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Engineering the Comfort-of-Wear for Next Generation Wearables

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Wearable technologies are becoming important for the fields of information technology and healthcare, driven mainly by societal issues such as the aging society and the current pandemic. Recently developed flexible/stretchable wearable devices have demonstrated their ability for long-term healthcare monitoring with improved signal integrity and multimodality. However, the adherence of wearers to such wearable devices cannot be determined only by the function. Here "comfort-of-wear" is identified as one of the most critical parameters for future wearables, similar to how clothes are chosen based on how comfortable they are. "Comfort-of-wear" is defined as the device's ability to not to disturb the wearers' daily life. Several engineering approaches are introduced to improve the comfort-of-wear of devices—via strategies that include improving flexibility by utilizing a combination of structures, materials, and systems. Finally, the future of wearables enabled by cutting-edge advanced electronic technologies is proposed.

1. Introduction

Wearable devices are becoming a normal part of everyday life. In addition to functions like notifying you of recent updates in your social network or your schedule or storage of payment information, their ability to monitor the health of its wearer is of importance especially under crises like a world-wide pandemic or the aging society. The rigid and compact body of commercialized wearables can monitor our heart rate or blood oxygen levels (SPO_2) by photoplethysmography (PPG) and our heart's electrical activity by electrocardiography (ECG). In addition, they can monitor body activities and state (exercise, sleep, body temperature, and stress levels) which are useful for the detection of irregularities in our bodily function.

Still, the skin contact area, which is the interface where physiological signals are obtained, is limited. Although conventional electronic materials are rigid, structural engineering approaches or soft electronic materials approaches have realized soft and conformable devices that can wrap over the complex shape of our body.[1,2] Among other things, imparting skin conformability to the device can significantly improve the signal integrity and reduce motion artifacts.[3,4] Improved mechanical flexibility enables highly sensitive sensors for physical parameters such as strain, pressure, and temperature.[5–8] Furthermore, fluid-based sensors have been realized including sweat-chemical sensors.[9–11] Moreover, skin-conformable displays have been realized to let wearers know the result of the physiological signals monitored by soft sensors.[12–15]

In addition to their sensing capability, it is very important to design for the "comfort-of-wear" of wearable devices. Comfort-of-wear can be defined by how the devices worn by the wearers can minimize the irregularity caused by the device's physical existence in their daily activities. This concept, among others, regulates the wearer's willingness to wear a wearable device. Although the comfort-of-wear of current rigid wearable devices (e.g., wristwatches or rings) is partially achieved by their small size, it is not enough for expanding the usage of wearable devices. For example, some people choose not to wear a watch or a wedding ring because of how it feels to wear. Small children or people with dementia tend to remove any irregular things (e.g., healthcare sensors and jewelry) on their body as their importance is difficult to be understood. Besides, the small area of current wearable devices limits the interaction with the wearers (e.g., display size and number of sensors). It is necessary to develop engineering approaches to make comfort-of-wear possible even if the device area is large. We predict that comfort-of-wear will be one of the deciding criteria for the further proliferation of next-generation healthcare monitoring devices (**Figure 1**a).

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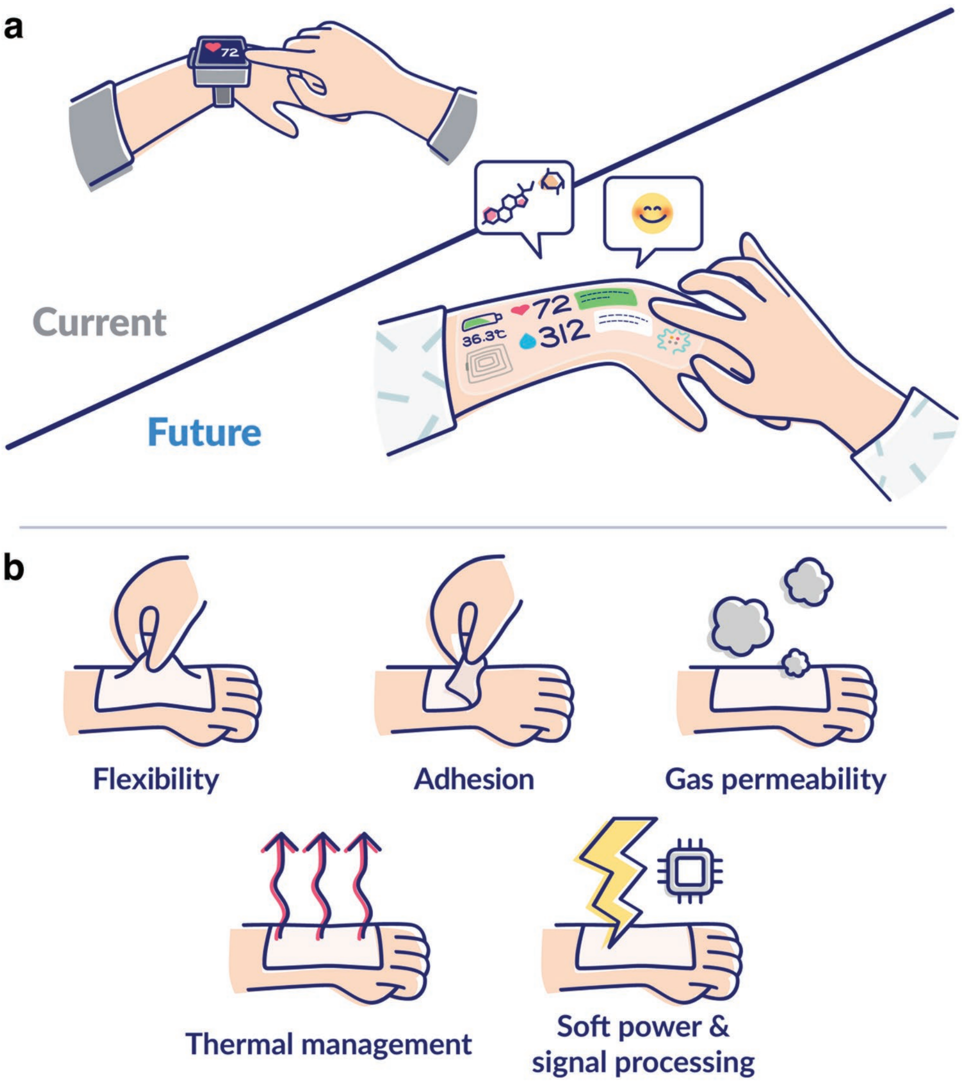

Figure 1. Conceptual illustration and design parameters for wearable device with improved comfort-of-wear. a) Progression toward the future wearables. b) Engineering design approaches to improve comfort-of-wear.

In an effort to quantify and compare the comfort-of-wear, we can borrow inspiration from requirements used by the textile industry. For textiles, parameters such as thickness, bending rigidity, compression rigidity, surface friction coefficient, surface roughness, and thermal conductivity are routinely measured in order to properly choose a textile for specialized needs, like swimming, mountain climbing, or personal protective equipment.[16,17] Other parameters that are important are thermal and water vapor resistance, moisture transfer, and air permeability. Various test equipment has been developed to quickly determine these characteristics according to international standards.[16] The ability of the wearable to augment the characteristics of the wearer is also an interesting concept, such as in the case of "bodyskin" swimsuits, which enable a human's drag to be minimized.[18] This specialized knowledge established in the textile industry serves as an excellent starting point for the definition of comfort-of-wear for wearable electronic devices.

Hence, this review focuses on the engineering approaches that enhance the comfort-of-wear of flexible/stretchable wearable devices. We identified several factors to determine the comfort-of-wear, including flexibility, adhesion, gas permeability, thermal management and soft power and signal processing (Figure 1b). In the following, we discuss the designs of either materials, devices, or system architectures, which influences comfort-of-wear. In the conclusion, we discuss the further future directions of wearables that every person would be willing to wear.

2. Engineering the Mechanical Properties of Wearable Devices

We first discuss comfort-of-wear from the viewpoint of mechanical properties. One of the advantages of achieving a satisfactory comfort-of-wear is that the device will not interfere with body movement. As an analogy, the clothes we wear in everyday life do not hinder our body movements, however protective equipment, like a spacesuit does. The mechanical difference between these garments boils down to bending stiffness[19] and stretchability; where bending stiffness defines the ability of a material to resist bending forces, and stretchability the degree to which a material can reversibly be strained. Materials that have a smaller bending stiffness are less likely interfere with the original deformation of the body. Furthermore, if a device is not stretchable, it may cause discomfort (e.g., tightness) and resist being stretched when the body is extended or contracted, or the device may fracture and fail. Therefore, depending on the placement position, the device must possess a stretchability that can follow the deformation of body surfaces, which can range from 30% on the skin,[20] and 100% or more on the joints.[21]

A device with a small bending stiffness can be worn without discomfort or resistance when attached to the skin or clothing. Therefore, methodologies to reduce the bending stiffness are important for comfort-of-wear. The bending stiffness (*EI*) is expressed by the following proportional relationship:[19]

$$EI \propto Eh^3 \tag{1}$$

whereby the bending stiffness (*EI*) is proportional to the Young's modulus (*E*) and the cube of thickness (*h*). Experimentally, the bending stiffness is reduced by a factor of about 10^4 by decreasing the substrate thickness from 76 to 2.5 µm. This has been exploited to enable devices on ultrathin polymer substrates to be laminated on delicate locations, such as the surface of the brain or spinal cord.[19] As a bonus, this enables the integration of thin-film devices, such as biopotential electrodes,[22–24] field-effect transistors,[25–27] photodiodes, and light-emitting diodes, without harming their electronic function.[12] For example, a transistor with an overall thickness of 2 µm was fabricated using a 1.2 µm PEN foil as the substrate, resulting in a device insensitive to bending (**Figure 2**a).[25] In addition, sensors that record biopotentials with a thickness of less than 300 nm have been developed.[4] One difficulty to keep in mind for this approach is the consequent fragility to tear and difficulty in handling of the device during processing. This could be somewhat circumvented by focusing on materials with a low *E*, allowing the thickness to be larger to achieve the same bending stiffness.

Another approach to reduce the bending stiffness is the use of mesh/nanomesh structures (Figure 2b,c).[19,28,29] They can be regarded as a composite of air and material, enabling the reduction of the effective Young's modulus. Nanomesh devices can even conform to the friction ridges on fingerprints although devices on a 1 µm thick plastic foil cannot. However, the ability to create circuitry by coating methods or mount components can be complicated by the porous nature of the substrate. The Young's modulus can be also reduced by choice of material. In most cases, soft (low Young's modulus) materials show stretchability, so both should be discussed simultaneously. Although typical soft materials like rubbers have been insulators, in recent years soft and stretchable conductors/semiconductors have been extensively studied.[6,20,28,30–33]

The Young's modulus of bulk Au and Ag, which are nonstretchable conductors, is ≈80 GPa, which is far from that

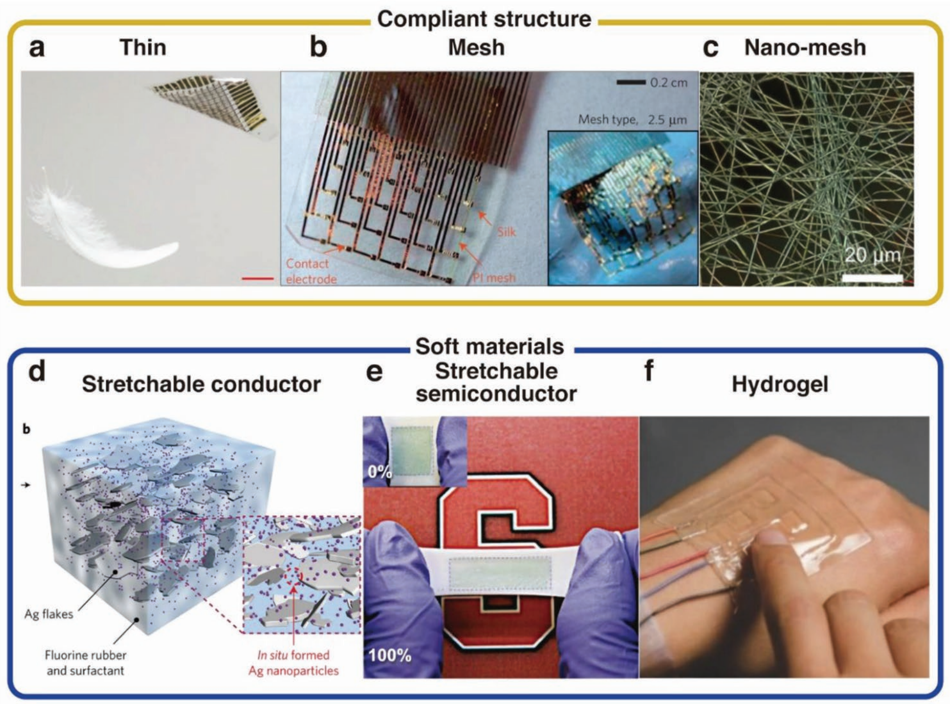

Figure 2. Engineering the mechanical properties of wearable devices. a–c) Structural strategies. a) Reducing thickness. Reproduced with permission.[25] Copyright 2013, Springer Nature. b) Mesh. Reproduced with permission.[19] Copyright 2010, Springer Nature. c) Nanomesh. Reproduced with permission.[28] Copyright 2020, American Association for the Advancement of Science. d–f) Soft materials strategies. d) Stretchable conductors. Reproduced with permission.[35] Copyright 2017, Springer Nature. e) Stretchable semiconductors. Reproduced with permission.[32] Copyright 2017, American Association for the Advancement of Science. f) Hydrogels. Reproduced with permission.[61] Copyright 2014, Wiley-VCH.

of human skin (0.42–0.85 MPa).[34] Stretchable conductors have been realized by various approaches.[1] These include composites,[20,35] liquid metals,[36–38] and conductive polymers.[31,39] For example, we reported composite of Ag flakes and elastomer has a Young's modulus of ≈10 MPa, along with a stretchability that is higher than 400% (Figure 2d).[20,35] Liquid metals show a significantly lower Young's modulus (<1 Pa) and extreme stretchability (>1000%).[37] Stretchable conducting polymers show a low Young's modulus of ≈50 MPa and high stretchability (>100%),[31] as well as biocompatibility.[40] Recent studies have also reported conductive materials with high robustness.[41–43] For example, LM-based conductive materials have achieved high repeatability of 10 000 stretch cycles at 50% stretch,[44] which is sufficient for the majority of wearable device applications. Additionally, the use of soft and self-healing electronic materials can realize damage-resilient electronics,[45] which can significantly improve the device life time.

Additionally, the development of soft and stretchable semiconductors is important. The Young's modulus of Si and Ge, which are nonstretchable semiconductors, is ≈100 GPa, and that of polycrystalline organic semiconductors are ≈3 GPa.[46] On the other hand, recently developed polymer semiconductors have been designed to show a Young's modulus of 10–100 MPa and possess significant stretchability (Figure 2e).[32,47] In this case, a stretchability higher than 100% can be achieved while maintaining the material's electrical performance.[32,48] In combination with stretchable conductors, stretchable semiconductor devices can be developed including transistor circuits,[49–53] photovoltaics,[54–57] and light emitting devices.[58,59] By virtue of these mechanical properties, such soft semiconductive devices will help yield a greatly improved comfort-of-wear in a final system. Still, the electrical properties of semiconductive polymers need to be improved for realistic applications. For example, the field effect mobility is 0.1–1 $cm^2 V^{-1} s^{-1}$, although that of flexible polycrystalline silicon or oxide semiconductors are reliably higher than 10 $cm^2 V^{-1} s^{-1}$.[60]

The next frontier in soft materials for future devices can be found in hydrogels (Figure 2f).[61–65] Hydrogels are composed of a crosslinked porous polymer network and water molecules occupying the spaces between the polymer chains. As a result, hydrogels are soft and moist and have physical properties such as human tissue. Additionally, hydrogels can have the ability of skin-like self-healing when supramolecular bonds, such as strong hydrogen bonds, are introduced.[66] This, along with its chemical structure, allows hydrogels to adhere intimately to human skin. Therefore, hydrogels are expected to be applied as an adhesive layer to bridge the gap between skin and wearable devices. For example, hydrogels based on polyacrylamide (PAAm) have an extremely low Young's modulus of just ≈8 kPa, even smaller than that of human skin.[67] Blending hydrogels with a conductive polymer can realize a high electron-ion mixed conductivity and a stretchability of more than 100% with tunable Young's modulus.[68]

3. Adhesion

In many use-cases, the wearable device must have intimate contact with the skin in order to function. The measurement of physiological signals (e.g., EXG or PPG) requires close and stable contact of the sensor with the skin.[4,69,70] One major challenge is finding methods that retain sufficient adhesion and comfort, even while sweating or in humid or underwater environments.[71] The required level and type of adhesion onto the body will depend strongly on the application—in some cases a user may want to frequently take on and off the device, whereas in others the device must remain in a certain position for long periods. Earlier, the bending stiffness was described as an important parameter that influences the comfort of the device—however another consequence is that the bending stiffness of the device can impact the adhesion of the device due to the enhancement of noncovalent interactions like van der Waals forces and electrostatic interactions. These adhesive interactions can be enhanced by utilized microstructures that contact the body, as has been masterfully demonstrated by using gecko-like structures.[72] The advantages of microstructured adhesives are the absence of residual adhesive on the opposing surface and its washability and thus reusability. More conventionally, pressure sensitive adhesives can be used, which can be based on materials including acrylates or silicones.[73] In this regard, a large library of biocompatible skin adhesives exists with varying degrees of tack, depending on the application. Adhesion to the skin can also be achieved using hydrogels. However, it is known that conventional materials can damage the skin over long-term usage due to high ionic activity. Besides, unencapsulated gels can dehydrate over time, reducing its adhesion and if used as a transducer, degrading its electronic properties. Therefore, methods to control water content or the introduction of skin-compatible ionic liquids instead of water can mitigate this issue.[62,74] To this end, it has been shown that a biocompatible ionic-liquid gel based electrode enabled 3 days of continuous EXG monitoring.[74]

4. Breathability

Breathability is another important factor for comfort-of-wear. The breathability of the skin mainly refers to water vapor permeability and is quantified as the water vapor flux ($g m^{-2} d^{-1}$).[75] If the breathability is low, the area where the device is worn is effectively sealed, and skin irritation or rashes may occur after prolonged use.[29] Additionally, if perspiration increases, the device may not be able to keep conformal contact necessary for proper device operation and will fall off. High breathability is achieved by using pores that allow water vapor to diffuse out of the layer. It is also dependent on the chemical structure of the material (hydrophobic or hydrophilic) and its ability to absorb and desorb moisture.[16] Breathable materials can be classified by their pore size. Another critical parameter is the overall thickness, since water or oxygen must traverse the entirety of the device. Generally, having thin-film materials is always superior for realizing a breathable device.

First, there are textile-type devices that possess mm sized pores (**Figure 3**a,b).[20,76] Textile-type devices are fabricated on garments instead of a device directly attached to the skin. Intuitively, electromyogram (EMG) or ECG sensors could be fabricated by directly printing stretchable conductive materials on clothes (Figure 3b).[20,35,70,77,78] Furthermore, displays that emit

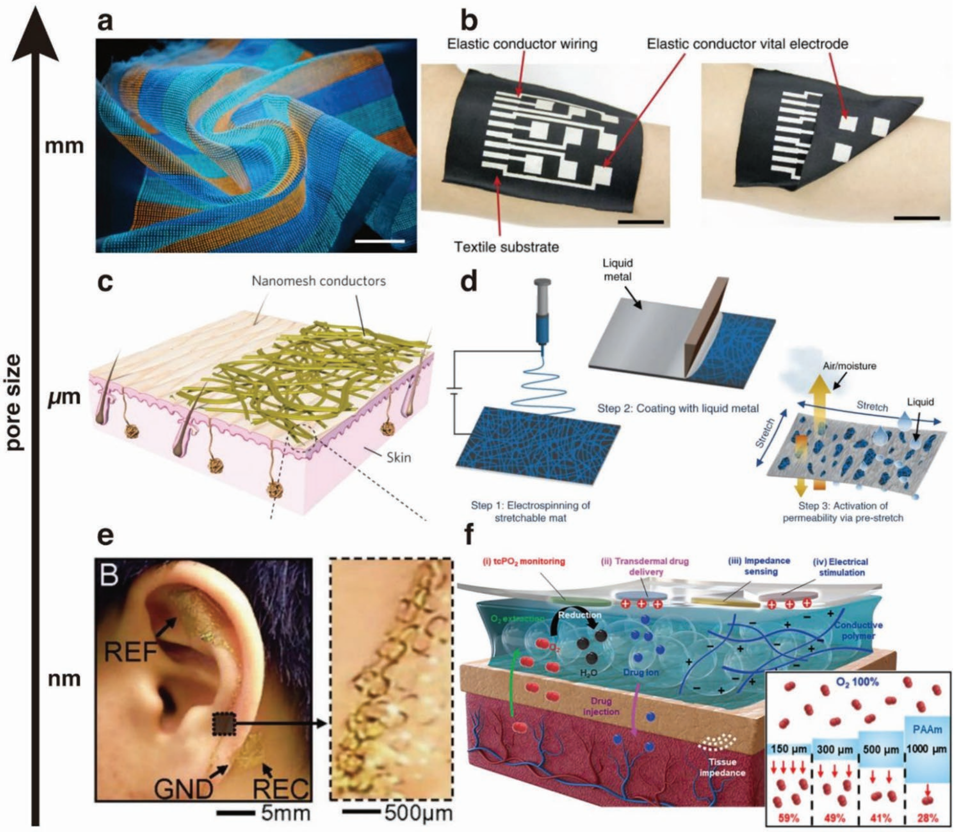

Figure 3. Breathability for comfort-of-wear, categorized by the size of pores. a,b) Millimeter size. a) The conductive weft and luminescent warp fibers are woven, so each interlaced weft and warp forms an light-emitting unit. Reproduced with permission.[76] Copyright 2021, Springer Nature. b) EMG system fabricated on a textile using Ag flakes. Reproduced under the terms of the CC-BY license.[20] Copyright 2015, Springer Nature. c,d) Micrometer size. c) Au nanomesh that adheres along the sweat pores. Reproduced with permission.[29] Copyright 2017, Springer Nature. d) Conductive material with high conductivity and air permeability by coating liquid metal on a fiber mat fabricated by electrospinning method. Reproduced with permission.[80] Copyright 2021, Springer Nature. e,f) Nanometer size. e) Electroencephalogram (EEG) measurement system laminated on the auricle and mastoid (left) and the magnified interconnect (right). Reproduced with permission.[81] Copyright 2015, National Academy of Sciences. f) Illustration of the structure, requirement, and roles of the hydrogel interface between human skin and the wearable bioelectronics. Amount of oxygen penetrating hydrogels with various thicknesses (right). Reproduced with permission.[67] Copyright 2021, American Association for the Advancement of Science.

light by knitted conductive and luminescent threads can also be integrated (Figure 3a).[79] The textile-type device has limited resolution and processability that arises due to the porosity from the fabric's knitting pattern. However, garments can be put on and off many times, and does not tend to cause skin irritation because air can freely pass through the fabric.

For pores on the order of µm in size, mesh-like devices can be fabricated by electrospinning or blow spinning (Figure 3c,d).[29,80] These devices, when applied to the skin, conform to the structure of sweat pores on the skin since the sweat pores are also µm in size.[29] The device thus does not interfere with perspiration, and can significantly reduce inflammatory skin reactions. In addition, since the device can have a small bending stiffness and high skin-conformability, the mechanical comfort-of-wear is also excellent.

Finally, there are thin-film rubbers and hydrogel films that have nm-sized pores, allowing for the transmission of gasses (Figure 3e).[81] Some thin-film rubbers (e.g., silicone) can have high breathability.[82] Besides, thin (<100 µm) hydrogels may have a high oxygen permeability (Figure 3f).[67] It has been demonstrated that thin-film rubbers do not cause skin irritation, even after two weeks of daily activities such as exercise, showering, and swimming.[81] In addition, the thin-film rubber is planar, thus it is possible to fabricate sophisticated devices using stretchable semiconductors and other materials.[50,51] Still, this approach to use ultrathin elastomers might have trouble handling a lot of perspiration because the pores are too small. Opening microscopic pores would be necessary depending on the use case.

5. Thermal Management

The heat capacity of the employed materials is an additional parameter which not only affects the comfort, but also the overall function of the wearable system. In the case of clothing, one can consider the differing heat transfer needs of summer (high heat flux) and winter clothing (isolating). The thermal comfort for a wearer is mainly determined by the local skin temperature.[83] Since flexible/stretchable wearable devices on skin are to be worn together with clothing, (e.g., patch on the chest) or on exposed parts of the body (e.g., wrist), heat transfer from the device to the environment should be maximized to obtain maximal comfort and leave the skin as unaffected as possible. The thermal losses from on-skin materials can be greatly enhanced or restricted by a variety of methods – including the structuring of substrates, as is done to enhance breathability, and the introduction of thermally reflective or transmissive coatings.[84,85]

As substrates and devices become thinner, the thermal mass of the wearable is significantly reduced, enhancing heat dissipation by radiative loss, while also enhancing the speed and accuracy of on-body or environmental measurements of temperature, since they can equilibrate faster with the measurement subject.[86] At the same time, one should be mindful about the heat generated by the wearable device, such that it does not harm the wearer. Sensors are low-power in general, but light-emitting displays or actuators may induce a large amount of Joule heating onto the body while the device operates. Thermal management of such heat-generating devices has been achieved by controlling the device operation,[13] or using materials with high thermal conductivity.[87]

6. Soft Power and Signal Processing

Although the use of compliant electronic materials can effectively improve the comfort-of-wear, some components in the whole systems can be difficult to realize in a soft or thin form, which include power supplies and processors. Currently, lithium-ion batteries are powering most of the wearable devices on the market, which contribute to the increase in hardness, volume, and weight of the overall wearable device. Another consideration is that lithium-ion batteries are potentially dangerous if punctured.[88] Generally, power sourcing limits where the device can be placed while simultaneously narrowing the application possibilities of wearable devices. Typical power requirements are on the order of microwatt–milliwatt for wearable devices such as ECG sensor, temperature sensor, glucose sensor and pulse oximeter.[89] In this section, we discuss the system design approaches used to reduce/eliminate these rigid components from wearable devices. There are mainly three types to power wearable devices with improved comfort-of-wear: self-powering, soft battery, and wireless power.

Self-powered devices can harvest energy from the surrounding environment to drive the devices,[90] which can reduce the need for external power supplies or help to reduce the power consumption of the whole system. The human body performs vital activities by converting energy sources from food into thermal, chemical, and mechanical energy.[91] Some self-powered devices have been developed that can capture some of this energy. Researchers have estimated the possible power that can be derived from various converted energy streams.[92] To harvest thermal energy, thermoelectric generators (TEG) and pyroelectric generators (PEGs) are used. Biofuel cells (BFCs) are used for chemical energy harvesting. Finally, for mechanical energy, Piezoelectric nanogenerators (PENG) and triboelectric nanogenerators (TENGs) are utilized.[91]

Most of the heat energy generated by humans is released into the surrounding environment.[93] TEGs and PEGs use this thermal energy to generate electric power, and since the human body is thermally regulated homeostatically, a stable source of power can be expected. These features are very attractive for 24/7 health monitoring applications. Thermoelectric modules consist of arrays of p- and n-type semiconductors. Rigid TEGs have traditionally been used for power generation with high efficiency, namely high "zT." The comfort of rigid TEGs improves by integrating very small devices on clothing,[94] making the generated energy small and devices far from a body which is a stable heat source. On the other hand, the high conformability of flexible TEG allows lower thermal interfacial resistance with our body and, consequently, a higher temperature differential across the TEG.[95–97] Although these devices are generally less efficient than rigid TEGs, TEGs with a high zT based on PEDOT have been reported, demonstrating the promise of these energy harvesters.[98] PEGs do not require a temperature gradient to harvest energy. They generate power when the temperature of the device changes. Since the skin and body temperature is affected by factors like human activity and the surrounding environment, the appropriate and safe location of PEGs must be carefully considered to optimally use the PEG.[99] Flexible PEG energy harvesters have been developed, including PEG-based[100] and polyvinylidene fluoride (PVDF)-based devices.[99,101]

Wearable mechanical energy harvesters are a very promising option for generating energy from body movements. TENGs convert kinetic energy into electrical energy through contact charging and electrostatic induction.[90] Their mechanical properties can be tuned to improve the comfort-of-wear, for example by using stretchable composite materials,[102] or shaping them to a fiber structure with breathability.[103]

Piezoelectric energy generators are another class of important mechanical harvesters. Although the typical piezoelectric material, lead zirconate titanate (PZT), is rigid, having a Young's modulus of 101 GPa.[104] However, the mixture of PZT microparticles and silicone elastomers realizes a soft generator with a 30% stretchability.[105,106] Another approach is to directly use polymeric materials, such as poly-L-lactic acid (Young's modulus: 3.2 GPa),[107] poly(para-phenylene ethynylene)s,[108] or PVDF (Young's modulus: 1.26 GPa)[109] and its copolymers which can be softer than piezoelectric ceramics.[110–113] In addition to a lower modulus relative to ceramics, PVDF's properties can be exploited in sensing applications due to its relatively low dielectric constant.[114] For example, a PVDF nanofiber sheet with a thickness of 6–7 μm was fabricated to realize a heart signal sensor with low bending stiffness and breathability (**Figure 4**a).[113] TENGs and PENGs can be used as a power source as well as a strain sensor for sensing mechanical deformation, thereby providing a self-powered movement sensor and heart monitoring. TENGs and PENGs can simultaneously act as sensors and power supplies, simplifying the total system.[102,113]

Another important approach to realize a self-powered wearable device is employing BFCs which use redox enzymes as catalysts to convert the chemical energy of metabolites present in biological fluids (e.g., sweat) into electricity.[115–117] Figure 4b shows a BFC utilizing lactic acid contained in sweat. Energy is obtained from the oxidation of lactic acid by lactate oxidase (LOx) immobilized on the bioanode and the reduction of oxygen by bilirubin oxidase (BOx) on the cathode. Among

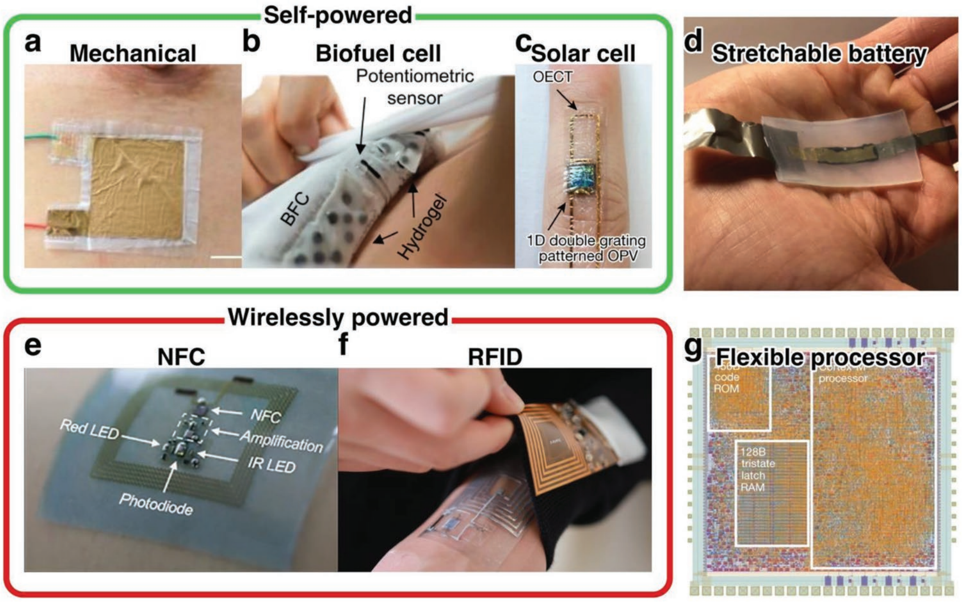

Figure 4. System design approaches to achieve soft power and signal processing. a) An all-nanofiber-based mechanoacoustic sensor. The power is generated by triboelectricity and piezoelectricity from the mechanical deformation. Reproduced with permission.[113] Copyright 2020, National Academy of Sciences. b) Textile-based biofuel cell. Reproduced under the terms of the CC-BY license.[122] Copyright 2021, Springer Nature. c) Ultraflexible organic photovoltaic. Reproduced with permission.[22] Copyright 2018, Springer Nature. d) Stretchable battery. Reproduced under the terms of the CC-BY license.[145] Copyright 2019, Springer Nature. e) NFC powered stretchable wireless epidermal optoelectronic system. Reproduced with permission.[150] Copyright 2016, American Association for the Advancement of Science. f) RFID powered stretchable on-skin sensor tag and flexible on-textile readout circuit. Reproduced with permission.[151] Copyright 2021, Springer Nature. g) Flexible 32-bit microprocessor. Reproduced with permission.[156] Copyright 2021, Springer Nature.

bioenergetic resources, lactate is present in sweat at a level of tens of millimoles, making it the most ideal power source for future skin-integrated electronic devices.[118] Flexible and stretchable BFCs have been made by using an island-bridge structure in which rigid electrodes are connected with flexible wires,[119] but the conformability of BFCs can be further improved by selecting softer materials for the electrodes that immobilize the enzymes.

Mechanical stimuli such as human motion and body fluid like sweat are not continuous sources of energy, which makes it difficult to reliably power other non-self-powered devices. This issue is circumvented by integration of mechanical generators, rectifiers, and energy storage capacitors to provide stable self-powering.[120,121] BFCs and TENGs are combined to provide continuous power supply to the sensor by fast start-up of TENG and long-time energy harvesting of BFC.[122]

Another self-powering method is light, thin, and flexible solar cells realized by thin active layers including organic semiconductors,[94,123] perovskites,[124,125] and copper indium gallium selenide (Figure 4c).[126–130] Compliant photovoltaics have been realized using organic photovoltaics and perovskite photovoltaics. Both of which are recently showing dramatic improvements in their power conversion efficiency (PCE).[131,132] As they can be processed at low temperatures, it is possible to fabricate them on plastics and ultrathin substrates, which, as discussed earlier, can dramatically improve the bending stiffness.[133–135] Furthermore, this allows them to be laminated onto other substrates such as textiles.[136,137] Recently, along with the demonstration of stretchable organic semiconductors and conductors, intrinsically stretchable photovoltaics have been developed. Their PCE is already over 10%,[55,56] showing the promise of these systems in approaching the performance of rigid or flexible cells. In addition to the comfort-of-wear, self-powered systems using flexible photovoltaics can provide a low-noise power source for sensors.[22] For more detailed discussions about designing systems for powering wearable devices using each of the above methods, the reader is suggested to check other detailed reviews on this subject.[138–140]

Since the output of these power sources vary depending on the stimulus from the living body or the incident light intensity, it will be necessary to combine multiple methods for a stable power supply. One solution is to use a supercapacitor,[141] or a stretchable battery.[142–145] These have high capacities and are deformable (Figure 4d). In addition, there is an approach to miniaturizing the device itself by using a stretchable battery as a substrate and building a circuit atop it. All of the components of the battery are intrinsically stretchable films, with total thickness of about 270 µm.[146]

When considering the entire system using wearable devices, sensors must be connected to high-performance electronic chips, which are usually rigid, for signal processing and storage. For the comfort of the device, this connection between soft sensors and chips can be done wirelessly where rigid chips can ideally be located far from soft skin surface or embedded in other devices such as smart phones. However, current wireless communication systems (Wi-Fi, Bluetooth, ZigBee, etc.) typically require both a rigid chip and sensors on the same substrate. Besides, they consume significant amounts of power.[118,147,148] Overall, this raises the complexity of the device while reducing the overall softness.

Among the wireless communication methods, externally powered methods such as radio frequency identification (RFID) or near field communication (NFC) are attractive options as they can reduce the power consumption and greatly simplify the structure of soft wearable devices (Figure 4e,f).[149–151] The antennas used in these methods can be made of stretchable conductors and atop stretchable substrates, making them compatible with the rest of the device and easy to attach to the body.[149] By the integration of a stretchable high-frequency diode to convert wirelessly transmitted alternating current (AC) DC power, the skin-attached wireless system can acquire direct current power that can operate various electronic devices.[151] Their short readout distance can be partially resolved by relaying signals from sensors located in various parts of the body to a central location where communication is easier or is powered via traditional methods.[152] With RFID technology, by choosing a communication system that does not require a communication chip, it is possible to make an entire system composed of soft parts.[149]

Another approach to eliminating rigid elements is to eliminate the use of electrical components. These systems display sensing results by using a chemical method of coloration. A personal UV sensor using photochemistry[153] and sensing of sweat using a colorimetric method[154,155] have been proposed. These devices are made by composites of UV-sensitive dyes or reactive materials with soft materials, which are soft and can conform to the human body.

7. Conclusion

Wearable devices that implement design principles that lead to enhanced comfort-of-wear will likely be more readily adopted by society. These principles include the exploitation of thin films for the effective reduction of stiffness, the use of low Young's modulus materials such as hydrogels or elastomers, the creation of nano- and microsized mesh structures to add breathability, and the removal or reduced usage of rigid components such as chips or passives. These principles can be applied to functional devices, such as energy harvesters, as well as sensor technologies such as biopotential electrodes for ECG or EMG and pressure/impact sensors. These elements together with flexible and stretchable circuits and display technologies form a system that can inform or influence the wearer's behavior.

In the near term, it will be important to find ways to reliably mount integrated circuit chips or passive components onto stretchable, flexible, or mesh-like substrates. This is challenging because of factors such as: the handling of substrates, accessible temperature budgets during fabrication, and limited available supporting materials like stretchable conductive adhesives or underfills. In the long term, however, creating truly stretchable or flexible alternatives to conventional components or chips will be needed to realize the ultimate comfort-of-wear device. Researchers are taking steps in this direction, creating remarkable devices such as flexible integrated circuits based on the inorganic semiconductor indium gallium zinc oxide (Figure 4g),[156] or organic semiconductors as well as flexible passives like negative temperature coefficient thermistors based on composite materials.[157] These approaches can also help to make flexible Bluetooth and NFC chips, simplifying external communication. However, it is imperative that attention is paid to problems surrounding the comfort-of-wear, namely, the device's aesthetic quality or the texture of the device and how the user feels it. For example, the transparency of wearable devices may be able to maintain the original appearance of our skin. Functionalities that give further function and feedback to the user, like haptics, should also be considered. Furthermore, in the near future, more attention must be paid to biosourced and biodegradable materials as global consciousness toward environmental issues grows. Importantly, these aspects about users' experience and perception of the wearable must be simultaneously considered with the electronic and mechanical design.

When all the above-described elements and design features are put together, future wearables with the ultimate comfort-of-wear can be actualized. This creates a situation where superior quality data of the wearer's health and activity can be gathered, thus allowing electronics to have a more direct impact on influencing our overall health and quality of life. Looking to the future, this impact will be strongly dependent on the development of data analysis techniques that properly use the data that comes from these ultimate comfort-of-wear devices. Additionally, the reliability of such devices will need to be improved to at least the level of current wearable devices and conform to a range of worldwide standards.[158] For garment-integrated electronics, the washability of the entire system must be considered.[159,160] Attaining satisfactory reliability or washability will require the creation of new materials that are mechanically robust, as well as new device concepts, with respect to system design and encapsulation strategies.

Indeed, from a scientific point of view, a lot of progress can be made to improve the comfort-of-wear and adoption of wearable devices by focusing on approaches like thickness reduction or the use of elastomeric substrates and sensors. However, to make a further step we may need significant input from psychologists, artists, and industrial designers in order to truly realize attractive products and solutions for the users themselves.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

flexible electronics, smart healthcare sensors, stretchable electronics, wearable electronics, wearables

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