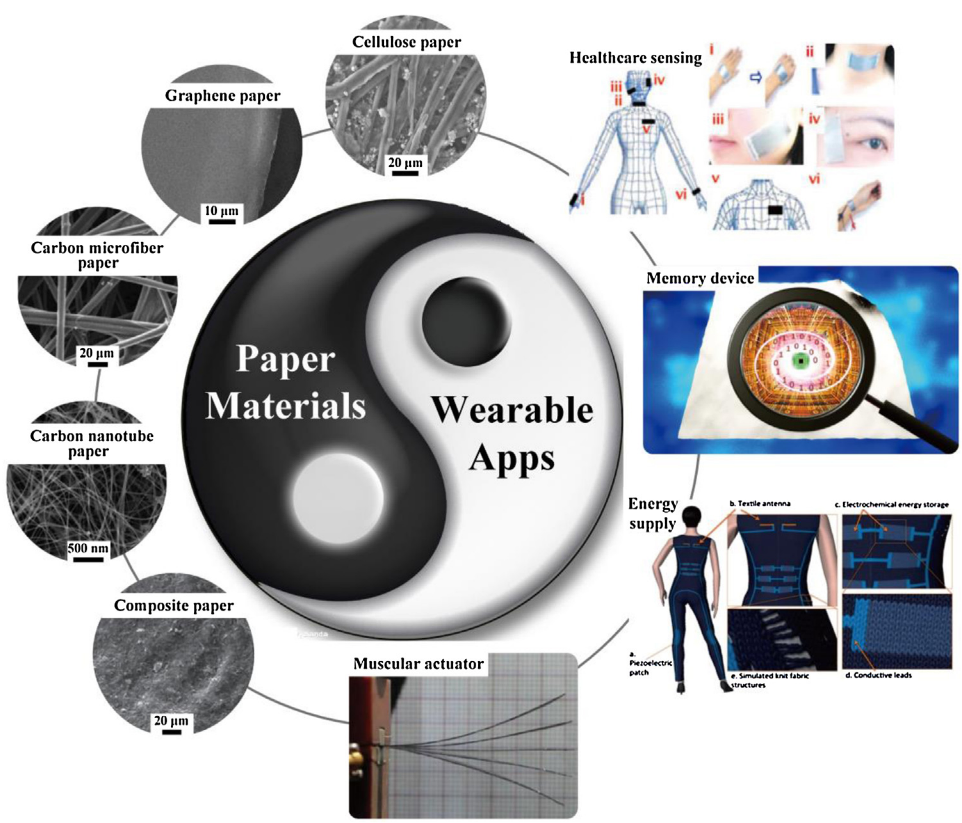

Fig. 1. Paper materials as promising substrates for burgeoning wearable electronics applications. Various paper materials with different compositions (*e.g.*, cellulose, graphene, carbon microfiber, carbon nanotube and composite materials) present a significant potential for applications in the rapidly growing wearable electronics industry for uses as healthcare sensors, memory devices, muscular actuators and energy supply [86,105,130,137,183,187,225,266,267].