Flexible Electronics, as an emerging and exciting research field, have brought great interest to the issue of how to make flexible electronic materials that offer both durability and high performance at strained states. With the advent of on-body wearable and implantable electronics, as well as increasing demands for human-friendly intelligent soft robots, enormous effort is being expended on highly flexible functional materials, especially stretchable electrodes, by both the academic and industrial communities. Among different deformation modes, stretchability is the most demanding and challenging. This review focuses on the latest advances in stretchable transparent electrodes based on a new design strategy known as kirigami (the art of paper cutting) and investigates the recent progress on novel applications, including skin-like electronics, implantable biodegradable devices, and bioinspired soft robotics. By comparing the optoelectrical and mechanical properties of different electrode materials, some of the most important outcomes with comments on their merits and demerits are raised. Key design considerations in terms of geometries, substrates, and adhesion are also discussed, offering insights into the universal strategies for engineering stretchable electrodes regardless of the material. It is suggested that highly stretchable and biocompatible electrodes will greatly boost the development of next-generation intelligent life-like electronics.

1. Introduction

Flexible transparent electrodes (FTEs) have attracted enormous attention in the past few years owing to their critical role in flexible electronics. Doped metal-oxide films, exemplified by indium tin oxide (ITO) films, are optically transparent and electrically conducting, and have dominated the field of optoelectronics for quite a few decades. However, ITO films are brittle, and prone to rupture when subjected to small strains. For FTEs on elastomeric substrates, bending is a common deformation mode. There also are several other deformation modes, such as folding, twisting, and stretching, among which stretching is the most demanding and challenging owing to the large applied strains accompanying the deformation process. FTEs that are highly stretchable can also withstand bending, folding, and twisting. Accordingly, highly stretchable electrodes are attracting increasing efforts, leading to the burgeoning of a new branch of materials research known as stretchable electronics.

The rapid development of stretchable electrodes has boosted the emerging field of skin-inspired electronics, from novel soft electronic materials\(^1\) to prototype human-friendly electronic devices, including biocompatible electronics and soft robots, as well as conformal human–machine interfaces (Figure 1). In the future, our senses will be greatly extended by electronics that are built into our clothes and accessories, attached to our skin, and even implanted in our bodies.\(^2\) Such biocompatible electronics, including wearable,\(^3,4\) epidermal devices,\(^5–12\) and implantable electronics,\(^9–12\) are playing increasingly important roles in human-health monitoring and biomedical applications, which will significantly change the future of healthcare as well as our relationships with electronics. Meanwhile, due to the advancements in soft materials and flexible electronic technologies, tremendous progress has been achieved in bioinspired soft robotics\(^13–17\). Biomimetic soft robots with skin-like sensors and soft actuators are anticipated to interact with humans and surrounding environments with significantly enhanced safety, high sensitivity, and adaptive responses, enabling a complete human–robot loop with seamless and intimate interactions.\(^18–19\)

Stretchability is of little concern for applications of flexible electrode materials in optoelectronic industry, but rather emphasis is placed on the materials’ performance in regard to optical transparency and electrical conductivity, which have been summarized and well discussed in many reviews.\(^20–23\) The focus here is on the stretchable mechanics of transparent electrodes with up-to-date structural design strategies and considerations, as well as their state-of-the-art and pioneering conceptual applications in future soft and stretchable electronics. This review begins with the introduction of several promising materials for...
stretchable FTEs by summarizing their properties and applications, as well as their strengths and weaknesses. Next, structural design principles for large stretchability are described utilizing a novel design tool, i.e., kirigami (the art of paper cutting), which offers a universal strategy for engineering stretchable electrodes regardless of the material. Other critical design considerations, including substrates and adhesion force, are also discussed. Finally, the latest representative research examples in bioinspired electronics, including skin-like electronics, degradable implants, and biomimetic soft robots, are reviewed, indicating the trends and challenges of future soft and stretchable electronics.

2. Materials

The need for flexible, transparent, and conducting materials has led to extensive investigations on several classes of nanomaterials, such as carbon nanotubes (CNTs), graphene sheets, metal nanowires, 

\[ R = \rho / t \]

and their composites. As a one-atom-thick 2D material with excellent mechanical and electrical properties, graphene shows great potential for flexible electronics.

The sheet resistance of a 2D film is expressed as \( R_{\text{sh}} = \rho / t \), where \( \rho \) is the electrical resistivity and \( t \) is the thickness of the film. High-quality graphene exhibits a sheet resistance \( R_{\text{sh}} \) of 100–1000 \( \Omega \text{ sq}^{-1} \) with a transparency higher than 90%. Electrodes made of graphene films show impressive mechanical bendability, making it a promising candidate for flexible touch screens.

Graphene sheets can also be stretchable. Previous studies have shown that large-scale graphene films grown by chemical vapor deposition can be stretched up to 30%, or repeatedly stretched to 6% for a few cycles. This might be attributed to the delocalized microcracks formed in the graphene films upon strain, which can accommodate applied strains by deflecting out-of-plane and retard strain localization in the stiff film accordingly. Moreover, by maintaining the percolating network of stacked graphene sheets with the addition of nanobridges, graphene electrodes can be even more stretchable with tensile strains up to 120%. Another widely used 2D thin film material for FTEs is poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS). Simply by spin coating, PEDOT:PSS films show a sheet resistance of 46 \( \Omega \text{ sq}^{-1} \) with a transmittance of \( \approx 82\% \) (at 550 nm). Thin PEDOT:PSS films are stretchable, and have been widely used in polymer light-emitting diodes (PLEDs), organic solar cells, organic thin film transistors, and supercapacitors. However, both graphene and PEDOT:PSS films show a relatively low conductivity, which limits their further applications in high-performance optoelectronics.

Theoretically, ultrathin metal films made of highly conducting metals such as Ag, Cu, and Au present a low sheet resistance and a high transparency that are superior to those of ITO films. If ignoring the nanoscale effect, a 1 nm thick Ag film has a sheet resistance of 16.5 \( \Omega \text{ sq}^{-1} \) and is nearly transparent at this thickness. However, owing to the Ostwald ripening effect with the formation of isolated metal islands, many thin metal films (e.g., Ag and Au) are not conductive until the film thickness exceeds a percolation threshold. Accordingly, the conductive metal films of increased thickness become opaque. Recently, a few methods have been proposed to make ultrathin but continuous metal films. Such thin metal films can be cyclically bent, stretched, and even scratched multiple times, exhibiting good mechanical durability. By applying a layer of transparent conducting polymer (i.e., PEDOT:PSS) as an anti-reflection coating (ARC), the optical transmittance of thin metal films can be further improved to >90% at a sheet resistance of

Siyang Huang is a research assistant professor in SUSTech Academy for Advanced Interdisciplinary Studies, Southern University of Science and Technology, China. She received her Ph.D. degree in materials science and engineering from Tsinghua University in 2014, followed by a postdoctoral period at the University of Houston, USA, from 2014 to 2017. Her scientific interests include the design and fabrication of nanostructured functional materials and their application in nanosensors and flexible electronics.

Zhefeng Ren is the M.D. Anderson Chair Professor in the Department of Physics and Director of the Texas Center for Superconductivity at the University of Houston. He received his Ph.D. from the Institute of Physics, Chinese Academy of Sciences. He was a postdoctoral fellow and research professor at SUNY Buffalo before joining Boston College as an associate professor. He specializes in thermoelectric materials and devices, flexible transparent electronics, photovoltaics, carbon nanotubes, superconductors, highly conductive materials, etc.

Chuan Fei Guo is an associate professor in the Department of Materials Science & Technology, Southern University of Science and Technology, China. He received his Ph.D. degree in condensed matter physics from the National Center for Nanoscience and Technology, (NCNST), Chinese Academy of Sciences, China. From 2011 to 2016, Dr. Guo worked as a postdoctoral fellow and research associate at Boston College and the University of Houston. He has ten years of experience in flexible electronics and advanced manufacturing.
Polymer solar cells using such electrodes exhibit a high power conversion efficiency of 10% and PLEDs using them outperform those based on conventional transparent conducting oxides. The method of depositing a layer of ultrathin and continuous metal films is far simpler and more cost-effective than doped metal oxide films, making it a promising method for manufacturing FTEs for practical applications.

Another class of FTEs is the network of 1D conducting nanomaterials, such as CNTs, and their composites. CNTs were first reported as flexible transparent electrodes in 2004 and have since been extensively explored for flexible electronics, including flexible energy storage devices and skin-like electronics. By uniaxial alignment of spring-like CNTs or CNT ribbons, highly stretchable transparent CNT films can be obtained with tensile strains of over 100%. However, CNT networks cannot exhibit good electrical conductivity and high optical transparency simultaneously, limiting their further applications in optoelectronic devices. Compared with CNTs, metal nanowires are much more conductive. During the past decade, numerous reports on low-temperature synthesized and solution-processed metal (Ag, Cu, etc.) nanowires have been presented, leading to much easier and cheaper manufacture of metal-nanowire-based FTEs. Among them, Ag nanowires exhibit the best optoelectrical performance at 89% transparency, superior to that of ITO films. AgNWs were first used as transparent electrodes for organic solar cells in 2008. Following this report, intensive investigation has been carried out to improve the overall performance of metal-NW electrodes. The Wiley group synthesized 20 nm thick AgNWs with an aspect ratio of >2000, and the AgNW network exhibits a sheet resistance of 130 Ω sq\(^{-1}\) at 99% transparency. The high transparency might be related to the fact that the thickness (20 nm) of the nanowires is far smaller than the wavelength of visible light (400–760 nm), so the nanostructures do not scatter light effectively. Owing to their superior optical transparency, flexible electrodes based on uniform AgNWs with a high aspect ratio are regarded as an ideal candidate for displays. AgNW inks and films have been commercialized, demonstrating their enormous potential as alternatives to ITO films. Although slightly less conductive, Cu is 1000 times more abundant and 100 times cheaper than Ag, making Cu nanowires (CuNWs) another popular candidate for flexible electrodes.

The metal-nanowire networks can be simultaneously highly conductive and transparent. However, such electrodes cannot maintain a fairly low sheet resistance under increased tensile strains. This is because the wire-to-wire junctions will break upon stretching, resulting in huge increases in contact resistance in the range from several ohms to gigaohms. Numerous studies have been reported on reducing or eliminating the wire-to-wire junction resistance. For example, AgNW percolation networks modified with graphene oxide show good optoelectrical properties as well as greatly enhanced stretchability up to 130%. The Cui group fabricated an interconnected metal network based on a nanotrough structure that completely eliminated the wire-to-wire junction problem, showing a one-time stretchability up to 50% in combination with impressive electrical conductance and optical transparency.

Ionic conductors, generally based on hydrogels containing salts, are emerging rapidly as a new class of transparent flexible electrodes. Ionic conductors exhibit a transparency close to 100% over the whole visible range and can be stretched to 100–1000%. Although ionic conductors have a much higher sheet resistance compared with electronic conductors at the strain-free state, their sheet resistance is lower than most stretchable electronic conductors at highly stretched states. In addition, ionic conductors are capable of operation at frequencies beyond 10 kHz and voltages above 10 kV, making applications in high-frequency devices possible. Ionic conductors can also be applied in biodevices by building nondamaging interfaces for ionic/biological and ionic/electronic signals. However, dehydration remains a major challenge for the long-term use of ionic conductors in actual applications.

Liquid metals are compelling materials for soft and stretchable electrodes as they are metallic conductors with infinite deformability. Different from mercury, gallium, and its alloys have low toxicity and are relatively safe to work with, offering great promise for flexible, stretchable, and soft, as well as reconfigurable, electronics. Recently, optically transparent and elastic liquid-metal-based circuits were realized by direct laser writing, demonstrating a low sheet resistance of 2.95 Ω sq\(^{-1}\) with a strain limit >100%. Benefiting from the combination
of metallic and fluidic properties, novel applications have been enabled by liquid metals. For example, self-healing stretchable wires, which can be used in reconfigurable circuit wiring, were reported by combining liquid metals and self-healing polymers.\(^\text{[80]}\) Highly stretchable triboelectric nanogenerators for wearable power sources were realized by using liquid metals as the electrode, demonstrating outstanding device stability under strains up to \(\approx 300\%\).\(^\text{[81]}\) Despite their promise, existing challenges have to be addressed for the widespread application of liquid metals, such as the chemical stability of liquid-metal inks,\(^\text{[82]}\) the unstable electrical contacts between liquid metals and other metal interconnects,\(^\text{[83]}\) and the controlled motion of liquid metals.\(^\text{[84]}\)

3. Stretchable Structural Designs

Typically, materials that are both highly conductive and transparent are not stretchable. However, by structural design with tailored geometries the intrinsically stiff materials can be structurally stretchable. Figure 2 illustrates the underlying deformation mechanisms: 1) Stiff materials with a 1D wavy (serpentine or spring-like) structure can be stretched. When the structure is pulled, the geometry changes its amplitude accordingly to accommodate the applied strain without causing stress concentration in the material itself (Figure 2a). The out-of-plane deformation plays an important role for the large stretchability. The Rogers group has adopted fractal and nested self-similar serpentine sub-millimeter 1D structures as the electrical interconnections for stretchable electronics,\(^\text{[85]}\) stretchable lithium ion batteries,\(^\text{[86]}\) and epidermal electronics.\(^\text{[7]}\) 2) Stiff materials can be stretched if tailored into a network. For example, although a piece of paper cannot be stretched, a paper mesh can be highly stretchable (Figure 2b).\(^\text{[87]}\) 3) If a metal film is engineered into a percolating network with ligaments tailored into serpentine shapes, it becomes highly stretchable (Figure 2c). Thus, a percolating network of metal serpentine ligaments is an ideal structure for stretchable transparent electrodes. Technically, it is difficult to fabricate a network of serpentine structures with nanoscale features in a cost-effective way. By using a novel method, called grain-boundary lithography, we have successfully synthesized 2D Au nanomeshes of interconnected serpentine ligaments (Figure 3a), exhibiting exceptionally large stretchability with optical transparency and sheet resistance comparable to ITO films.\(^\text{[87]}\) The Au nanomesh on PDMS can be stretched one time to 160% with the sheet resistance increasing from 21 to 65 \(\Omega\) sq\(^{-1}\), and it can be cyclically stretched to 100% for 1000 cycles with sheet resistance increasing by only a few times. The large stretchability stems from two aspects. First, in the elastic regime, the stretchability lies in the fact that the meshes are elongated and the ligaments can easily deform out-of-plane. Second, beyond the elastic regime, distributed cracks form and

![Figure 2](image_url)

Figure 2. a) Stretchable 1D structures: wavy (upper) and spring-like (lower) geometries. b) Stiff materials such as paper that cannot be stretched become stretchable if tailored into a network by kirigami cutting. Reproduced with permission.\(^\text{[87]}\) Copyright 2014, Nature Publishing Group. c) Networks with straight (left) and serpentine (right) ligaments are both stretchable, and the latter shows greatly improved stretchability.
the nanomesh deforms into a larger network with a nested self-similar layout. Such a hierarchical network gives rise to the large stretchability. This is quite similar to the design of 1D self-similar interconnects from the Rogers group (Figure 3b), for which the stretchability can be significantly improved by using two levels of wavy structures. However, in contrast to the 1D self-similar serpentine structure, theoretically the metal nanomesh can be infinitely stretched if the size of the network is large enough. As the size of cracks increases, the mesh becomes more stretchable. As long as the crack size is far smaller than the width of the network, the network remains electrically conductive. Recently, we successfully designed and fabricated a highly stretchable transparent electrode combining nanomeshes with well-defined 1D wavy structures. By applying prestrains an in-plane buckled structure was introduced into the interconnected Au nanotrough network, resulting in large stretchability up to 300% and cyclic stretching to 100% for 100 000 cycles with no fatigue. Such multilevel stretchable geometries offer a new design strategy for ultrastretchable electronics.

Macroscale paper models can be used to mimic the deformation mode of the Au nanomesh. In the elastic regime, the deformation is determined by the structure rather than the scale or the intrinsic mechanical properties of the material. This viewpoint has been widely accepted in metamaterials to design materials with negative Poisson’s ratios. The Suo group adopted this method to study the stretchability of 1D materials early in 2005. Blees et al. used paper kirigami to mimic the deformation of graphene meshes and observed that the nanoscale graphene deformed in the same way as the macroscale paper mesh. Shyu et al. also used the same kirigami pattern to engineer elasticity in intrinsically rigid nano-composites, resulting in a significant increase of ultimate strain from 4 to 370% (Figure 4a). Our group demonstrated that the stretchability of kirigami patterns could be changed by tuning the topology with serpentine lines (Figure 4b). Inspired by the results of the paper models, the Au nanomesh can be engineered into particular patterns with high stretchability up to 300% while exhibiting a sheet resistance of 28 Ω sq$^{-1}$ and optical transmittance larger than 90% at the highly strained state (Figure 4c). The Rogers and Huang’s group further demonstrated that the kirigami approach can be applied to 3D mesostructures in micro/nanomembranes. All of these studies illustrate one principle: high deformability can be achieved in rigid materials by structural designs regardless of the intrinsic mechanical properties or the size of the material. Therefore, it is valid to use large-scale paper kirigami or other macroscale materials to study the stretchability of nanostructured materials, such as metals, graphene, composites, ceramics, and even multilayer devices. Additionally, other novel applications have been enabled by kirigami designs. For example, dynamic kirigami structures were constructed for efficient solar tracking in thin-film solar cells (Figure 4d).

![Figure 3. a) Fabrication of metal nanomeshes of interconnected nanoserpentines by grain-boundary lithography (left). Scale bars, 500 nm. Upper right: sheet resistance ($R_s$) and relative sheet resistance change ($R_s/R_0$) (inset) as a function of tensile strain for Au nanomeshes. The sample with a mesh-size to line-width ratio ($M/W$) of 18 (red triangles) shows better stretchability than that with $M/W$ of 8 (black squares). Lower right: change in resistance versus cycles (up to 1000 cycles) of Au nanomeshes. Magenta symbols represent 100% strain while black symbols represent 50% strain. Reproduced with permission. Copyright 2014, Nature Publishing Group. b) Optical image of the Cu electrode pads and self-similar interconnects on a Si wafer (left, scale bar is 2 mm), and experimental and computational studies of stretchability of interconnects with self-similar serpentine layouts (right). Reproduced with permission. Copyright 2013, Nature Publishing Group.](image-url)
4. Effect of Substrates and Adhesion

In stretchable electrodes, the roles of substrates as well as the interfacial adhesion strength between the conductive material and the underlying substrate are often neglected. However, the mechanical properties of the substrate are of critical importance. Generally, the substrate should be soft enough to allow conductive materials to deform out-of-plane. For example, in a Au nanomesh/PDMS bilayer system, the large difference of the Young’s modulus between Au and PDMS (five orders of magnitude) allows the Au ligaments to deflect into the substrate freely, so that the stretchable geometry of Au can work effectively. If the Young’s modulus of PDMS substrate were close to that of Au, this deformation mode would not take effect and the Au mesh could not be stretched accordingly.

Adhesion force also plays an important role since the interfacial force between the metal nanomesh and the underlying PDMS affects the rupture modes of the metal mesh upon stretching. When the adhesion is poor, the overall stress level in the metal nanomesh is relatively low, but the localized stress is high enough to cause ruptures at some points. Proper adhesion can effectively prohibit the existing cracks from developing into catastrophic ones and allows cracks to emerge elsewhere. As a result, the cracks are distributed uniformly across the entire film, and overall the metal nanomesh is still interconnected and electrically conductive even when it is highly stretched. This rupture mode is recognized as “delocalized rupture” or “distributed rupture” (Figure 5a).

With stronger adhesion, the crack size becomes smaller at the same strain level. When the adhesion is too strong, the nanomesh breaks into isolated islands at elevated strains and the cracks form a network (i.e., a complementary geometry with delocalized rupture), which would no longer be electrically conductive. This failure mode is known as “localized rupture” (Figure 5b). For localized rupture, the metal nanomesh network cannot form dense and delocalized cracks since the ligaments of a metal nanomesh network cannot slip locally upon straining. Experimental results have shown that the Au nanomesh completely fails at 65% strain when it is firmly bonded to a sticky PDMS substrate, while on untreated PDMS substrates with proper adhesion it can be stretched to strains larger than 200% (Figure 5c). These results clearly demonstrate that proper adhesion is critical to the stretchability of networks, and neither weak nor strong adhesion is beneficial for good stretchability (Figure 5d). This raises a concern that poor stretchability may result when we try to improve the scratch resistance of electrodes by enhancing the adhesion, or when electrodes are embedded in devices with a multilayered layout (e.g., PLEDs, organic solar cells). To be clear, the effect of adhesion on stretchability can be improved for continuous films because debonded films typically rupture at a small strain of ~1%. Applying a prestrain might be effective for improving the stretchability of...
well-bonded or embedded metal networks. However, prestrains in films may cause surface wrinkling or folding, which leads to adverse effects such as high surface roughness with a haze problem. With proper structural designs, in-plane buckled structures could be obtained, which show great promise as transparent electrodes for stretchable device integration.[102]

5. Applications

For optoelectronic devices, large stretchability is not a prerequisite because in most cases they are only required to be bendable or foldable (e.g., foldable mobile phones[103] and wearable smart lenses[104]). In comparison, epidermal and implantable electronic devices are expected to be stretchable in order to accommodate the complex deformations of skins or biological tissues. Some tissues and organs of the human body are under constantly repeated large strains. For example, organs such as the heart, arteries and alveoli undergo periodic areal strains of up to several tens of percent. The commonly used needle-like or membrane-like electrodes cannot be mounted on the surfaces of such organs or tissues, and thus they are unable to detect useful physiological signals or exert in-vivo medical treatments. Therefore, highly stretchable and conformable electrodes are becoming indispensable for skin-like electronics, which offer promise for next-generation healthcare and biomedical applications.

5.1. On-body Applications

Stretchable electrodes are found in many inspired applications on and in our bodies, ranging from wearable and on-skin devices to implanted electronics. Owing to the intrinsic flexibility, breathability, and comfort of fabrics, smart textiles are receiving increasing attention by offering a versatile platform for seamless integration of portable electronics into our daily life.[105] By coating with electronically active materials (e.g., carbon,[106] electrode composites/metal,[107] and conjugated polymers[108]) or by direct carbonization,[109,110] these commonly available, mass-producible, and cost-effective fabrics, yarns/threads, and garments can be transformed into various wearable electronics. As depicted in Figure 6, a myriad of physical and physiological measurements can be performed via wearable electronics. For example, real-time monitoring of muscle activities (e.g., walking,[111] jogging,[112] and eye blinking[113]) can provide valuable information (e.g., plantar pressure distribution, electromyography, and motion frequency) for clinical gait analysis, muscle fatigue evaluation, and assessment of a person’s fatigue state, which can improve exercise performance and even prevent unexpected catastrophic situations. Owing to the recent advances in flexible epidermal electronic technologies, continuous and long-term tracking of vital physiological signals, such as heart rate,[4] artery pulse pressure and temperature,[114] blood flow,[115] and blood oxygen,[8] can be realized during daily activities in a manner that is mechanically invisible to users. Moreover, diseases, such as diabetes and glaucoma can be diagnosed and managed with noninvasive skin-like sensors that offer real-time detection of indicator levels (e.g., blood glucose concentration and intraocular pressure) with transcutaneous therapeutic treatment.[3,93,94] With the advent of biocompatible and bioresorbable materials, flexible implantable electronics have been developed for in vivo recording of internal conditions (e.g., intracranial pressure and temperature[116], electrophysiology (e.g., electrocardiography (ECG)[117,118] electrocorticography (ECoG)[112] and electrospinography),[11] and clinical biomedical therapy,[119] offering desirable qualities as compared with commercially available clinical devices. Through intimate and conformal interfacing with dynamic curvilinear tissues, biodegradable, transient implants can provide accurate and reproducible measurements of neural signals and physiological activity, while eliminating the risks, cost, and damage associated

Figure 5. a,b) SEM images of distributed and localized ruptures of Au nanomeshes at a strain of 100% and 80%, respectively. c) Resistance change as a function of tensile strain for Au meshes on as-cured (A-AuNM, red circles), chemically bonded PDMS (S-AuNM, black squares), and embedded AuNM (blue triangles). d) Finite elemental analysis of the stress and the deformation of the ligaments of a nonbonded Au nanomesh (left) and a perfectly bonded Au nanomesh (right) supported on a PDMS substrate. All panels reproduced with permission.[101] Copyright 2016, American Chemical Society.
with secondary surgical extraction.\textsuperscript{[12,120–123]} Additionally, soft neural interfaces hold great promise for modulating physiological functions and treating neural disorders (e.g., chronic pain), as well as for neuroprosthetic applications.\textsuperscript{[9,11,65]} The Lacour group developed a conformal “e-Dura” implantation by using flexible metal electrodes and used it to restore locomotion of the paralyzed rats with spinal cord injuries through electrical stimulation.\textsuperscript{[11]} The Bao group has proposed and engineered bioinspired mechanoreceptors and artificial afferent nerves that can detect pressure and integrate action signals by stimulating somatosensory neurons, suggesting potential applications in neurorobotics and neuroprosthetics.\textsuperscript{[65,67]}

Electronic wearables and implants rely on power sources for operation. Conventional energy storage devices are bulky and rigid, and they are unable to accommodate dynamic body strains for use as wearables. To realize truly autonomous wearable operations, integration of flexible and stretchable power sources into wearable systems is highly desired. By using novel stretchable electrodes and by adopting particular structural designs (e.g., helical springs and serpentines), considerable progress has been seen in flexible energy storage devices, including batteries\textsuperscript{[37,86,107,124,125]} and supercapacitors\textsuperscript{[62,64,110,126]} which demonstrate substantial promise for the realization of untethered wearable systems. Recently, emerging technologies for harvesting power from biological systems have offered attractive alternatives for self-sustainable biomedical devices. In vivo powering of wearables and implants (e.g., cardiac pacemakers) have been demonstrated with biocompatible piezoelectric and triboelectric generators, which can harvest mechanical energy directly from natural motions of the living body, such as walking, arm shaking, and hand patting;\textsuperscript{[81]} arterial pulses;\textsuperscript{[127]} breathing;\textsuperscript{[128]} and contractile and relaxation motions of the heart, lungs, and diaphragm.\textsuperscript{[129]} It is expected that such self-powered wearables can solve the power consumption issue for implantable and wearable healthcare devices.

5.2. Bioinspired Soft Robots

Soft robotics has grown into a popular research field in the past few years. Compared to conventional robots, soft robots have many admirable features, such as safe human–machine

Figure 6. On-body applications of flexible electronics enable continuous and long-term tracking of vital physiological signals, disease detection, and medical therapy.
interaction, adaptability to dynamic environments, simple control systems and low cost, all of which enable a wide range of novel applications that cannot be achieved by conventional cold, rigid machines. Soft robots are especially suitable for those challenging tasks in which robots are in intimate contact with biosystems, such as minimally invasive surgery, implantable medical therapy, and rehabilitation assistance. Additionally, soft robotic technologies can help to build life-like artificial organs (e.g., human body simulators) and prostheses. With a bionic aesthetic appearance as well as spatiotemporal sensing and transduction abilities, such prostheses can significantly improve the user’s experience.

In nature, soft tissues are constantly interacting with dynamic and complicated environments in an effective, adaptable, and robust way. Inspired by living creatures, biomimetic robots that have skin-like sensory perception and are capable of complex motions are under intensive investigation, where the introduction of soft materials into the design and building of robots is key. E-skins are emerging rapidly as a new research field with the goal of matching or even surpassing the performance of human skin. Mechanical compliance is a prerequisite for e-skins to accommodate complex dynamic environments while maintaining their multiple functionalities. In this regard, an ultralight and flexible design has been developed for compliant electronics, enabling the integration of imperceptible sensing systems with great conformability to 3D surfaces (Figure 7a).

Natural skin, as the interface of living creatures with the outside environment, provides versatile functionalities to facilitate many of their essential activities. For example, human skin can respond to numerous tactile and thermal stimuli, exhibiting a remarkable capacity for object recognition, texture discrimination, slip detection, temperature sensing, and sensory-motor feedback. However, commercial artificial skin and prosthetic limbs have neither tactile sensing, nor the ability to communicate with the brain. The Kim group demonstrated smart prosthetic skin equipped with flexible strain, pressure, and temperature...
sensors; associated humidity sensors; electroresistive heaters; and stretchable multielectrode arrays, providing multisensory reception with compliant interfacing with the peripheral nervous system (Figure 7b).[141] Inspired by the visual communication and camouflage strategies employed by cephalopods, a hyperelastic light-emitting capacitor capable of touch sensing and active color changing has been designed and integrated into the skin of a soft robot, providing dynamic coloration and sensory feedback from both external and internal stimuli (Figure 7c).[142]

Additionally, natural sensory receptors are found in high densities in sensitive areas of human skin, such as the fingertips, providing high-resolution force information useful for object shape and texture discrimination.[138,143–145] The Bao group introduced a fabrication process for highly flexible transistor arrays with high yield and uniformity based on intrinsically stretchable polymers. Such mechanically compliant and robust transistor arrays show an unprecedented device density and device count that enable them to surpass the spatial resolution of biological skin (Figure 7d).[66]

Self-healing is another vital function of human skin, the emulation of which allows e-skins to function reliably as protection barriers and to continuously sense the dynamic environments despite being subjected to constant damage. A number of strategies have been exploited to incorporate the self-healing capability into electronic materials. For example, skin-like healable field-effect transistors were reported by introducing weak hydrogen bonding into semiconducting polymers as noncovalent dynamic cross-linkers (Figure 7e).[146] The field-effect mobility of these stretchable organic transistors can be fully recovered after a solvent and thermal healing treat-
ment. Flexible piezoresistive e-skins composed of a urea-based polymer with nanostructured nickel microparticles have also been developed, demonstrating a repeatable self-healing property within a healing time of 15 s (Figure 7f). \[147\] Recently, a hydrogel-based mechanically adaptable ionic skin was reported, exhibiting high pressure sensitivity as well as autonomous self-healability (Figure 7g). \[148\]

In addition to the skin-like sensory perception endowed by e-skins, biomimetic behaviors enabled by various soft actuators are receiving extensive efforts. In line with the intricate biological motions, biomimetic soft actuators are engineered with the capabilities of large and continuous deformations with theoretically infinite degrees of freedom. Thereinto, flexible electrodes are the critical components for a major class of electrically driven soft actuators. To date, a variety of flexible conductive materials and stretchable geometric designs have been developed to accommodate the large strains accompanying the actuation process of highly deformable soft robots. For instance, a self-contained soft composite material composed of a silicone elastomer with fluid-filled micro bubbles has been fabricated and can be electrically actuated by a spring-like resistive wire, exhibiting large strains up to 900% upon liquid-vapor transition (Figure 8a). \[149\] Fully soft robots have been constructed with open-mesh patterned ultrathin gold electrodes as heaters for thermally responsive artificial muscles, demonstrating adaptive crawling locomotion like an inchworm (Figure 8b). \[150\] Compliant metal electrodes with particular designed patterns have also been widely used in dielectric elastomer actuators (DEAs) and biohybrid systems. For example, soft grippers with a sandwich-like DEA structure are able to manipulate deformable, fragile, and even flat objects by employing a compliant interdigitated electrode geometry (Figure 8c). \[151\] Notably, a batoid-fish-inspired biohybrid system was designed with integration of flexible Au microelectrodes in a serpentine layout. \[152\] By mimicking the alignment of the skeletal and muscular architecture of a stingray, such bioinspired soft robots can provide self-actuating motions (Figure 8d). Other compliant conductive materials such as printed conductive wires (Figure 8e) \[153\] and carbon black (Figure 8f) \[154\] have also been reported, enabling the overall mechanical compliance of soft actuator modules.

Recently, ionic hydrogels and ionic fluids have emerged as inexpensive, compliant, and transparent electrodes for DEAs. \[77,155\] Because these novel conductive materials are optically transparent, leptocephali-inspired camouflage and stealth sailing capabilities can be realized in soft-bodied robots that are driven by a soft electroactive structure consisting of DEAs and ionically conductive hydrogels (Figure 9a). \[156\] The Tolley group reported a translucent swimming soft robot consisting of DEAs with frameless fluid electrodes (Figure 9b), suggesting its potential applications in surveillance and the unobtrusive study of marine life. \[155\]

6. Summary and Perspectives

To conclude, stretchable electrodes are critical and indispensable components of flexible electronics. Strategic designs and fabrication of highly stretchable and fatigue-free electrodes enable novel applications including on-body electronics, implantable...
devices, and soft robots, as well as compliant human–machine interfaces. In addition to good mechanical compliance with soft body tissues and artificial muscles, unique properties such as biocompatibility and biodegradability are also highly desirable for implantable electronics, enabling safe intimate biointegration without the additional risk, cost and damage associated with secondary surgeries. Soft robots with skin-like sensors and biomimetic actuators are changing the way we see and interact with machines. The rapid development of e-skins and artificial muscles has enabled next-generation life-like robots that have skin-like sensory perception and are capable of complex motions.

Despite the inspiring progress achieved thus far, considerable challenges still coexist with the huge opportunities in this field. Flexible hybrid healthcare monitoring systems, fusing physical, chemical, and electrophysiological sensors on the same wearable platform, are in ever-increasing demand since they can offer a more comprehensive picture of an individual’s physiological state. Additionally, the development of integrated autonomous smart systems, which consist of multiple flexible electronic components including sensing, actuation, data transmission and analysis, power sources, and even sustainable power harvesting units, represents a rising trend in soft electronics. Such smart systems are expected to embody a closed feedback loop that can be responsive to both internal and external stimuli in real time. It is foreseeable that with the advent of the era of soft electronics and artificial intelligence, the conformal integration of stretchable electrodes and electronics into living bodies, as well as the development of fully soft bodied robots with sophisticated architectural designs and a closed sensing-actuation feedback loop, will become increasingly important interdisciplinary topics in the near future.

Acknowledgements
S.H. and Y.L. contributed equally to this work. This work was supported by the National Natural Science Foundation of China (Nos. 51771089 and 51802141), the “Guangdong Innovative and Entrepreneurial Research Team Program” (under Contract Nos. 2016ZT06G587 and 2017ZT07C071), the “Science Technology and Innovation Committee of Shenzhen Municipality” (Grant Nos. JCYJ2017081711714314 and JCYJ20160613160524999), and the work performed at the University of Houston is supported by the Basic Energy Science Program of the U.S. Department of Energy under Contract DE-SC0010831.

Conflict of Interest
The authors declare no conflict of interest.

Keywords
e-skins, flexible electronics, kirigami, soft robotics, stretchable transparent electrodes

Received: August 24, 2018
Revised: September 27, 2018
Published online:

学霸图书馆

www.xuebalib.com

本文献由“学霸图书馆-文献云下载”收集自网络，仅供学习交流使用。

学霸图书馆（www.xuebalib.com）是一个“整合众多图书馆数据库资源，提供一站式文献检索和下载服务”的24小时在线不限IP图书馆。

图书馆致力于便利、促进学习与科研，提供最强文献下载服务。

图书馆导航：

图书馆首页 文献云下载 图书馆入口 外文数据库大全 疑难文献辅助工具