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Research Article

MATERIALS AND MECHANICAL DESIGN APPROACHES FOR WEARABLE HEALTH-CARE MONITORING DEVICE

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Abstract

Wearable health-care monitoring devices have emerged as crucial tools for continuous health monitoring and personalized medicine. Medical diagnosis tool requires intimate interfaces with our skin to detect the precise bio signals from our body. This paper explores innovative materials and mechanical design approaches aimed at enhancing the performance, comfort, and usability of such devices. There have been many progresses in materials and geometrical design to enhance the stretchability and wearing-comfort, which is essential aspect of wearable medical applications. The integration of advanced materials, and novel geometric design plays animportant role in ensuring the seamless integration of these devices into users' daily lives. The first section of the paper introduces the general technology of wearable electronics and current limitations for medical diagnosis application in terms of accurate interactions. Next section discusses materials, emphasizing the importance of biocompatible and skin-friendly materials for the construction of wearable health-care devices. Special attention is given to the latest advancements in flexible and stretchable materials, enabling the creation of conformable devices that can adapt to the dynamic movements of the human body.Then, we review the mechanical design strategies that focus on optimizing the form factor and structural integrity of wearable devices. Design considerations include the development of lightweight and thin-film structures, as well as the incorporation of modular components to facilitate customization and scalability. At last, we address the integration of sensor technologies with the mechanical framework, highlighting the need for seamless synergy between the device's form and function. This involves the incorporation of miniaturized sensors for vital sign monitoring, motion tracking, and environmental sensing, allowing for a comprehensive health assessment.

Keywords: Mechanical, Health-care.

INTRODUCTION

Wearable electronics is emerging field covering various kinds of research area ranging from bio-implantable device, skin-integrated biomedical device, soft robotics. By using this key technology, the integration of wearable health-care monitoring devices into our daily lives has become increasingly prevalent, offering the promise of personalized and continuous health tracking. These wearable devices, typically worn on the body, have revolutionized the traditional healthcare landscape by providing real-time data, personalized insights, and a continuous connection between individuals and their health metrics (Johnson *et al.,* 2021). Conventional health-care system has still many challenges to provide personalized treatment as it depends on a few numbers of doctors. In the future, medical system requires more personalized and accurate diagnosis system, especially for controlling the transmission of diseases, which helps to protect entire communities and populations from widespread outbreaks, reducing the overall burden on healthcare systems. To step forward to this efficient system, personalized wearable health-care system would be developed by integrating with various kind of advanced technologies. The integration of sensors, connectivity, and smart algorithms has paved the way for a new era in healthcare, fostering improved patient outcomes, preventive care, and enhanced overall well-being. The effectiveness of these devices hinges not only on advanced sensor technologies but also on the careful selection of materials and thoughtful mechanical design approaches. The biomedical research explores the domain of flexible and stretchable electronics crafted for monitoring health through wearable devices. It emphasizes the importance of replicating the physical traits of the skin to ensure adaptable and durable contact with the body's surface (Sang *et al.,* 2022). As the skin can deform up to 15%, electronic devices must not only flex to match skin contours but also stretch in tandem with natural body movements. The primary obstacle stems from the mechanical property differences between biological tissues and the materials composing electronic devices. The review delves into the realm of flexible and stretchable electronics designed for wearable health monitoring. It underscores the necessity of mirroring the physical characteristics of the epidermis to establish compliant and resilient contact with the skin. The skin's ability to deform up to 15% necessitates electronic devices not only to bend in conformity with skin topography but also to stretch during natural body motion. The central challenge lies in the mechanical property disparity between biological tissues and the materials constituting electronic devices. Our skin is soft and has curve-linear structure, which is easily deformed in dynamic movement of our body. For this reason, realization of soft medical device is prior issue. Researchers deploy a range of strategies to address this challenge. There are two strategies for improving mechanical and functional properties of wearable medical device: i) design soft materials and ii) geometrical design.We will address these two approaches and discuss how to improve the wearable platform for the future medical system.

Functional soft materials for on-skin electronics

Wearable healthcare devices have emerged as revolutionary tools that integrate technology with healthcare, providing individuals with personalized and real-time health monitoring. These devices are typically worn on the body and can track various health metrics, offering users valuable insights into their well-being. The importance of wearable healthcare

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devices extends beyond mere convenience, as they contribute significantly to proactive health management and the overall improvement of healthcare outcomes. By continuously monitoring health parameters, wearable devices empower individuals to take preventive measures. Early identification of potential health issues can lead to timely interventions, reducing the risk of more serious conditions and improving overall health outcomes. To fabricate the intimate skin-integrated wearable medical system, conventional bulky and rigid materials have many challenges in terms of mechanics and functions. The terms "electronic tattoo," "skin-like," and "epidermal" is related to functional devices that are attached to the skin and possess deformable physical characteristics such as thin, elasticity, strechability, and thermal masses that closely resemble those of the epidermis (Liu *et al.,* 2017). This similarity allows these devices to establish flexible and sturdy contact with the skin. The epidermis is capable of elastic deformation up to 15%, possessing an elastic modulus ranging from 10 kPa to a few hundred kPa. Consequently, any electronic device designed for the epidermis must not only be able to bend to match the skin's topography but also stretch to accommodate strains during natural body movements.

Figure 1 presents an overview of materials organized by their elastic modulus, along with typical strategies employed to create highly flexible and stretchable devices on the skin. It is evident that the most significant mismatch in mechanical properties often occurs between biological tissues (such as the brain, skin, and cartilage) and the materials utilized as active functional layers in electronic devices (such as silicon and gold). The polymeric materials supporting and encapsulating these devices exhibit elastic moduli much closer to those of biological tissues. One-dimensional and two-dimensional inorganic materials, including CNTs, graphene, and transition-metal dichalcogenides (TMDCs), exhibit promising electrical and mechanical properties (Qiao *et al.,* 2018; Kanoun *et al.,* 2021). Yet, their incorporation into flexible/stretchable systems is still in early stage of development. Metal oxides, with their diverse properties spanning electrical, optical, and acoustic domains, emerge as an alternative to organic and silicon materials. These oxides can be deposited on large scales at room temperature, boasting electron mobilities exceeding 10 cm²/(V s). Ongoing efforts in studying and engineering p-type oxide semiconductors can result in advances in flexible optoelectronics and digital circuits.

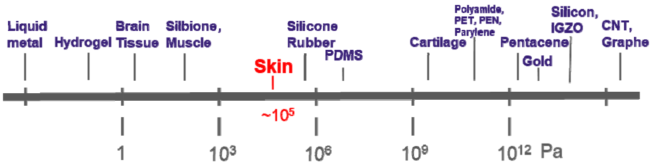

Figure 1. Modulus of skin comparing with potential materials

Geometrical parameters for providing stretch ability

To address issues arising from this disparity in mechanical properties among various materials, structural optimization of device layouts and the development of assembly schemes for active layers are common approaches.The thickness of an object is crucial, particularly when considering its mechanical properties, which scale with the cube of the thickness. Fortunately, recent advancements in thin-film processing and nanotechnology have facilitated the development and integration of extremely thin polymeric, metallic, and semiconducting materials to create active electronic devices. For instance, ultrathin single crystalline silicon nanomembranes (Si NMs), ranging from 100 to 200 nm in thickness, can be fabricated and transferred to thin-polymer substrates. This integration allows for bending to small radii of curvature without fracture, owing to a significant reduction in bending stiffness, once again proportional to the cube of the thickness.

Recent studies have also introduced methods for producing large-area organic and/or inorganic devices on ultrathin substrates, enabling bending radii as small as tens of microns, even when employing materials with relatively large elastic moduli. Another technique for enhancing mechanical stability involves encapsulating materials to position the active layers on the zero-strain plane (Figure 2). Basically, the elastic encapsulation layer could mechanically protect the active materials located in zero-strain plane by stress-relaxation process (Kim *et al.,* 2016). In addition to reducing thickness and employing high-performance materials, the mechanical stability of electronic devices can be enhanced through structural design.Adoption of serpentine or mech design is simple strategies to provide softness and stretchability to materials. Even rigid materials such as silicon, metal, and non-flexible plastic could be bent without mechanical failure with geometrical design. Serpentine is horseshoe-like design, which could provide mechanical stretchability by providing freedom of deformation in geometrical flexibility.

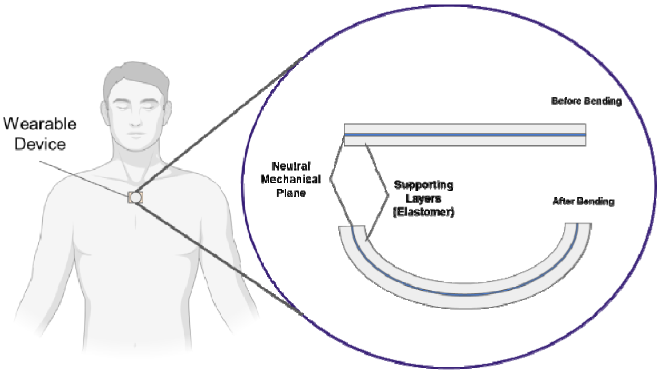

Figure 2. Mechanical zero plane for stable wearable medical device

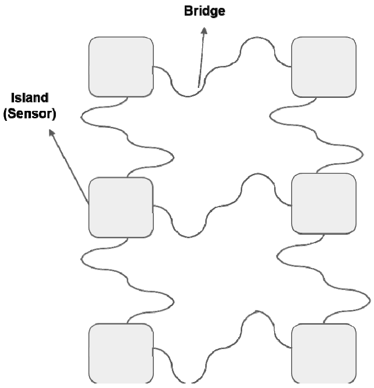

Figure 3. Geometrical design for providing deformability of wearable device

A prevalent strategy involves "island-bridge" layouts, where conductive traces (bridges) connect high-performance but rigid functional components (islands), as illustrated in Figure 3

(Zhang *et al.,* 2014). These conductive traces provide low effective stiffness, accommodating the stretching of the overall system while minimizing strains in the functional components themselves. Ensuring long-term reliability necessitates interconnects that deform solely elastically during use, avoiding plastic deformation that could result in accumulated damage over time. Serpentine-shaped structures, comprising periodic arcs and straight segments, find widespread adoption in connecting rigid islands atop soft elastomers. Going beyond the island-bridge layouts, additional strategies encompass transferring devices to pretensioned elastomers and employing tiling techniques.

Dimensions of functional nano materials

Designadvanced materials that can ensure intimate contact with the skin requires an explorationof the materials used for soft medical devices. Achieving softness, which could be characterized by modulus, is key process for developing wearable platform. Particularly, the wearing-comfort dominantly depends on modulus. If the mechcnial modulus is similar with skin, human might feel very comfortable when they wear the device. Metal nanomaterials possess flexibility and lightness compared to their bulk counterparts while providing electrical and thermal conductivities. By combining with stretchable elastomer matrix, they can create conductive pathway inside of the matrix, enabling soft and conductive nanocomposites. These nanostructured metal-based materials are categorized based on their dimensions, including 0-dimensional (0D, nanoparticles), 1-dimensional (1D, nanowires), and 2-demensional (2D, nanosheets) nanomaterials. While 0D nanomaterials have a higher percolation threshold than 1D or 2D counterparts, they enhance contact quality in percolated networks even in large stress as it can be rearranged freely inside of the matrix. 1D or 2D nanomaterials are more commonly used in conductive nanocomposites due to their lower percolation threshold. Nevertheless, 0D nanomaterials can improve the contact quality within the percolated network of 1D or 2D nanomaterials. Consequently, 0D nanomaterials are often used with 1D or 2D nanomaterials, creating a hybrid filler material type. This section will discuss further on soft conductive nanocomposites incorporating 0D, 1D, or 2D metal nanomaterials. Firstly, Metal nanoparticles (NPs), such as gold, palladium, silver, and platinum, exhibit unique electrical, thermal, and magnetic properties due to their small size. However, constructing a conductive percolation network with 0D metal nanomaterials alone is challenging due to low aspect ratio. As a solution, 0D metal nanomaterials are often added to nanocomposites with 1D or 2D nanomaterials to enhance electrical conductivity without compromising the mechanical properties of the original nanocomposites.One of widely used nanomaterial is 1D wire-based materials. 1D metal nanomaterials have significant advantage for creating highly percolated conducting networks. An effective approach to fabricate soft conductive nanocomposites with 1D metal nanomaterials involves generating a 2D percolated network of these nanomaterials on the surface of an elastic substrate. The surface is finally coated with an additional layer of elastomer. This method results in the formation of a 2D conductive network of metal nanomaterials embedded within the elastomer. Fabricating a 2D percolated metal nanowire network embedded in elastomer is a straightforward process. However, integrating this network with other device components is challenging because many elastomers, such as silicone and hydrogels, are incompatible with conventional patterning process, which is important process for design the platform. To overcome this limitation, molding or printing a homogeneous mixture of 1D metal nanowires in elastomer is considered a preferable method. This alternative approach facilitates the fabrication of diverse devices using nanocomposites. The use of 1D nanomaterials with a high aspect ratio and branched shape is recommended to enhance contact probability between filler materials,. Additionally, improving the quality of contacts can be achieved by removing insulating ligands through a washing process and implementing a welding process. Last form of nanomaterial is 2D plate-type nanomaterials. Metal nanosheets, nanoplates, and nanoflakes are categorized as 2D nanomaterials, possessing a high aspect ratio similar to 1D metal nanomaterials. These 2D metal nanomaterials hold significant potential for constructing a conductive percolated network within a polymer matrix. However, despite their high aspect ratio, the number of 2D metal nanomaterials is lower than that of 1D counterparts at the same weight fraction, leading to a reduced chance of contacts between them. Nevertheless, 2D nanomaterials, forming area contacts instead of point contacts seen in 1D nanomaterials, can exhibit lower contact resistance. Due to these advantages and disadvantages, both 1D and 2D metal nanomaterials are employed as filler materials for soft conductive nanocomposites, with 1D nanomaterials being more commonly used.

Ideally, using only one type of nanomaterial is preferred to quantitative research. However, it is still challenge to achieve high conductivity by using this approach. Combining two types of filler materials in stretchable conductive nanocomposites produces synergistic effects, enhancing overall performance compared to using a single filler type. This approach, utilizing dual materials with varied dimensions and mechanical properties, improves characteristics such as electrical conductivity, mechanical deformability, and magnetic properties. For instance, a hybrid strategy, such as combining nanomaterials with conducting polymers or different softness, strengthens the connectivity of conductive filler materials in the percolation network. This not only reduces the required nanomaterial amount for equivalent conductivity but also improves mechanical properties like high stretchability. The hybrid-type filler strategy can also add or enhance other properties, such as magnetic or thermal features.

Conclusion

In this review paper, we review the development of wearable health-care monitoring devices in terms of advanced materials and various promising strategies of mechanical design approaches to ensure optimal performance and user comfort. The choice of biocompatible and soft materials is crucial to prevent allergic reactions and skin irritations, while also ensuring durability and flexibility. As we reviewed above, soft materials are prior candidate in terms of mechanical properties and functionality. We need to design the functional soft materials, which has electrical functions such as conductivity, dielectric property, semi conductive property as well as mechanical softness. Another promising alternative way could be geometrical design of materials. With various mechanical structures, we could provide stretchability, softness and conformality, which could enhance the wearing comfort of wearable medical devices. As wearable health-care monitoring devices continue to play a vital role in revolutionizing personalized healthcare, the synergy between material selection and mechanical design will undoubtedly contribute to the success of these devices in providing accurate, real-time health data while seamlessly integrating into users' daily lives. This holistic approach not only fosters innovation but also addresses the multifaceted challenges associated with wearable health-care technology, ultimately paving the way for a more connected and proactive approach to individual health management

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