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Lighting the Path to Precision Healthcare: Advances and Applications of Wearable Photonic Sensors

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Recent advancements in wearable photonic sensors have marked a transformative era in healthcare, enabling non-invasive, real-time, portable, and personalized medical monitoring. These sensors leverage the unique properties of light toward high-performance sensing in form factors optimized for real-world use. Their ability to offer solutions to a broad spectrum of medical challenges – from routine health monitoring to managing chronic conditions, inspires a rapidly growing translational market. This review explores the design and development of wearable photonic sensors toward various healthcare applications. The photonic sensing strategies that power these technologies are first presented, alongside a discussion of the factors that define optimal use-cases for each approach. The means by which these mechanisms are integrated into wearable formats are then discussed, with considerations toward material selection for comfort and functionality, component fabrication, and power management. Recent developments in the space are detailed, accounting for both physical and chemical stimuli detection through various non-invasive biofluids. Finally, a comprehensive situational overview identifies critical challenges toward translation, alongside promising solutions. Associated future outlooks detail emerging trends and mechanisms that stand to enable the integration of these technologies into mainstream healthcare practice, toward advancing personalized medicine and improving patient outcomes.

1. Introduction

Accessible precision healthcare technologies stand to revolutionize modern healthcare by enabling early disease detection, timely intervention, and preventive care, yielding better health outcomes and improving quality of life. Wearable sensors have shown significant promise in this space, offering real-time health monitoring of diverse physiological markers through human skin and non-invasive biofluids such as sweat, interstitial fluid, saliva, and tears.[1–5] Paired with their miniaturized form factor, ease-of-use, and real-time readout, these devices have shown great promise in bridging the gap between daily life and clinical care.[6,7] This would both reduce the burden of routine monitoring on healthcare facilities and make health monitoring more accessible to underserved populations.

Wearable sensing has been increasingly explored through mechanical, electrical, and photonic approaches. While mechanical and electrical sensing strategies have yielded high target sensitivity, resultant platforms often require extensive supportive equipment and are more susceptible to environmental noise and fouling relative to their photonic counterparts.[6,8] Photonic sensors also offer high design versatility due to the diverse mechanisms through which light can be manipulated for detection. Namely, reflection, absorption, fluorescence, refraction, and scattering principles have all been employed to measure clinically relevant physical and chemical stimuli (**Figure 1**).[9,10] The development of such wearable sensors is guided by four key objectives: 1) optimizing photonic analytical approaches, 2) engineering materials that support photonic wearable functionality, 3) implementing scalable fabrication processes for the miniaturization, mass production, and versatile applications, and 4) integrating advanced power management strategies for effective real-world performance.

With regards to the first objective, the development of new optical sensing modalities – such as optical fibers, alongside the wearable-focused optimization of conventional modalities – such as fluorescence and colorimetric sensing, has yielded substantial advancements.[11] These innovations have significantly enhanced the sensitivity, selectivity, stability, and multiplexing capabilities of reported devices, fostering further exploration and progress in this field.

Efforts to design and develop functional materials for wearable photonic sensing aim to amplify optical signal response and improve real-world useability. These goals are achieved through the incorporation of sensor-specific photoactive agents and functional substrate materials. Substrate materials, in particular, have

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The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/adma.202419161

DOI: 10.1002/adma.202419161

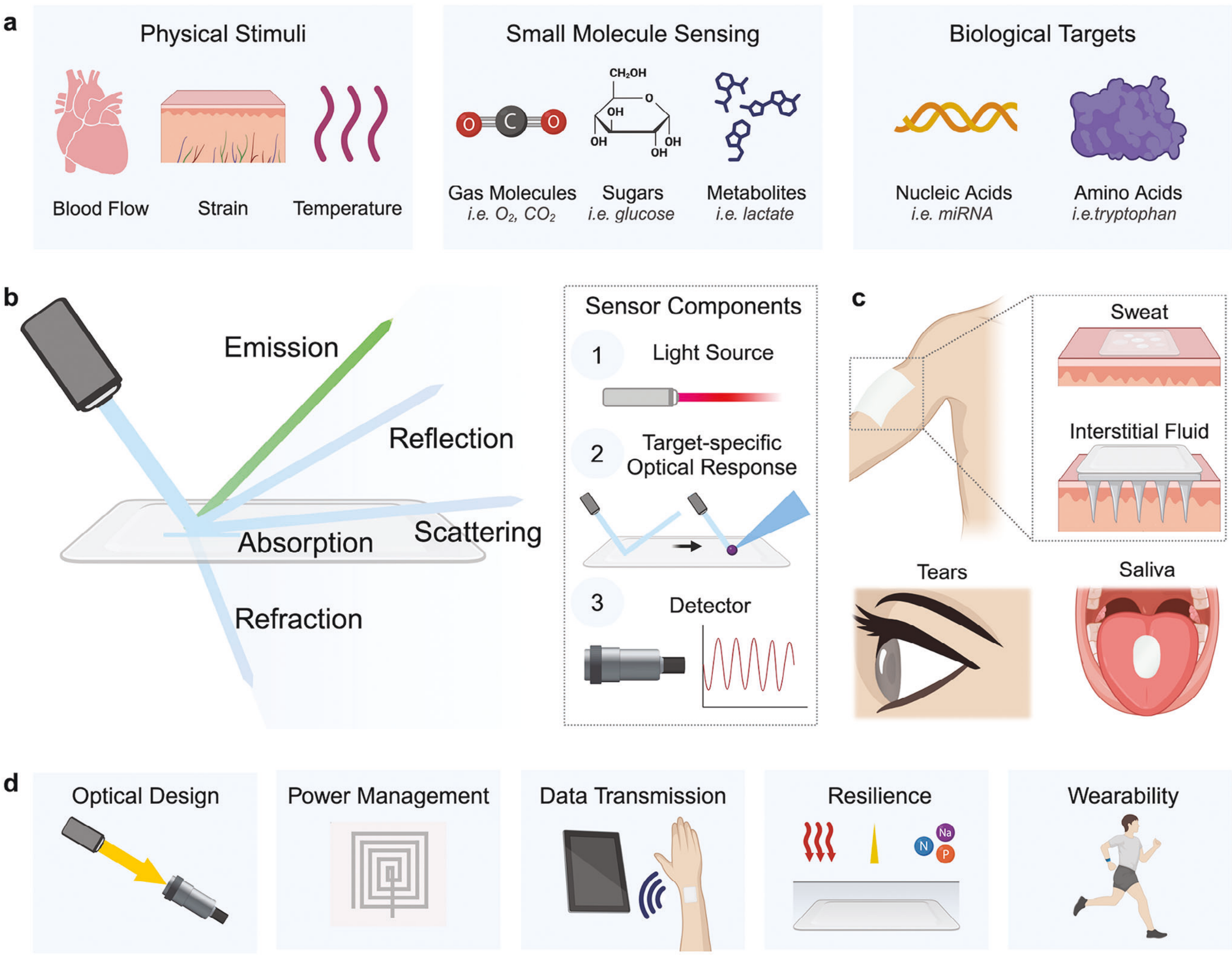

Figure 1. Overview of wearable photonic sensing. a) Common physical and chemical target stimuli detected by photonic wearable sensors. b) Light modulation mechanisms used for sensing, alongside key sensor components required within conventional photonic sensing cascades. c) Biofluids employed toward on-body sensing applications. d) Key considerations in the development of comprehensive wearable photonic sensor systems. Figure produced using BioRender.

seen notable innovation in recent years, enabling applications in delicate sensing environments such as the eye and facilitating more complex on-body sensing cascades for high-performance detection.[10,12] Meanwhile, advancements in photonic component fabrication have resulted in compact, lightweight designs that align with the demands for portability, scalability, and customer comfort. Paired with the progress made in power management, these developments have made continuous, real-world health monitoring increasingly feasible and effective.

In this review, we first review key photonic sensing approaches and the underlying optical principles that enable their functionality. We then discuss the material strategies, fabrication approaches, and power management solutions currently employed in wearable photonic sensor development today. Building on these foundational discussions, we review the applications of photonic wearables in physical and chemical health monitoring. Lastly, we provide a comprehensive situational assessment of the field, accompanied by a forward-looking perspective on the steps needed to advance wearable photonic sensors toward real-world implementation and their growth in the commercial translational market.

2. Photonic Sensing Approaches Employed Within Wearable Platforms

To enable optical sensing, various mechanisms for target-mediated photon manipulation have been devised. Broadly, they employ physical and chemical strategies to yield platforms that offer detectable changes in incident light following exposure to target stimuli. Section 2 details the fundamental principles that enable the most common photonic sensing approaches, alongside a discussion of the use cases for which they are optimally suited.

2.1. Optical Waveguides

Optical waveguides have been increasingly employed within wearable sensing.[13] Fiber form factors are particularly common, owing to their lightweight and flexible nature, excellent signal stability, and robust sensing capabilities. These fibers generally comprise a three-layered structure, consisting of an inner core for light transmission, a surrounding cladding layer for wave guidance, and an outer coating layer that protects the two functional inner layers (**Figure 2a**).[11,14] The cladding layer is composed of a material with a lower index of refraction than the inner core. Based on the numerical aperture and angle of acceptance of a given optical fiber, light entering the fiber at a sufficiently high angle of incidence will induce an angle of refraction exceeding 90°, yielding total internal reflection at the core-cladding boundary.[14] The required angle of incidence can be determined through the following equation:

$$n_{\text{core}} \sin\left(\theta_{\text{core}}\right) = n_{\text{cladding}} \sin\left(\theta_{\text{cladding}}\right), \text{ where } n_{\text{core}} > n_{\text{cladding}} \quad (1)$$

where n denotes the index of refraction. Meeting this condition enables effective transmission of light through the entire length of a fiber with no loss in signal intensity.[14,15]

As light transmission through optical fibers is extremely consistent, changes in transmission can be directly correlated to changes in the sensing environment. Here, wavelength interrogation and intensity modulation represent the two key mechanisms employed toward quantitative analysis. Wavelength interrogation is most commonly implemented through fiber Bragg gratings (FBGs).[11,16] Here, a segment of the optical fiber core hosts periodic variations in refractive index, resulting in the reflection of a specific wavelength of light, while maintaining the transmission of all others. The reflected wavelength, known as the Bragg wavelength, is determined by the effective refractive index of the core (n_{eff}) and the grating's period (Λ),[16] as follows:

$$\lambda_{\text{Bragg}} = 2 n_{\text{eff}} \Lambda \quad (2)$$

Changes in temperature and pressure can induce changes in both the refractive index and grating period through thermal expansion and strain of the fiber, respectively.[11] The resultant shift in the Bragg wavelength offers a quantitative measure of these clinically applicable physical parameters. Common wearable applications of this approach include temperature, respiratory, blood pressure, and body motion monitoring.[17] Alternatively, wavelength interrogation can also be pursued through fiber interferometry, where monitoring changes in interference patterns produced through the diffraction of propagating light. While interferometric sensors offer exceptionally high sensitivity, FBG sensors are preferred for wearable applications given their increased resistance to external noise, ease of multiplexing, and lower cost.[11]

On the other hand, intensity modulation uses changes in output light intensity to determine changes in the sensing environment.[18] Similar to wavelength interrogation, changes in temperature, pressure, and strain sensors have been extensively reported using this approach. Here, optical fibers designed with distinct structures, fabricated through the splicing of multiple core materials, or coated with environment-responsive agents are regularly employed.[11,19,20] When target changes in the sensing environment occur, such fiber modifications permit light to be coupled out of the optic fiber core, resulting in decreased intensity. As these sensors require only a simple photodetector for operation, associated costs are significantly lower. However, their lower sensitivity and susceptibility to fluctuations in source optical power make them less reliable. As such, they are best suited for low-cost applications where a high degree of sensing performance is not necessary.[21]

Optical fiber sensors that target chemical agents are pursued based on the same core principles that enable the monitoring of physical targets. The difference lies in the various modifications that are introduced onto these fibers, which make their light transmission properties highly responsive to specific targets.[22] Most commonly, this is induced through target-induced shifts in the fiber's refractive index. Namely, ion-reactive polymer coatings and plasmon resonance-capable metallic coatings offer effective sensing mechanisms. Mechanisms for evoking selectivity toward more elusive chemical targets have involved coating fiber surfaces and tips with highly specific recognition elements, such as antibodies.[23,24] Importantly, the evanescent field – the region in which biomarker-induced changes in fiber properties can be detected, is in the nanometer range.[24] As such, a key consideration in the design of optical fiber chemical sensors involves the determination of an appropriate coating deposition protocol. Self-assembled monolayer deposition, layer-by-layer assembly, chemical vapor deposition, and various micro- and nanofabrication approaches have been employed in this space.[25,26] Protocol selection is largely guided by the nature of the material to be deposited.

2.2. Surface Plasmon Resonance

In principle, surface plasmon resonance (SPR) refers to the excitation of surface plasmons – collective oscillations of free electrons, present at a metal-dielectric interface.[27] Resonance occurs only when polarized light hits the metal interface under total internal reflection conditions, with a frequency and angle of incidence that induces energy transfer to surface plasmons. This energy transfer yields a reduction in the intensity of reflected light. By keeping the frequency of incident light consistent, changes in the refractive index at the metal interface can be monitored through shifts in the resonance angle (Figure 2b).[27] As changes in refractive index at the metal interface are easily evoked by molecular interactions, effective sensing is enabled. Importantly, SPR can also be employed on a miniaturized scale using metallic nanoparticles. Here, localized SPR (LSPR) allows for the detection of the same resonance-induced sensing shifts, offering flexibility in sensor design and enhanced target sensitivity.[28]

While physical changes in the sensing environment can be detected using SPR through changes in the refractive index of either the metal layer or the sensing medium itself, this approach is most regularly employed toward chemical sensing.[28,29] Here, material interventions involving agents such as metal oxides, polymeric films, and carbon-based nanomaterials have been used to enable high-performance sensing.[30,31] Importantly, SPR-based sensing is often integrated as a transduction approach within other photonic signaling devices. Namely, its application within optical fibers – through the deposition of a metal coating within the fiber structure, has been broadly reported.[32,33]

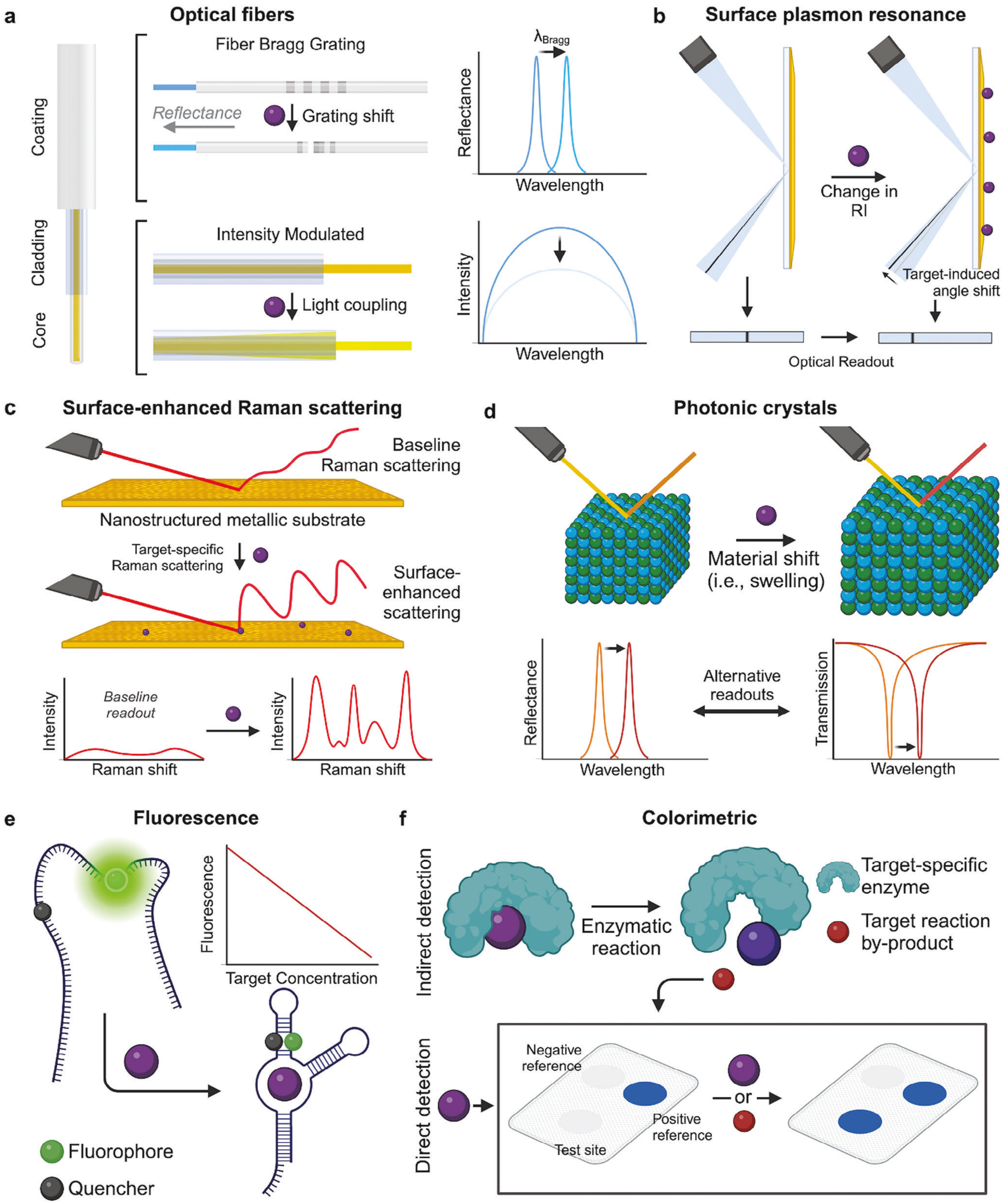

Figure 2. Common mechanisms employed toward photonic sensing. a) Optical fiber-enabled Fiber Bragg Grating and intensity-modulated sensors. b) Surface plasmon resonance-based sensing. RI, refractive index. c) Surface-enhanced Raman scattering toward ultrasensitive sensing. d) Light-modulating materials interact with target agents, yielding a change in optical properties. e) Fluorescence sensing through target-mediated changes in emission. f) Colorimetric sensing through direct or indirect detection mechanisms, involving either the target or a by-product produced through a target-mediated reaction. Figure produced using BioRender.

2.3. Surface-Enhanced Raman Scattering

Raman scattering refers to the small fraction of photons that are inelastic scattered when light interacts with a molecular entity.[34] These photons engage with the vibrational modes of the chemical bonds present within the molecule. This results in an energy exchange between the photons and engaged molecule, yielding scattered light that differs in energy from the incident light (Figure 2c).[34] As the shifts in light energy are specific to the nature of the bonds within the engaged molecule, Raman spectroscopy can identify distinct molecular targets with high specificity through the pattern of inelastically scattered light that is reflected off of the specimen.[35]

Surface-enhanced raman scattering (SERS) offers a mechanism to amplify weak Raman scattering signals by factors of 10^5–10^{14}.[36] This process involves the integration of metallic substrates composed of LSPR-capable nanostructures. When exposed to incident light, LSPR excitation induces a significant increase in the strength of the electric field at the nanostructured metal surface.[37] This, in turn, amplifies the specimen's induced dipole moment. As scattering intensity is directly proportional to the square of the induced dipole moment, this process yields a significant enhancement in Raman signal. Owing to this, these sensors have demonstrated single target molecule-level sensitivity, affording an unmatched degree of target responsiveness in the optical sensing space.[35,37]

With regard to wearable sensing, the built-in specificity of SERS sensing enables label-free detection of diverse molecular targets. Widespread wearable systems have been reported toward the direct detection of small molecular biomarkers, as well in the indirect sensing of larger targets through the detection of their molecular by-products.[38] Unfortunately, the real-world applicability of these sensors remains limited due to signal variability caused by inconsistencies in fabricated metallic nanostructures and challenges in the miniaturization of signal readout components.[38]

2.4. Standalone Material Modulation

While their integration into waveguide-based sensors offers one use-case, materials that have the ability to modulate light can also be used in standalone form factors to enable target-induced shifts in applied light (Figure 2d).[39] Key materials in this space include photonic crystals and photo-responsive polymer hydrogels.[39,40] Looking at photonic crystals as a mechanistic example, these agents are composed of materials with varying refractive indices that are periodically arranged at the nanoscale level. This periodic variation creates photonic band gaps (PBGs), owing to the Braggs scattering effect. Accordingly, light traveling at wavelengths within the PBG cannot propagate through the crystal, as the periodic structure of the material induces destructive interference. The size and position of the PBG are determined by the structural properties of a given crystal, as well as the angle and polarization of the incident light.[39]

Several mechanisms for leveraging the inherent optical properties of light-modulating materials toward sensing have been reported. On a base material level, they can be produced using agents that are responsive to target stimuli. This is specifically suited for physical and chemical detection targets, wherein temperature and pH sensors have been developed using hydrogels that swell or contract in response to shifts in the sensing environment.[40,41] Such structural changes induce a shift in how photons interact with the material, yielding an altered optical output that can be correlated with the magnitude of change in the target stimulus. The integration of various biorecognition elements into such materials has also been reported.[40]

Approaches to improve the sensitivity of such sensors generally rely on increasing either target-binding efficiency or the intensity of the output signal. Looking again at photonic crystals, the simple integration of metal nanoparticles has afforded significant benefits, as their plasmonic effects amplify target-induced PBG shifts.[42] Alternatively, the integration of porous material into photonic crystal matrices has also been shown to offer improvements in performance due to the resultant increase in analyte diffusion. While such improvements have been observed using various porous polymer materials, the employment of metal-organic frameworks (MOFs) is particularly beneficial in use-cases requiring applications requiring high sensitivity.[43] These agents pair high structural porosity with high target-specific tunability, supporting their use within trace-target environments. The compatibility of these signal amplification approaches within a given sensor depends on the nature of the target analyte and the conditions of the sensing environment.

2.5. Fluorescence

Fluorescence is one of the most commonly employed optical signaling mechanisms in sensing applications, owing to its high transduction performance and versatility. In this process, photonic energy excites molecules capable of absorbing light at specific wavelengths. When these excited molecules return to a lower energy state, they emit light at a longer wavelength.[6] Fluorescence-based approaches are generally employed toward chemical sensing applications, wherein target-interacting indicators and fluorescently labeled probes generate highly specific optical output. Quantifying output at the emission wavelength of the employed fluorescent agent enables direct quantification of the sensing target (Figure 2e).[6]

As wearable fluorescence sensors rely on low-power excitation light sources and simple readout components, employed fluorescent agents need to be highly excitable under limited excitation conditions. Many chemical fluorescence indicators have supported this objective, wherein binding to their respective target induces a shift in fluorescence output. Key clinical applications that have been enabled through such indicators include ions (i.e., chlorine, calcium), metabolites (i.e., glucose, lactate), gas (i.e., oxygen), and pH monitoring.[44–46]

In cases where chemical indicators specific to the target do not exist, fluorescence sensing may be enabled by employing fluorescently labeled biorecognition elements such as antibodies, aptamers, and DNAzymes.[47,48] These agents have been broadly employed within bench-top sensing applications and, more recently, within diagnostic microneedle form factors. While their use within photonic wearables has been suggested in recent literature, their use in such continuous health monitoring applications remains under development.

2.6. Colorimetry

Colorimetric signal transduction relies on chromophore molecules that experience changes in their electron state in response to target exposure. This induces a shift in the wavelength of photons that are absorbed by the molecule, yielding a change in color (Figure 2f).[49] The environmental mechanisms for inducing such shifts in electron state include changes in pH, ion concentration, and the gain or less of electrons. Chemical sensing can thus be implemented through the incorporation of a suitable target-responsive chromophore molecule, with widespread reports available for the detection of clinically relevant ions and metabolites.[49] For the detection of targets that do not directly evoke electron state shifts within typical chromophores, colorimetric sensing mechanisms can be designed through an indirect sensing mechanism. This includes enzymes that interact with target agents and produce electron donors or acceptors as by-products. These by-products engage in secondary redox reactions with suitable chromophores to generate target-specific color change.[49] Such sensing cascades have been effectively implemented toward the sensing of physiological markers within liquid clinical samples such as sweat. This has made on-body microfluidics a key component within colorimetric wearable sensing.[50]

The primary benefit of colorimetric transduction is that it is power-free and requires no complex equipment for readout.[49] These traits are optimal for consumer-level wearable applications. Rather, quantification can be enabled through optical images gathered and obtained using a smartphone. The primary hindrance in application here lies in the low sensitivity of such platforms compared to more technically advanced photonic approaches, as well as the environment-induced color variation within captured images.[50] Significant efforts have thus been dedicated toward employing advanced image analysis and artificial intelligence mechanisms toward more accurate calibration and quantification of colorimetric outputs (**Table 1**).[51]

3. Key Elements in Developing Wearable Photonic Sensors

Recent advances indicate three interconnected strategies to develop effective wearable photonic sensors under real-world applications: 1) Development of functional materials capable of supporting precise photonic sensing while maintaining compatibility with wearable form factors; 2) Development of scalable and precise fabrication methods to enable the production of high-performance but miniaturized photonic devices; 3) Development of efficient power management strategies to ensure reliable, long-term operation. Functional materials form the foundation of wearable photonics, encompassing light-emitting and light-responsive materials as well as substrates that provide structural and functional support. The following section first reviews advantageous materials that stand out for their unique properties in photonic sensing, ensuring compatibility with diverse real-world sensing scenarios. Beyond material selections, advanced fabrication techniques such as nano-micro patterning, roll-to-roll printing, and additive 3D printing play crucial roles in transforming these materials into functional devices. Moreover, wearable photonic devices need to incorporate power management solutions, which range from battery-powered designs to innovative self-powered systems to ensure continuous operation in real-world scenarios. Together, these elements systematically form the foundation for developing practical, scalable, and efficient wearable photonic sensing devices.

3.1. Functional Materials in Supporting Wearable Integrations

The design of the optical sensing cascade determines the effectiveness of a given photonic sensor. To this end, identifying the optimal functional materials for a given platform is instrumental. To begin the sensing cascade, generating light at specific wavelengths and intensities is a prerequisite for many optical approaches, such as fluorescence sensing, photoplethysmography (PPG), pulse oximetry detection, and spectroscopy.[65] Once sample exposure has occurred, effectively capturing and analyzing the reflected, transmitted, or scattered light is necessary to obtain a quantitative readout. Accomplishing such functions in a wearable format has been achieved by integrating diverse light-emitting and light-responsive materials. Concurrently, it is crucial to select a base substrate that effectively supports a given wearable photonic sensor in its target application environment. Current progress in wearable substrates indicates silicone elastomers, plastics, hydrogels, textiles, and paper as suitable for distinct wearable biosensors.[6,9,2] This section details the exact factors that educate optical design and substrate selection.

3.1.1. Light-Emitting and Light-Responsive Components For Wearable Sensing

Light-emitting materials (**Figure 3a**) are substances capable of generating light when subjected to an external stimulus, such as electrical current (electroluminescence),[66] photon excitation (photoluminescence),[67] or a particular chemical reaction (chemiluminescence).[65] Notable organic light-emitting diodes (OLEDs) in the space include polymer-based emitters (PFO, Poly 9,9-dioctylfluorene),[68] small molecule emitters (Tris(8-hydroxyquinoline)aluminum),[69] phosphorescent materials (iridium-based complexes),[70] and TADF emitters (thermally activated delayed fluorescence, 4CzIPN).[71] The popularity of these materials within wearables has been driven by their thin (less than 1 mm) and flexible form factors. They also offer customizable emission under tunable wavelengths across the visible light and near-infrared (NIR) spectrum, which is crucial for fluorescence and NIR-based detections. Besides these advantages, OLED has also been shown to offer dual functionality as both a light source and a display for sensing devices.[72] Despite these advantages, light-emitting diodes (LEDs) remain more suitable under specific use cases. For example, as OLEDs offer comparatively lower brightness, LEDs offer a solution for platforms that require high light output. From a commercial perspective, LEDs' relatively lower cost and high moisture and oxygen stability offer key advantages for mass production and deployment.[73] Selecting the light-emitting material most appropriate for a specific platform and use case thus defines a key consideration toward both effective performance and translatability.

Table 1. Summary of wearable photonic sensing approaches.

Approach	Principle	Common Use-Case	Advantages	Limitations	Refs.
Optical waveguides	Light transmitted through optical fibers; target-induced changes in transmitted light	Physical stimuli monitoring (temperature, pressure, motion)	High sensitivity, lightweight, flexible, high signal stability	Complex fabrication, high cost, power source dependence	[11,14,17]
Surface plasmon resonance	Target-mediated excitation of surface plasmon at metal-dielectric interface induces shift in resonance angle	Chemical sensing through diverse material modifications (metal oxides, polymeric films, carbon-based nanomaterials)	High sensitivity, rapid response time, nanomaterial-enabled miniaturization	Complex fabrication, high cost, power source dependence, limited material options	[52,53]
Surface-enhanced Raman scattering	Metallic nanostructure-mediated enhancement of target-induced inelastic scattering	Chemical sensing with the presence of a single target molecule resulting in the output of a detectable signal	Extremely high sensitivity, high specificity, compatible with diverse molecular targets	Complex fabrication, high cost, power source dependence, signal variability from nanostructure inconsistencies	[54–56]
Standalone material modulation	Target-induced shift in the optical properties of light-modulating materials	Physical and chemical sensing broadly explored, with nanoscale modifications for target-specific optimization	Simple design, cost-effective, high tunability for target applications	Comparatively lower sensitivity and specificity, slower response time, material degradation risk	[57–59]
Fluorescence	Photonic excitation of molecules resulting in light emission; intensity correlates with target quantity	Chemical sensing using fluorescence indicators and biorecognition elements	Can offer high sensitivity, low power needs, form factor versatility, miniaturization	Prone to environmental interference, signal degradation over time	[44–46,60]
Colorimetry	Chromophore molecules undergo change in response to target, yielding change in color	Chemical sensing through change in chromophore molecule induced directly or indirectly by target	Low cost, power-free, equipment-free readout, miniaturization	Low sensitivity, difficult to quantify, risk of reagent degradation	[61–64]

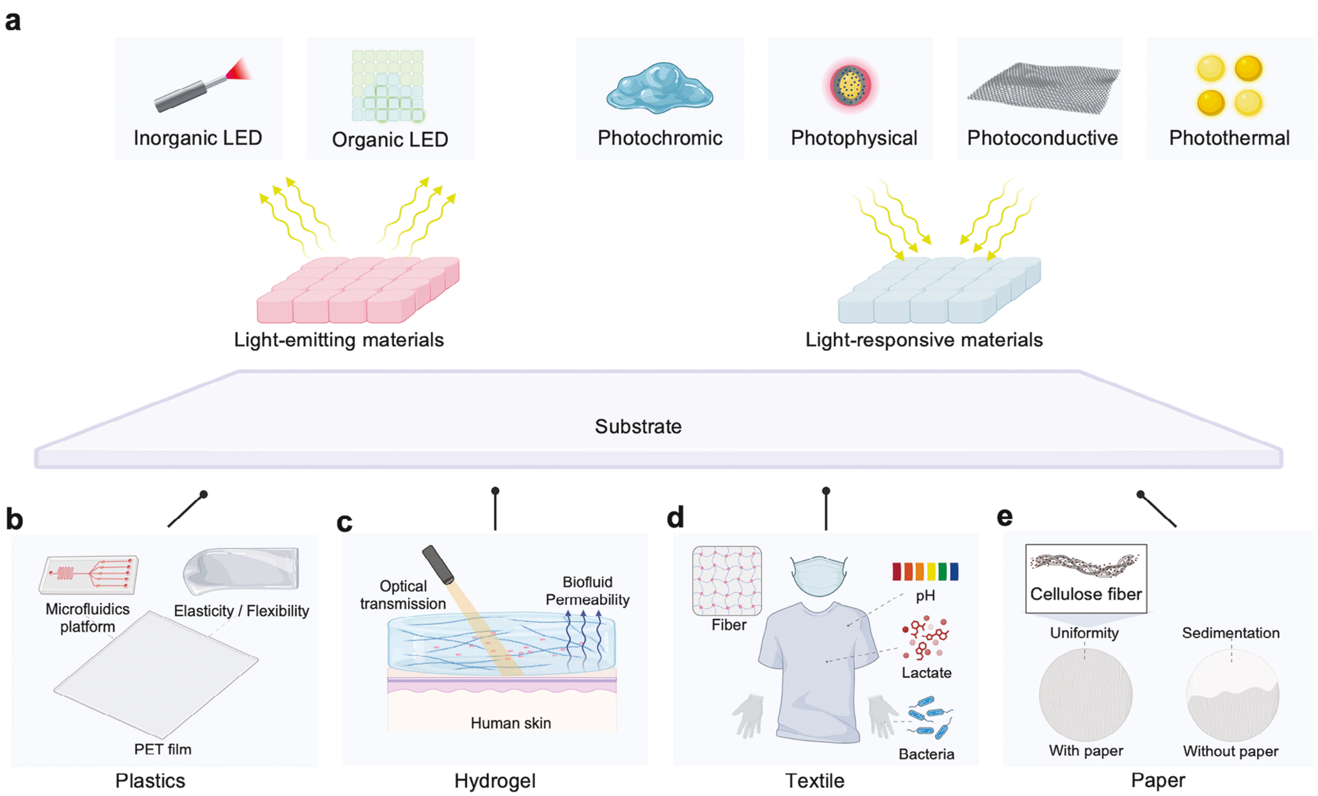

Figure 3. Functional materials enhancing wearable performance of photonic sensing devices. a) Representative examples of light-emitting and light-responsive materials b) Plastics-based substrates including polyethylene terephthalate (PET) and polydimethylsiloxane (PDMS) are highlighted for their stretchability, transparency, and proven compatibility with microfluidics. c) Hydrogel-based substrates with high transparency, biofluid permeability, and conductivity properties provide advantages in photonic sensing. d) Textile-based substrates including natural fibers and synthetic fibers, offer flexible integration into daily clothing and the potential for durability across washing cycles. e) Paper-based substrates derived from cellulose provide lightweight, biodegradability, and cost-effectiveness in supporting the transport of biofluids and the immobilization of functional photonic materials, such as colorimetric nanoparticle assays and fluorescent dyes. Figure produced using BioRender.

Light-responsive materials are substances that undergo specific changes in their structural, chemical, or energy states upon exposure to light (Figure 3a).[10] These changes can manifest as shifts in color, shape, conductivity, or mechanical properties depending on the material's composition and the properties of the incident light. Light-responsive materials as components within wearable photonic devices have played key roles in both sensing and signal transduction. For example, photochromic materials (e.g., stimulus-hydrogel, colorimetric dyes) undergo reversible structural changes when exposed to light that induce a shift in their optical properties.[74,75] As many of these dyes are simultaneously sensitive to distinct physical and chemical stimuli, the nature and extent of these optical shifts can be influenced by their presence in the surrounding environment. As the optical shifts experienced by photochromic materials often present themselves as color changes visible to the naked eye, the readout is simple – a key consideration toward commercial wearable photonic device implementation.[61,62] In a similar vein, photophysical materials also undergo light-induced optical shifts. However, these shifts are driven only by changes in the material's energy state rather than structure.[76] Consisting of agents such as fluorophores and quantum dots, this class of materials can be used for both the direct detection of target stimuli or the transduction of stimuli-driven molecular changes that subsequently induce a change in the nature or extent of their optical output.[77,78]

Also commonly used for signal transduction, photoconductive materials (e.g. graphene oxide, zinc oxide, cadmium sulfide, pentacene, and PbS) are another class of light-responsive materials.[10,79] These agents respond to light by generating charge carriers that enable light transduction into electrical signals for sensing. This ability has made them popular within wearable photonic sensing, as they can bridge the gap between optical input and electrical signal output. In particular, photodiodes have become one of the most widely used photoconductive materials in wearable optoelectronics, where they are regularly optimized to detect certain wavelengths of light with high sensitivity to meet the needs of a given application.[80]

Finally, photothermal materials (e.g., metallic nanomaterials) present unique offerings for wearable sensing, wherein they convert absorbed light energy into heat.[81] When stimuli that influence the thermal properties of the given material are present in the sensing environment, the resultant change in material temperature acts as a transducer. Importantly, compared with photoconductive and photochromic materials, photothermal materials offer high absorption of near-infrared (NIR) light, which enables deep tissue penetration, making them ideal for optoacoustic imaging and thermal therapy.[10]

3.1.2. Advantageous Polymer Substrate for Wearable Photonics Sensors

Natural and artificial polymer materials have played crucial roles in supporting the conversion of conventional biosensors into conformable wearable form factors, due to their stretchability, flexibility, mechanical robustness, and biocompatibility (Figure 3b-e). Historically, silicone elastomers such as polydimethylsiloxane (PDMS) and plastics such as polyethylene terephthalate (PET) have been particularly popular choices, due to their proven commercial track record and suitability for microfluidic integration (Figure 3b).[61,82–85] Yet, with the various functionalities now being introduced into photonic wearable sensors, use cases have arisen for diverse materials that can be broadly grouped as hydrogels, textiles, and paper substrates.

Hydrogels are 3D, crosslinked polymer networks that can uniquely retain and absorb significant amounts of water or biological fluids without dissolving.[86,87] Significant advantages of using hydrogels in wearable photonic sensing lies in their transparency, refractive index tunability, and ability to transmit light across various wavelengths (Figure 3c).[88] These properties make them suitable for the incorporation of photonic elements, such as waveguides and light-responsive materials.[89] Furthermore, the porosity of hydrogels permits the diffusion of analytes from biofluids, facilitating real-time monitoring.[90] These benefits overcome key limitations of PDMS, which has fixed optical properties and is hydrophobic to bio-fluidics. Various hydrogels have been tailored to act as not only the underlying physical substrate within wearable photonic devices but also to offer functional roles. Namely, conductive hydrogels have been developed to facilitate electrical signal transduction within photonic sensing cascades through the incorporation of ions (e.g., sodium, potassium, and chloride), conductive polymers (e.g., polyaniline and polypyrrole), and carbon-based nanomaterials (e.g., graphene and carbon nanotubes).[88,91] (**Table 2**)

Textile fabrics have gained significant attention in the wearable photonic sensing space due to their flexibility, lightweight structure, and non-disruptive integration into daily clothing (Figure 3d).[96] This latter advantage presents distinctive potential for real-world translation in the future. Textile substrates of wearable photonic sensors mainly contain natural fibers (e.g., cellulose, cotton, and silk fibroin), synthetic fibers (e.g., polyester, nylon, and spandex), and conductive fibers. Conductive textile fibers are composed of agents such as carbon-based materials and metallic conductors (e.g., silver and copper), which create the environment necessary for the functional integration of photonic components (e.g., LEDs, photodetectors, and waveguides) within the fabric.[98] As such, their specialty lies in the ability to function both as a structural matrix and as a host for integrated photonic and electronic components. Another notable advantage of textile fabrics is their ability to endure repeated washing cycles, maintaining their structural integrity and functionality over time. The washability provides the platform for recyclable biosensors.[96] Compared to hydrogels, textiles maintain stability across various environments, while hydrogels are prone to dehydration and environmental degradation.[99,100]

Finally, paper-based substrates are primarily composed of cellulose derived from natural sources such as wood pulp and recycled materials (Figure 3e).[63,101] Its use is supported by

Table 2. Comparison of functional substrates for wearable photonic sensing devices.

Functional substrate type	Main application scenario	Advantages	Limitations	Sensitivity to environmental factors	Proposed solutions	Refs.
Silicone Elastomers (e.g., PDMS)	Flexible substrates for microfluidic biofluid sensing and wearable optical waveguides	High flexibility, stretchability, biocompatibility	Hydrophobicity with biofluid interactions	Sensitive to temperature and UV exposure	Incorporate hydrophilic coatings or additives	[62–64,92–94]
Polyethylene Terephthalate (PET)	Transparent substrates for optical sensing and microfluidic devices	Excellent optical clarity, mechanical stability, and low cost	Brittle under high strain and limited stretchability	Sensitive to UV degradation and thermal deformation	Apply coatings to improve durability and UV resistance	[6,84,85]
Hydrogels	Transparent and tunable substrates for optical waveguides, biofluid sensing, and biomarker diffusion platforms	High transparency, tunable refractive index, biofluid permeability	Prone to dehydration, relatively low mechanical stability	Sensitive to humidity and temperature	Use composite hydrogels or hybrid materials	[95,96]
Textile Fabrics	Integrated platforms for smart clothing devices in multimodal sensing in healthcare	Lightweight, washable, and easily integrated into clothing	Limited precision in sensor fabrication due to porous structure	Absorbs moisture and contaminants	Incorporate conductive coatings or protective fibers onto surface	[93,96,97]
Paper Substrates	Cost-effective substrates for paper-fluidics or matrix for various chemical assays(colorimetric)	Biodegradable, cost-effective, capillary-driven biofluid handling	Fragility and low durability in wet conditions	Sensitive to moisture and humidity	Add water-resistant coatings or lamination	[62,63]

its highly biodegradable, environment-friendly, lightweight, and cost-effective nature.[101] Besides these advantages, its porosity allows the absorption and immobilization of functional photonic materials (e.g., colorimetric nanoparticle assays, fluorescent dyes, and conductive inks).[63] When considering microfluidic sensing cascades, paper-based substrates are also often used to fix functional nanoparticles, mitigating the bleeding, sedimentation, and non-uniformity of liquid assays during wearable applications.[63] Compared with another conventional substrate that requires additional channel fabrication for fluidic handling, paper substrates facilitate capillary-driven transport of biofluids, yielding a simpler, most cost-effective design.

3.2. Fabrication Methods of Photonic Components For Wearable Integrations

This section covers various advanced techniques used in the production of photonic components that are integrated into wearable devices. These methods include nanopatterning, roll-to-roll printing, and additive 3D printing, each offering unique benefits for scalability, customization, and integration flexibility. These fabrication techniques are instrumental in the development of highly functional, miniaturized photonic devices, which can be used in diverse applications like health monitoring, augmented reality, and smart textiles. The focus of this section is on how these methods contribute to the efficient production and performance of wearable photonic sensors, supporting their potential for commercialization and widespread use.

3.2.1. Nano-Micro Patterning

Nano-micro patterning encompasses a range of techniques, including lithography and transfer printing, that enable precise patterning of materials at the nano-micro scale.[102,103] These techniques are instrumental in creating photonic components for wearable devices. Among them, nanolithography employs methods such as electron beam lithography (EBL),[104,105] nanoimprint lithography (NIL),[106,107] and photolithography to define nanoscale features on substrates. These features govern light propagation, reflection, and absorption, facilitating the development of intricate photonic structures like waveguides,[108] photonic crystals,[109] and metasurfaces.[110] The high resolution offered by nanolithography enhances the sensitivity, efficiency, and functionality of diverse applications.[106] Recent advances in integrating photonics with silicon nanoelectronics have demonstrated the potential for advanced system-on-a-chip (SoC) applications.[102] By combining polycrystalline silicon photonic platforms with CMOS processes, researchers have overcome significant technical barriers. This integration enables cost-effective mass production while maintaining compatibility with existing CMOS transistor performance. Photonic components such as high-speed optical modulators, waveguides, and avalanche photodetectors can now be incorporated into bulk silicon substrates. These innovations are pivotal for high-bandwidth optical interconnects, meeting the demands of high-performance computing. For wearable photonic devices, this integration offers enhanced scalability, reduced production costs, and improved performance.

Beyond lithography, transfer printing for nano-micro materials provides a more flexible and scalable approach for fabricating nanostructures on diverse substrates.[103,107,111–123] While transfer printing may not achieve the ultra-high precision of top-down lithographic methods, this process efficiently produces high-resolution (sub-20 nm) nanostructures with nearly 100% yield, making it ideal for large-scale production.[103] Moreover, advanced 3D cross-point plasmonic nanoarchitectures fabricated using transfer printing have shown exceptional promise in enhancing light-matter interactions.[113] For instance, these structures amplify Raman signals through the formation of dense “hot spots” at multilayered nanowire intersections, greatly benefiting SERS applications (**Figure 4a**).[113] Such achievement of scalable, high-resolution fabrication on diverse surfaces underscores the potential of transfer printing for wearable photonic devices (Figure 4b).[113] Transfer printing-based photonics can also be utilized for the fabrication of holograms, color filters, and strain sensors, expanding its applicability across different fields.[112]

3.2.2. Roll-to-Roll Printing

Roll-to-roll printing is emerging as a highly scalable and cost-efficient method for fabricating wearable photonic sensors that are compatible with diverse materials.[119,124–130] Its continuous production process supports the creation of large-area photonic devices, such as wearable patches, tapes, and textiles, enabling seamless integration into garments. The ability to mass-produce flexible optical components without compromising quality or performance is crucial for ensuring affordability and accessibility to a broader population.

This technique involves printing optical waveguides and sensors onto flexible substrates, such as plastic films or fabrics, facilitating the development of lightweight, adaptable photonic components that can be effortlessly integrated into wearable designs. For example, roll-to-roll slot-die coating and lamination have been used to fabricate hydroxypropyl-cellulose (HPC) photonic laminates that respond to mechanical stimuli, producing pressure maps visible to the naked eye (Figure 4c,d).[130] Additionally, as roll-to-roll printing allows for the integration of multiple optical components on a single flexible substrate, multifunctional sensors capable of monitoring multiple health parameters simultaneously can be produced in a form factor that remains lightweight and comfortable. The cost-effective, high-throughput production capabilities of roll-to-roll printing make it an attractive alternative to conventional batch processing techniques, which are slower and more expensive. While maintaining precision and uniformity at high processing speeds remains a challenge, advancements in printing methods, such as gravure and inkjet printing, have significantly improved resolution and pattern quality. These developments solidify roll-to-roll printing as a practical solution for scalable, flexible photonic device fabrication.

3.2.3. Additive 3D Printing

Additive 3D printing is emerging as an innovative approach for fabricating photonic components for wearable integrations due

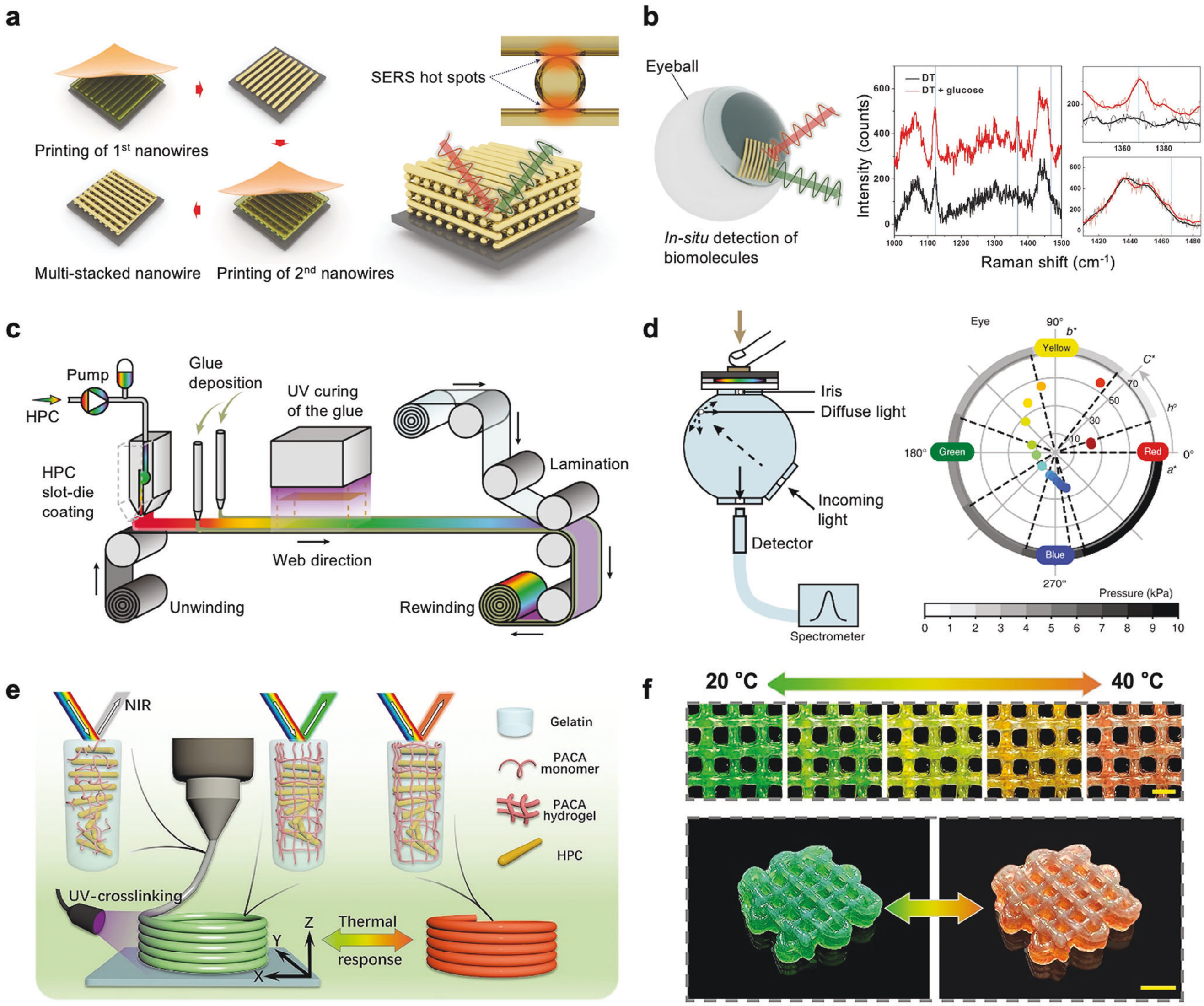

Figure 4. Fabrication methods of wearable photonics. a,b) Nano-micro patterning process and its application in photonic sensors; Reproduced with permission.[113] Copyright 2016, John Wiley and Sons. a) Schematic illustration of the nano-micro patterning procedure for 3D cross-point plasmonic nanoarchitectures. b) SERS-based transfer-printed glucose monitoring sensor integrated into a contact lens. c,d) Roll-to-roll printing process and its application in photonic sensors; Reproduced under the terms of the CC-BY 4.0 license.[130] Copyright 2018, Authors. Published by Springer Nature. c) Schematic illustration of roll-to-roll printing for the fabrication of HPC-laminated films. d) Illustration of a colorimetric film-based pressure sensor, including the setup and results for pressure-induced color change measurement. e,f) Additive 3D printing process and its application in photonic sensors; Reproduced with permission.[142] Copyright 2022, PNAS. e) Schematic illustration of an additive 3D printing-based cholesteric cellulose structure composed of HPC, gelatin, and hydrogel. f) Color variation of a 3D-printed colorimetric temperature sensor under different temperatures (20–40 °C).

to its design flexibility and rapid prototyping capabilities.[131–134] In 3D printing, material is deposited layer-by-layer to create complex structures, enabling the fabrication of customized photonic elements that can conform to the shape and requirements of wearable devices. Techniques such as fused deposition modeling (FDM),[135,136] stereolithography (SLA),[137–139] and inkjet-based printing[140,141] are used to produce waveguides, optical interconnects, and micro-optical structures. This approach is particularly advantageous in wearable photonics because it allows for the on-demand production of intricate optical components with geometries that may be challenging to achieve using traditional methods. Recent advancements include using cholesteric cellulose liquid crystal ink to achieve 3D structural coloration, providing vivid, stable color appearances with unique optical features such as thermal responsiveness (Figure 4e).[142] This printable ink, composed of cholesteric cellulose liquid crystals, gelatin, and a thermal-responsive hydrogel, enables the production of 3D objects with angle-independent colors and dual thermal responsiveness, which is beneficial for various wearable applications (Figure 4f).[142] One of the primary advantages of additive 3D printing is its ability to integrate different materials, such as polymers and composites, to achieve multifunctional photonic components. This versatility enables the production of wearables with integrated sensing, light modulation, and communication functionalities tailored for specific applications such as health monitoring and augmented reality. Despite its advantages, 3D printing for wearable photonics faces challenges related to the resolution and material limitations of current printing technologies. Achieving nanoscale precision is still difficult, which restricts the application of 3D printing in the fabrication of some high-performance photonic structures. Ongoing research into new printable materials and higher-resolution printing techniques is overcoming miniaturization challenges and enabling high-precision printing, making 3D printing increasingly viable for wearable photonic device fabrication (**Table 3**).[143]

3.3. Power Management Strategies For Wearable Photonics

Efficient power management is a critical aspect within wearable photonic device development, particularly when designing for continuous on-body, real-time monitoring applications using optoelectronics. The power requirements of wearable devices vary depending on their sensing and communication capabilities, making effective power management crucial for long-term operation and user comfort. In this section, we discuss three power management approaches: battery-operated photonics, wireless charging, and self-powered photonics.

3.3.1. Battery-Powered Wearable Photonics

Batteries are commonly used within wearable sensors due to their reliability and ability to provide stable power.[145–147] Integrating a battery into photonic sensors enables continuous sensing and data transmission, making them particularly suitable for high-performance wearable devices. Among the options, lithium-ion and lithium-polymer batteries are frequently employed due to their high energy density and rechargeable properties. The primary advantage of battery-operated systems lies in their capacity to power complex sensor configurations with high precision and stability, facilitating the integration of multiple photonic components within a single sensor. However, increasing the battery size to extend usage time introduces challenges related to convenience, as larger batteries increase the bulk and reduce the portability of devices. This trade-off is particularly significant in wearable medical applications, where device size and weight are critical factors. For instance, wearable photonic sensors typically utilize batteries around 1 cm in size, providing approximately several hours of operation, depending on the power demands of the photonic components. Recent studies have employed various approaches toward refining battery integration within wearable photonics.[148–151] For example, a modular device has been developed using a replaceable, magnetically coupled battery system that enables continuous monitoring of vital parameters such as cerebral oxygenation, heart rate, and peripheral oxygenation (**Figure 5a**).[148] This design not only minimizes the device's size and weight but also allows for battery replacement without detaching the sensor from the patient's skin. This feature is particularly beneficial for pediatric and neonatal patients, where maintaining skin integrity and continuous monitoring are critical. Additionally, the device's lightweight and flexible design ensures minimal interference with the patient's

Table 3. Comparison of fabrication strategies for photonic devices.

Fabrication strategies		Materials	Advantages	Limitations	Applications	Refs.
Nano-micro patterning	Lithography	Polycrystalline silicon, SU-8, photoresists	Ultra-high resolution, well-established process	High cost, complex process, limited scalability	Wave guides, Photonic crystals, Optical modulator	[104–109,144]
	Transfer printing	Elastomer, nanomembranes	High flexibility, compatibility with various substrates	Delamination risk, alignment challenges	Hologram, color filter, SERS	[103,111–123]
Roll-to-roll printing		Inks, flexible polymers	High throughput, cost-effective, Mass production	Limited resolution, material durability	Large-area photonic sensors; tapes, textiles	[119,124–130]
Additive 3D printing		Dielectric elastomers, conductive polymers UV-curable resins	Customizable, rapid prototyping, low waste	Limited resolution, mechanical robustness issues	Wave guides, Optical structure, Colorimetric sensor,	[131–134]

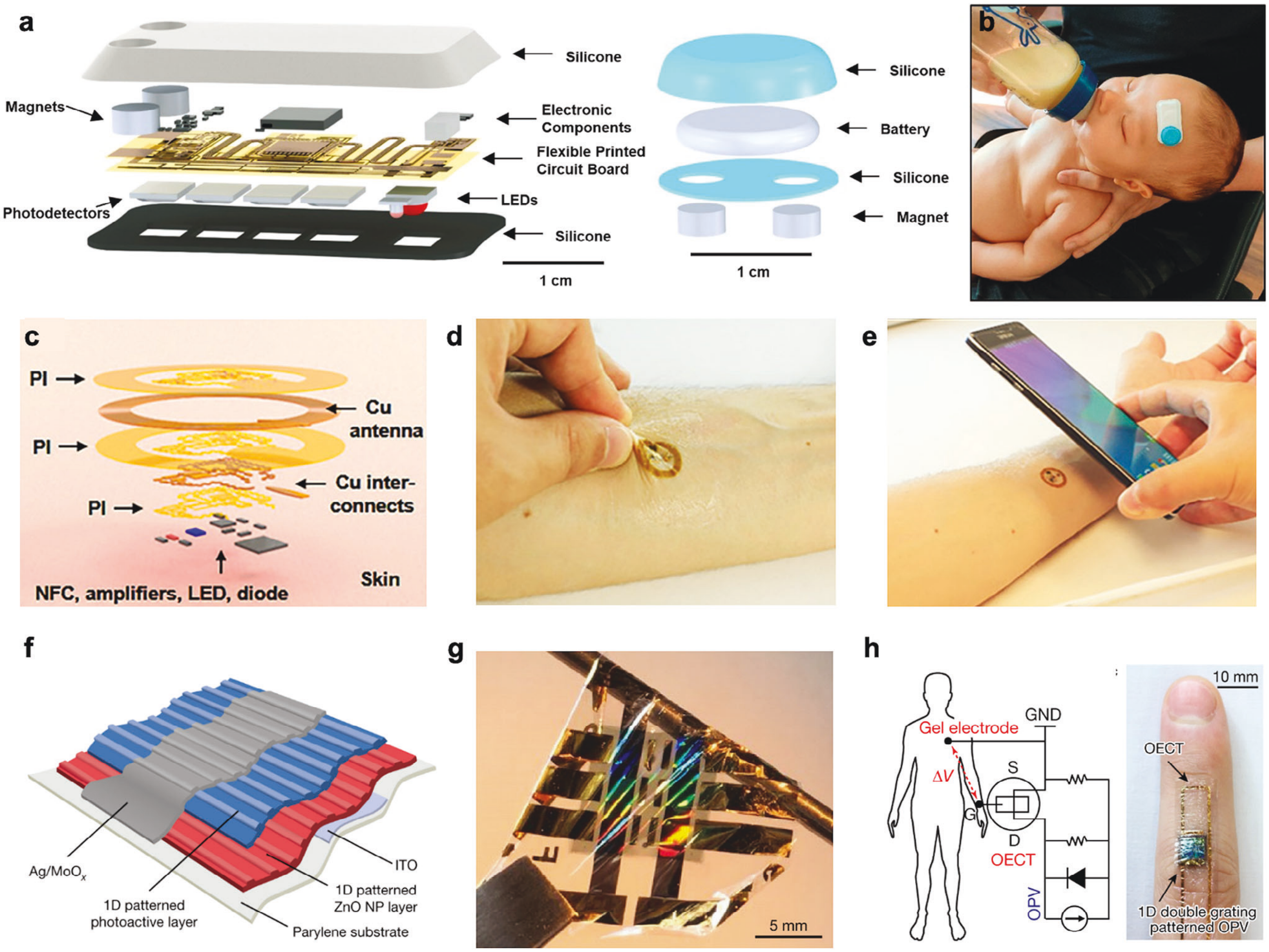

Figure 5. Power solutions for wearable photonic sensors. a,b) Battery-powered wireless, photonic device for cerebral hemodynamics monitoring of pediatric patients; Reproduced with permission.[148] Copyright 2020, PNAS. a) Schematic illustration of the device. b) Photograph of the device mounted on the forehead of the infant. c–e) Battery-free, wireless photonic device for optical characterization of the skin; Reproduced with permission license.[155] Copyright 2016, AAAS. c) Schematic illustration of the device, integrated with flexible printed circuit board, electronics, photonics. d) Photograph of a device mounted on the skin. e) Photograph of wireless power transfer for the operation of the photonic device mounted on human skin. f–h) Self-powered photonic electronics integrated with organic photovoltaics (OPV); Reproduced with permission.[174] Copyright 2018, Spring Nature. f) Schematic illustration of double grating patterned flexible OPV. g) Photograph of OPV device wrapped over spatula. h) Diagram and photograph for self-powered photonic device attached to a finger for cardiac signal recording.

natural movements and comfort, showcasing the potential of battery-operated systems to overcome traditional limitations in wearable sensors (Figure 5b).[148] With regards to data transmission, battery-powered systems generally integrate a Bluetooth Low Energy (BLE) module for efficient, real-time wireless communication of sensor data, which is especially advantageous in remote patient monitoring. The BLE functionality ensures that the device can seamlessly transmit vital information to healthcare providers, further enhancing the utility of wearable photonic sensors in medical applications.

3.3.2. Battery-Free, Wireless Power Transferred Wearable Photonics

Wireless, battery-free wearable devices represent a significant advancement in wearable technology, offering unique benefits over traditional battery-powered devices.[145,152–154] In particular, near field communication (NFC) technology has been a focus for providing efficient power transfer to these devices. NFC-enabled sensors eliminate the need for onboard batteries, thereby reducing the bulk and weight of wearable systems, which is especially advantageous for long-term medical monitoring applications where minimizing discomfort and maximizing ease of use are critical. Long-term monitoring is further supported by the continuous operation offered by these devices, overcoming limitations associated with battery life. Examples of such a device are described in a study on battery-free, stretchable optoelectronic systems.[155–158,80,159] These photonic devices operate on a polyimide-based flexible printed circuit board integrated with a copper antenna and NFC chip (Figure 5c).[155] The absence of a battery allows for an ultrathin thickness of ~100 µm, enabling the device to adhere closely to the skin like a tattoo (Figure 5d).

Through electromagnetic induction between the device's coil and an NFC-enabled smartphone coil, these devices facilitate both power transfer for photonic operation and wireless data communication (Figure 5e). Interestingly, such wireless power transfer-enabled photonic devices have been integrated into antenna-equipped clinical beds, enabling scenarios where the full-body condition of patients lying on the bed can be diagnosed and monitored in real-time.[80] Such applications underscore the versatility of this approach, extending use cases to comprehensive, non-invasive clinical monitoring.

Despite these benefits, these devices face several significant challenges. Because they rely on power transfer from external coils, they can only operate within the proximity of these coils. For example, most wireless power transferred sensors used in animal studies are designed to work inside cages equipped for continuous power transmission.[160–164] In human applications, NFC-enabled wearable sensors receive power through electromagnetic induction from smartphones or antenna-integrated clinical beds.[80,165–169] However, they can only function when the primary coil is aligned with the sensor coil, which limits their usability.

3.3.3. Self-Powered Wearable Photonics

Self-powered photonic sensors have emerged as a compelling solution for wearable applications, offering sustainable and maintenance-free operation by harnessing ambient energy from wasted or renewable primary energy sources.[170–173] Unlike wireless power transfer methods, these systems utilize innovative energy harvesting technologies, such as organic photovoltaics (OPVs),[174,175] triboelectric nanogenerators (TENGs),[176–179] and thermoelectric nanogenerators (TNGs),[180–182] to power wearable photonics sensors.

Solar energy, particularly through OPVs, has been extensively explored for self-powered wearables due to its adaptability to lightweight and flexible designs.[174,175] A notable example is a recent study on ultra-flexible organic photovoltaics with nano-grating patterns, achieving a power-conversion efficiency of 10.5% and a power-per-weight value of 11.46 W g^{-1} (Figure 5f,g).[174] These OPVs, fabricated on ultra-thin parylene substrates, demonstrate excellent mechanical durability and stable power generation under various lighting and deformation conditions. By integrating these OPVs with organic electrochemical transistors (OECTs), researchers have achieved self-powered, skin-conformable cardiac sensors capable of detecting biological signals with high signal-to-noise ratios, even under low light conditions (Figure 5h). This advancement highlights the potential of solar energy-based wearable photonics for precise, continuous monitoring in clinical and ambulatory settings. Further progress has been made with OPV arrays, where series-connected OPV cells have been optimized to increase both output voltage and power stability. For example, the integration of a 10-cell OPV array enabled efficient energy supply to polymer light-emitting diodes (PLEDs) in a self-powered PPG sensor. This design demonstrated stable blood pulse detection with a frequency of 77 beats per minute (bpm) under indoor light conditions. The modular array configuration not only improved energy harvesting efficiency but also ensured consistent operation in variable lighting environments.[175]

TENGs and TNGs offer alternative methods for self-powered wearable sensors. TENGs generate electricity from mechanical motion, such as walking or joint movements, making them ideal for dynamic, motion-rich settings.[176–179] TNGs, by contrast, convert temperature gradients between the body and ambient air into electrical energy, providing reliable power in controlled thermal environments.[180–182] These approaches are particularly advantageous in scenarios with limited access to consistent lighting.

While self-powered wearable systems promise numerous benefits, their real-world deployment faces challenges. Solar-powered systems depend on light availability, which can limit functionality in dim or indoor environments. For TENGs, performance is highly sensitive to environmental conditions, particularly humidity. In wet or highly humid environments, the presence of water molecules on surfaces inhibits triboelectric charging, causing a steep decline in energy harvesting efficiency. Similarly, TNGs face challenges related to heat dissipation and their reliance on the Seebeck effect, which requires a stable temperature gradient for power generation. This dependency limits their use to steady-state temperature monitoring applications, where such gradients can be reliably maintained. Addressing these limitations through hybrid configurations is a promising approach. For example, combining OPVs with TENGs or TNGs can leverage complementary energy sources, such as light and mechanical or thermal energy, to improve overall performance.[170,176]

4. Healthcare Applications of Wearable Photonic Sensors

Wearable photonic sensors are emerging as transformative tools in healthcare, enabling non-invasive and real-time monitoring of not only physical signals measurable on the skin but also chemical signals derived from biofluids such as sweat, interstitial fluid, and tears. These sensors leverage the interactions between light and biological tissues or fluids – such as absorption, reflection, scattering, emission, and transmission, to extract meaningful data and provide insights into an individual's health status. Physical signals include parameters like heart rate, strain, and temperature, while chemical signals encompass alternative biofluids like sweat, interstitial fluids, and tears to target various chemical information, such as pH, electrolytes (e.g., Ca^{2+}, Na^{+}, Cl^{-}), metabolites (e.g., glucose, lactate), proteins (e.g., cytokine, Matrix Metalloproteinase-9) and drugs (e.g., nicotine), exosomes such as glucose, lactate, and proteins. By integrating advanced materials, optical technologies, and miniaturized electronics, wearable photonic devices can track a wide range of physical and chemical parameters, such as glucose monitoring for diabetes management or heart rate tracking for cardiovascular health. These capabilities contribute significantly to early diagnosis, disease management, and personalized healthcare.

4.1. Physical Signals Monitoring

Monitoring physical signals is a fundamental aspect of wearable photonic sensors, providing essential data about the body's physiological state and environmental interactions. These sensors are designed to measure diverse parameters, such as cardiovascular signals, tactile feedback, and temperature variations, offering critical insights into the user's health and well-being. By accurately capturing these physical signals, wearable devices enable early detection of abnormalities, improve disease management, and enhance the quality of care in both clinical and home settings.

4.1.1. Cardiovascular Signal Sensors

Cardiovascular signal sensors, such as PPG sensors, utilize the optical properties of blood to measure vital signals like heart rate and oxygen saturation. These sensors typically consist of two different LEDs – commonly red and infrared – and a photodetector, such as a photodiode or phototransistor. The LEDs emit light into the skin, which penetrates the underlying arteries and veins. With its dynamic flow and oxygenation levels, blood absorbs light differently depending on its oxygen content and volume within the vessels. The photodetector measures the intensity of light that is either reflected back or transmitted through the skin. Variations in light absorption, driven by the pulsatile nature of arterial blood flow, generate the PPG signal. Arteries, which carry oxygen-rich blood, exhibit distinct absorption patterns compared to veins, which return oxygen-depleted blood to the heart. By analyzing these periodic changes in light absorption, PPG sensors can calculate heart rate, oxygen saturation (SpO_2), and even blood volume changes (**Figure 6a**).[183–185] This non-invasive, real-time monitoring method has become an essential tool in wearable healthcare technology for its simplicity, reliability, and ability to provide continuous cardiovascular data. To enhance the convenience of traditional wired, finger-mounted PPG sensors, wireless communication-based PPG sensors have been proposed.[148,155–157,183,186–189] These sensors operate using a wireless communication module and are equipped with infrared (IR) and red (RED) LEDs, along with a photodiode. Furthermore, to minimize the impact of external light during measurements, the system is encapsulated in a flexible polymer, effectively shielding it from ambient light interference (Figure 6b).[156] This design replaces bulky traditional systems with a miniaturized form factor, maintaining close adhesion to the skin while ensuring stable data collection. By measuring the reflected light from each LED on the skin, the device extracts cardiovascular signals based on the differences in light absorption between arteries and veins (Figure 6c). Building upon the concept of wireless photonic cardiovascular signal sensors, a notable development involves a wireless oximeter device designed for peripheral application on the lower limb, which measures SpO_2 and pulse rates using dual-wavelength PPG (Figure 6d).[188] The oximeter is designed for peripheral applications, such as placement on the foot or wrist, providing flexibility for different patient anatomies. Its soft, flexible construction ensures compatibility with the delicate skin of neonates and reduces the risk of irritation. Clinical evaluations demonstrated that the device achieves high accuracy in SpO_2 measurements, with deviations well within acceptable limits when compared to FDA-approved commercial systems. These findings highlight its potential for reliable, continuous monitoring in critical care environments, improving patient comfort while maintaining clinical-grade performance (Figure 6e).

4.1.2. Tactile Sensor

Tactile sensors measure parameters such as strain,[190–194,59,195,196,90] pressure,[197–200] and deformation,[201,202] enabling precise detection of physical interactions and environmental forces acting on the body. These sensors are indispensable in fields such as prosthetics,[192] rehabilitation,[203] and wearable robotics,[196] where understanding touch and pressure distribution is vital. Photonic tactile sensors utilize optical techniques to achieve high sensitivity and accuracy, often employing flexible and stretchable materials to ensure seamless integration with the human body. These systems measure physical changes by detecting variations in light transmission or reflection caused by mechanical deformation (Figure 6e). For instance, physical forces such as compression or tension alter the spacing between the light source and the photodiode or shift their relative positions. These changes affect the number of light rays reaching the photodiode, resulting in measurable variations in optical signals. This principle forms the foundation for detecting and quantifying mechanical stimuli using photonic tactile sensors.

Photonic strain sensors include light-transmittance and optical fiber-based sensors, which utilize changes in light properties such as intensity or wavelength in response to mechanical deformation, have also been explored. An innovative example is a self-powered strain sensor based on piezo-transmittance mechanisms and auxetic metamaterials (Figure 6f).[190,191] The sensor detects strain-induced changes in optical transmittance within an auxetic structure of elastomer film patterned with rotating square units. The auxetic structure—which has a negative Poisson's ratio—enhances sensitivity while reducing stiffness, resulting in a high gauge factor, long-term stability, and minimal hysteresis. The sensor shows the practical application of Figure 6g.

Additionally, optical fiber-based strain sensors utilize the transmission of light through fibers to measure strain based on changes in light intensity or phase, offering a highly sensitive and flexible method of sensing. For example, flexible and wearable photonic-crystal fiber interferometer embedded in a PDMS have also been employed for physiological monitoring, demonstrating their utility in providing reliable strain sensing in healthcare applications.[195] Another example involves combining multiple optical waveguides with commercial LEDs and photodiodes to create a glove-based device, demonstrating the potential for haptic interaction in wearable formats.[192] Those stretchable optical waveguides have been successfully integrated into a soft prosthetic hand, providing precise strain sensing capabilities while being chemically inert and exhibiting low hysteresis.[192] The developed sensor was further utilized for a self-powered human motion monitoring (HMM) system during weight training. Specifically, a one-arm dumbbell row was performed to validate the sensor's capability in posture correction. To simultaneously track posture accuracy and muscle development, the sensors were placed on joints prone to injury and on target muscles, allowing real-time monitoring of muscle activity and joint dorsiflexion.[192] (Figure 6g) Advances in pressure sensing further highlight the potential of photonic tactile sensors for wearable applications.[197–200] One example integrates a microporous elastomer with thin-film organic solar cells, forming a self-powered pressure sensor that detects static and dynamic

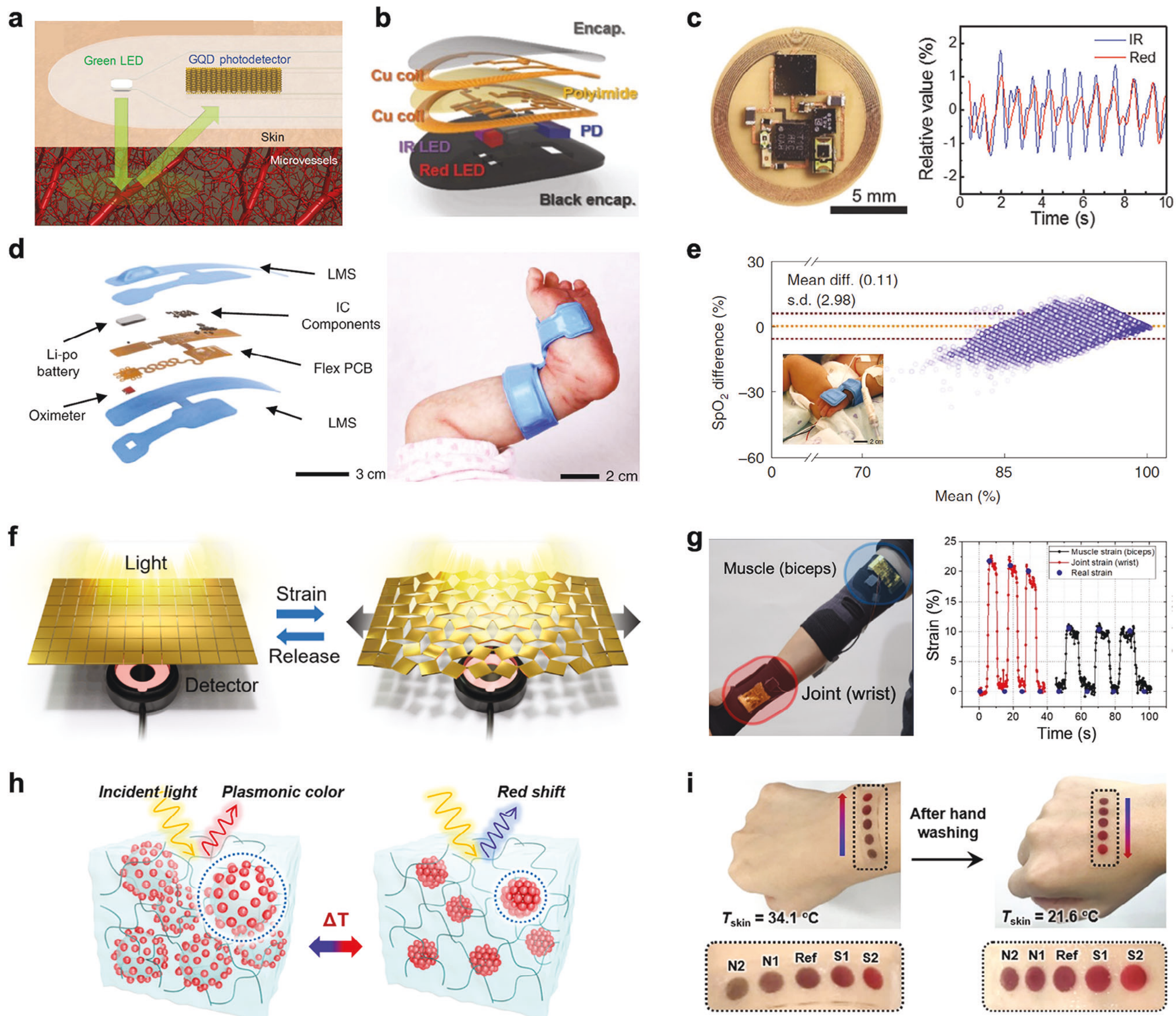

Figure 6. Applications in physical signals monitoring. a) Working mechanism of a wearable photoplethysmography (PPG) sensor based on measuring reflectance differences of specific light wavelengths from skin vasculature; Reproduced with permission.[185] Copyright 2019, AAAS. b,c) Miniaturized PPG sensor utilizing differences in absorption and reflectance of two LED wavelengths; Reproduced with permission.[156] Copyright 2017, John Wiley and Sons. b) Schematic illustration of an NFC-based wearable miniaturized PPG sensor. c) Individual signals obtained from the IR and RED LEDs of the miniaturized wearable PPG sensor. d,e) Wearable PPG sensors applied in clinical evaluations, including monitoring heart activity in children; Reproduced with permission.[188] Copyright 2020, Springer Nature. d) Schematic illustration and photograph of a BLE-based PPG sensor mounted on the lower limb. e) Clinical evaluation of PPG sensors for SpO_2 monitoring. f,g) Self-powered strain sensor based on piezo-transmittance of auxetic structured metamaterial; Reproduced with permission.[190] Copyright 2021, Elsevier. f) Working mechanism of an auxetic-structure-based photonic strain sensor, detecting changes in light transmittance induced by applied strain. g) Photograph and measurement of strain signals corresponding to different postures, with the sensor mounted on the arm. h,i) Wearable colorimetric patch based on thermoresponsive plasmonic microgels; Reproduced under the terms of the CC-BY 4.0 license.[41] Copyright 2018, Authors. Published by Springer Nature. h) Working mechanism of the colorimetric temperature sensor. i) Photograph of a colorimetric sensor mounted on the human body, showing color changes in response to temperature variation (34.1–21.6 °C).

pressures by measuring changes in light transmittance as micropores close under compression.[197] Additionally, customizable opaque tilted structures in another pressure sensor design allow for tailored sensitivity and pressure ranges.[198] These structures modulate light transmittance under applied pressure, and the system converts this into electrical signals using integrated solar cells. These photonic tactile sensors are unaffected by ambient conditions like temperature or humidity, demonstrating their robustness and versatility in applications such as breath monitoring[204] and robotic control systems.

4.1.3. Temperature sensor

Temperature sensors integrated into wearable photonic devices enable precise monitoring of on-body temperatures. These sensors play a crucial role in managing health by tracking vital parameters such as fever, inflammation, and overall thermal comfort. Two primary types of photonic temperature sensors are optical fiber-based sensors and colorimetric sensors.

Optical fiber-based temperature sensing has employed FBG sensors, surface plasmon resonance-based sensors, and thermoluminescence-based sensors.[193,195,202,205–212] As discussed, FBG sensors operate by creating periodic patterns within the optical fiber that reflect specific wavelengths of light.[202,208,210,213] This method is based on wavelength modulation, where temperature changes lead to variations in the refractive index or grating spacing, which in turn alter the reflected wavelength. For instance, PDMS encapsulation with a highly linear and negative thermo-optic coefficient is used, where the decrease in refractive index due to temperature rise causes a proportional blue shift in the interference spectrum, enabling precise ratiometric temperature sensing.[213] SPR-based sensors utilize the interaction between light and free electrons on a metal surface to generate surface plasmon waves. Changes in temperature affect the refractive index near the metal surface, which shifts the resonance condition.[193,206] For instance, an SPR temperature sensing system has been developed by integrating a side-polished fiber with a smartphone platform, where the SPR response is recorded and processed to measure temperature changes, achieving a sensitivity of 0.0018 a.u./°C in the range of 30–70°C. Additionally, thermoluminescence-based sensors use materials, such as those containing Mn^{2+} ions, that exhibit changes in fluorescence emission in response to temperature variations.[209,211] A dual-wavelength emitting material, $Li_2ZnSiO_4:Mn^{2+}$, has been developed, incorporating stretchable optical fibers for wearable applications, which allows stable ratiometric temperature sensing with good precision and repeatability.[209]

Colorimetric temperature sensors operate based on visual color changes in response to temperature variations.[41,59,142,214–218] These sensors are often designed using materials that undergo a distinct color shift when exposed to different temperatures.[41](Figure 6h) he developed sensor array patch that demonstrated its capability by visually displaying different color patterns corresponding to the temperature of various surfaces, such as human skin (wrist and back of the hand) and a beaker containing water. For example, the patch showed distinct color changes at 34.1 °C on the wrist, 21.6 °C on the back of the hand after washing, and 29.0 °C on the beaker surface.[41] (Figure 6i) Due to their simplicity, colorimetric temperature sensors are highly attractive for wearable applications. They allow individuals without engineering knowledge to easily interpret temperature information visually. However, while these sensors are highly convenient, they tend to have lower accuracy compared to optical fiber-based temperature sensors, which limits their use in scenarios that require precise temperature monitoring.

Photonic temperature sensors, whether based on optical fibers or colorimetric principles, can be seamlessly integrated into wearable platforms, enhancing their utility in both medical and everyday applications. Their rapid response times and minimal invasiveness make them ideal for continuous health monitoring and personalized care.

4.2. Chemical Signals Monitoring

Wearable photonic chemical sensors offer non-invasive, real-time, in-situ monitoring of various critical chemical biomarkers. These systems have largely relied on integrating optical sensing mechanisms – such as colorimetry, fluorescence, and SERS, with smart wearable technologies – such as microfluidics, paper fluidics, and microneedles, to enable in-situ sample collection and high-performance analysis of various biofluids. This section reviews advances in the application of wearable photonic sensors toward chemical sensing through the lens of three key biofluids explored to date – sweat, interstitial fluid (ISF), and tears.

4.2.1. Sweat-Based Wearable Photonic Sensors

Sweat is secreted by the eccrine, apocrine, and sebaceous glands. Eccrine sweat has captured significant attention from researchers for wearable biosensing due to its rich chemical composition and non-invasive accessibility.[219] Sweat contains a complex mixture of electrolytes (e.g., sodium, potassium, chloride), metabolites (e.g., glucose, lactate, vitamins, uric acid), proteins (e.g., cytokines, C-reactive protein), hormones (e.g., cortisol, oestradiol), and other small molecules.[6,12,219–221,85,222] The composition of sweat is influenced by various factors, including skin hydration status, diet, exercise, environmental conditions, and overall health, which makes it a dynamic and informative biofluid for monitoring physiological and pathological conditions. Colorimetry, fluorescence, and SERS have all been employed toward wearable photonic sweat sensing.

Wearable colorimetric sweat sensing involves interactions between sweat biomarkers and chemically-responsive sensing agents that yield visible changes in color. As this approach is generally deployed in a battery-free format that outputs intuitive signals visible to the user without any equipment, power management and signal readout components are not needed. This offers a significant translational advantage.[63,64,83,96,223–229] To advance these systems, recent works have focused on developing wearable modules that offer autonomous sample collection and colorimetric assay execution with high sensitivity and selectivity. Concurrently, smartphone camera-based readout technologies have been emphasized, to enable user-led quantitative readout. Here, one notable work integrated microfluidic technology and colorimetric sensing onto a wearable chip that adhered to the skin (**Figure 7a**).[61] The microfluidic design offered robust sweat collection – up to 50 uL over 6 hs. The sensor was used to detect sweat pH, lactate at concentrations between 1.5 and 100 mM, and glucose levels at concentrations as low as 5 μM, and chloride. Smartphone-mediated photo capture and analysis was enabled through wireless data communication (Figure 7b). Unfortunately, such crude image capture mechanisms are highly susceptible to interference and inconsistencies. Thus, while the quantitative readouts derived from the images in this study showed a degree of correlation with the quantitative results of a laboratory-based analysis, there is an ongoing need for improved image processing mechanisms (Figure 7c). Still, effective detection of biomarkers with high clinical relevance – lactate for exercise intolerance and hypoxia-related conditions, glucose for diabetes monitoring, and chloride for

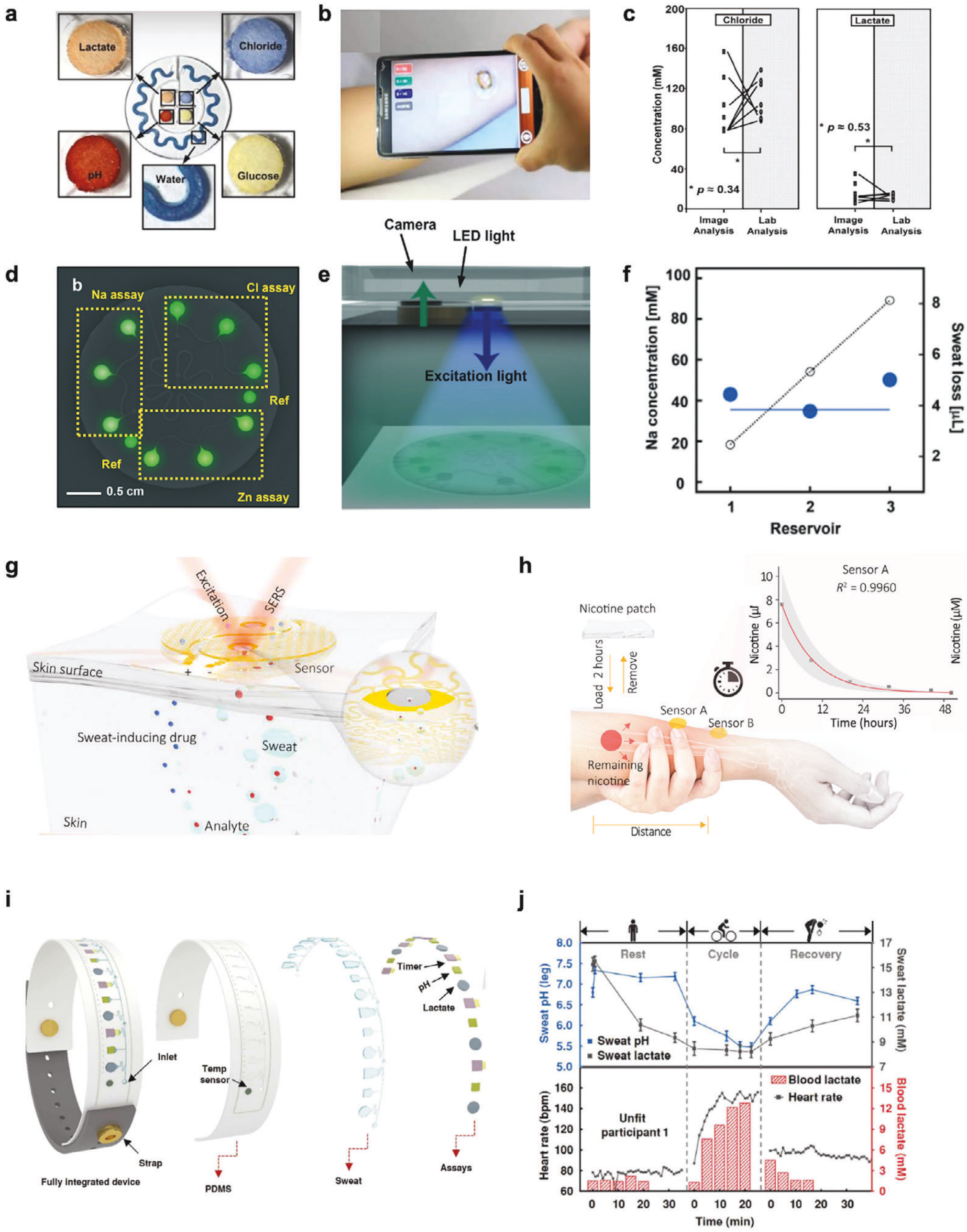

Figure 7. Applications of wearable photonic sensing device in sweat monitoring. a) Diagram illustration of an epidermal wearable microfluidic patch integrated with multiplexed colorimetric sensing modules for detecting sweat biomarkers, including pH, lactate, and chloride, with autonomous sweat collection capabilities; b) Diagram of the in-situ sweat patch data collection process with a smartphone camera to capture and analyze biomarker concentrations. c) On-body measurement results of the multiplex microfluidic colorimetric patch: Correlation between chloride and lactate concentrations measured by the colorimetric patch during on-body tests and laboratory-based analyses, demonstrating clinical relevance and accuracy. a–c) Reproduced with permission.[61] Copyright 2016, AAAS. d) Diagram illustration of a skin-interfaced microfluidic device for fluorescent sensing chloride, sodium, and zinc in sweat. e) Image illustration of the smartphone-based in-situ fluorometric imaging module: Visual representation of the smartphone-integrated imaging module used for capturing fluorescence intensity, enabling quantitative analysis of biomarkers in sweat. f) One representative measurement result of the fluorescent microfluidic patch during the on-body test (sweat Na^+ concentration) in human trials, demonstrating the sensitivity and usability of the device. d–f) Reproduced with permission.[232] Copyright 2018, the Royal Society of Chemistry. g) Schematic illustration of one plasmonic metamaterial–integrated wearable SERS sensing device for ultra-sensitive biomarker detection in drug metabolism monitoring. h) In vivo nicotine monitoring: Demonstration of the nicotine decay profile monitored using the SERS device after a nicotine patch application, enabling personalized therapy management. g,h) Reproduced with permission.[236] Copyright 2021, AAAS. i) Dynamic continuous colorimetric sensing device: Schematic illustration of one skin-interfaced time-dynamics microfluidic band for continuous sweat pH and lactate analysis during exercise. j) On-body working performance of colorimetric sweat elastic band: in vivo time-dynamics sensing result on sweat pH and lactate during exercise, providing insights into muscle fatigue and metabolic states. i,j) Reproduced with permission.[63] Copyright 2024, AAAS.

cystic fibrosis detection, suggests translational potential. Ultimately, the major limitation that continues to hinder colorimetric sensing is its relatively low sensitivity compared to other sensing approaches.

To this end, wearable fluorescence-based sweat sensors have been explored as an alternative. Enabled through a target-induced increase in emitted light at a particular wavelength, wearable fluorescent sensors often provide superior sensitivity relative to colorimetric devices due to the intrinsic signal amplification of fluorescence emission.[77,78,230–232] Recent advances in wearable fluorescence-based sweat sensing has involved improvements in fluorescent probe design (e.g. synthetic fluorophores like rhodamine and fluorescein, nanomaterials like quantum dots and carbon dots),[232,233] sample processing mechanisms (e.g. microfluidics and paper-fluidics),[231,232,234] and fluorescence data collection (e.g. embedded readers like photodiode and external readers like a smartphone).[232,235] Figure 7d demonstrates one fluorescence-based skin-interfaced microfluidic device coupled with a smartphone-based imaging module for the real-time quantitative analysis of chloride, sodium, and zinc in sweat.[232] These markers can provide immediate insights into hydration status, electrolyte balance, and nutritional deficiencies. Like many works in this space, this system employed an inexpensive LED paired with an optical filter to emits light at a specific wavelength to excite fluorophores present in the microfluidic reservoirs (Figure 7e). Emitted light can then be captured using a smartphone camera integrated with an optical filter, enabling the quantification of sweat biomarkers through fluorescence intensity (Figure 7f). Importantly, currently reported wearable fluorescence-based sweat sensors remain largely limited to sweat pH, glucose, lactate, chloride, and urea. This indicates significant room for future developments toward a wider range of targets.

Finally, SERS has been explored to address the ultra-sensitivity and molecular-level needs of certain wearable sensing applications. Compared with colorimetric and fluorescent sensing approaches, current progress in wearable SERS has offered breakthroughs in detecting trace-level biomarkers such as acetaminophen, nicotine, urea, and 2-fluoro-methamphetamine (2-FMA) in sweat.[236–240] For example, one design paired a silk fibroin film (SFF) base layer with a silver nanowire (AgNW) layer to enhance Raman signals, achieving a sweat 2-FMA limit of detection (LOD) of 50 ng cm^{-2} on human cadaver skin.[237] This demonstrates potential toward drug abuse monitoring and personalized therapy management. Another reported wearable SERS device employed a flexible microfluidic chip integrated with an Au nanosphere cone array. This sensor demonstrated noninvasive acetaminophen detection in sweat, providing insights into drug metabolism and pharmacokinetics. Importantly, one major challenge toward the employment of wearable SERS sensing has been substrate stability in response to on-body conformational stress. This has inspired the development of SERS devices with higher substrate stability, through unique mechanical designs and modified material properties (Figure 7g).[236,239] For example, the combination of an island-bridge mechanical design, guard ring protection, and a flexible PMMA substrate protecting the SERS-active plasmonic metafilm was shown to effectively enhance SERS substrate stability against conformal and mechanical stresses. Applied toward nicotine pharmacokinetics monitoring, nicotine decay profiles were monitored following the application of a 2-h nicotine patch on the skin (Figure 7h). The collection of decay curves stands to enable personalized nicotine therapy through tailored therapeutic windows for smoking cessation and improved patient compliance. Despite these advancements, the durability of these flexible substrates and the portability of Raman spectrometers remain key challenges toward translation.

With considerations toward a few overarching challenges in the photonic sweat sensing space„ continuous, time-dynamics capabilities remain a key objective in the space. Here, a wearable colorimetric sensing band that achieved time-dynamic detection of sweat pH and lactate with a non-enzymatic colorimetric timer offers promise (Figure 7i).[63] Resultant continuous time-dynamic sweat pH and lactate information revealed the iontophoresis-stimulated sweat of unfit subjects dropped significantly from pH 7.5 to pH 5.5 during exercise, reflecting increased muscle acidity and fatigue (Figure 7j).

4.2.2. Interstitial Fluids-Based Wearable Photonic Sensors

ISF is the biofluid between cells in tissues, which serves as a critical medium for exchanging nutrients, oxygen, and waste products between cells and the bloodstream. Its composition contains a rich array of biochemical constituents, such as electrolytes (e.g., sodium, potassium, calcium, chloride), metabolites (e.g., glucose, lactate), hormones (e.g., insulin, cortisol), proteins (e.g., cytokines), and intake drugs.[5,241] Compared with other non-invasive biofluids, the unique advantage of ISF is its stronger biochemical correlation with blood plasma.

Researchers have found that the key to achieving wearable photonic sensing on real-time ISF diagnostics is employing reliable ISF extraction platforms, such as microneedles.[242–245] One early-stage approach to detecting pH, glucose, and albumin in ISF involved injecting a chromogenic dye-containing dermal tattoo into the dermis, yielding real-time minimally-invasive diabetes monitoring (**Figure 8a**).[246] This sensor achieved visible color changes in response to metabolite concentration, as detected through smartphone imaging. When applied to ex vivo porcine skin, the RGB values collected by smartphone showed color response to glucose levels from 0 to 50 mmol L^{-1} (Figure 8b). However, dermal tattoo technology requires special equipment and trained expertise in operations, limiting translatability.

More recent advances in ISF sensing focus on wearable microneedle technology. Microneedles are micro-scale needle-like structures that penetrate the skin's outermost layer (stratum corneum) without reaching deeper layers that contain pain-sensitive nerves, thus avoiding user pain.[241] Figure 8c depicts a colorimetric microneedle with a bilateral core-shell microneedle patch (MNP) that was developed for rapid lactate analysis.[247] Unlike conventional single-color MNP, the bilateral core-shell structure separated reactive components to enable a dual-color response dependent on lactate levels for higher detection accuracy. The dual-colorimetric device showed it can track dynamic lactate concentration changes (red line) in rat serum after exercise and correlate them with the colorimetric RGB values measured by the MNP (Figure 8d). This correlation indicates potential toward real-time exercise physiology and fitness monitoring.

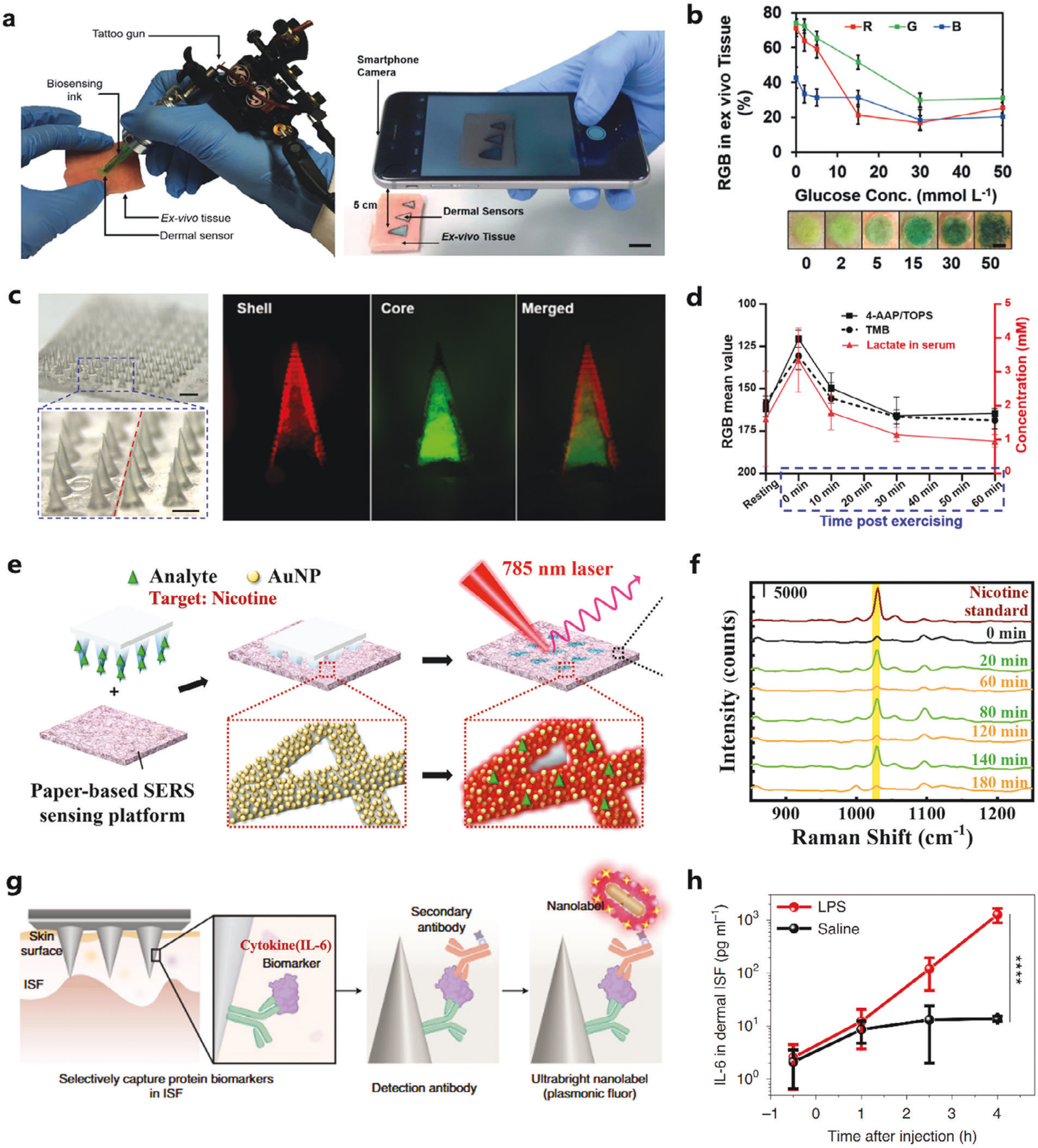

Figure 8. Applications of wearable photonic sensing device in interstitial fluid monitoring. a) Colorimetric dermal tattoo sensor: Diagram illustrating a minimally invasive dermal tattoo integrated with chromogenic dyes for real-time detection of ISF biomarkers, including pH, glucose, and albumin, through smartphone imaging. b) In vivo working performance: Demonstration of the sensor's glucose-sensing capabilities, showing visible color changes in response to glucose concentrations ranging from 0 to 50 mmol L^{-1}, validated on ex vivo porcine skin. a,b) Reproduced with permission[246] Copyright 2019, Wiley-VCH GmbH. c) Bilateral core-shell microneedle patch: Schematic showing a dual-colorimetric microneedle platform for lactate detection in ISF, highlighting its dual-color response for improved accuracy. d) In vivo lactate monitoring: In vivo measurement of lactate concentration changes in rat serum during exercise, demonstrating the correlation between colorimetric response and lactate levels. c,d) Reproduce with permission.[247] Copyright 2022, Elsevier B.V. e) SERS-enabled microneedle sensing patch: Diagram of a hydrogel microneedle integrated with a cellulose-paper-based SERS platform for trace-level ISF biomarker detection, employing gold nanoparticles to enhance Raman signals. f) In vivo nicotine monitoring: Validation of nicotine pharmacokinetics through in vivo SERS measurements following nicotine patch application, demonstrating the potential for personalized therapy. e,f) Reproduced with permission.[248] Copyright 2023, Wiley-VCH GmbH. g) Fluorescent microneedle sensor: Schematic of a bilayered microneedle device for ultra-sensitive fluorescent detection of inflammatory biomarkers such as interleukin-6 in ISF. h) On-body performance validation: In vivo monitoring of interleukin-6 concentrations in mice, demonstrating the device's ability to detect inflammatory responses with high sensitivity and precision. g,h) Reproduced with permission.[242] Copyright 2021, Springer Nature.

Recognizing that ISF contains rich biomarkers, its use toward the detection of trace-level biomarkers has also been explored. To this end, Figure 8e demonstrates the integration of a hydrogel MNP with a cellulose-paper-based SERS platform, where the MNP offers effective ISF extraction while the paper platform is optimized for sensing.[248] Specifically, the cellulose paper was functionalized with AuNPs to form plasmonic hotspots, enabling the generation of molecular fingerprint spectra of analytes. Its capabilities were demonstrated through the effective detection of nicotine following the application of a nicotine patch (Figure 8f). Another ultra-sensitive MNP-based ISF sensing patch was employed for the fluorescent detection of interleukin-6 (IL-6) in interstitial fluid using plasmonic fluor-enhanced immunoassay techniques(Figure 8g).[242] This bilayered design incorporated a polystyrene microneedle functionalized with antibodies and a magnetic backing layer, facilitating highly specific biomarker capture directly from the ISF. By using an ultrabright plasmonic fluor nanolabel, the platform achieved a remarkable limit of detection (LOD) of 0.33 pg mL^{-1}, achieving sensitivity improvements nearly 800-fold over conventional methods(Figure 8g). Effective IL-6 detection within mice suggests potential toward inflammatory response monitoring (Figure 8h). As microneedles appear poised for continued impact in the ISF sensing space, future improvements may lie in developing more robust materials that improve the durability and stability of microneedles for longer-term monitoring, and integrating new functionalization mechanisms that power novel sensing applications.

4.2.3. Tears-Based Wearable Photonic Sensors

Tears are secreted by the lacrimal glands in the eyes, which play essential roles in maintaining ocular health, providing lubrication, and protecting against pathogens. It contains a wealth of biochemical information to reflect both localized and systemic health conditions, including electrolytes (sodium, potassium, chloride, bicarbonate), metabolites (ascorbic acid, urea, glucose, lactate), proteins (immunoglobulins, metalloproteinase-9, lysozymes, lactoferrin), lipids (tear film lipids), extracellular vesicles (exosomes), and potential intake drugs.[249] Considering the presence of certain unique biomarkers in tears related to ocular health, developing wearable photonic sensors for tear sensing is of significant interest. To this end, multiplex in-situ biosensing of vitamin C, calcium, protein, and tear pH has been demonstrated, with integrated data processing through a smartphone interface (**Figure 9**a).[250] Even though the biomarkers targeted in this work are conventional stimuli that have been detected within other biofluids, the integrated system offers insight toward the design of effective wearable tear sensors capable of robust data collection (Figure 9b). In addition, the AI-assisted deep-learning module presented in this work contributes to the growing body of literature seeking to improve the accuracy of colorimetric data readout.

More recent advances in developing wearable tear-based photonic sensors have focused on developing smart contact lenses. For example, one dual-function wearable contact lens (Figure 9c) was designed for simultaneous intraocular pressure (IOP) and matrix metalloproteinase-9 (MMP-9) monitoring in tears. This involved using antiopal structural color for IOP detection alongside a peptide-modified gold nanobowl (AuNB) SERS substrate for MMP-9 sensing.[251] On-body studies demonstrated effective monitoring of both sensing targets (Figure 9d). This platform offers significant potential toward ocular health monitoring, with MMP-9 detection particularly useful toward tracking inflammation and tissue remodeling in diseases such as dry eye syndrome and glaucoma. Outside of ocular disease tracking, smart contact lenses targeting tear exosomes – which can acts as biomarker for cancer, has also been demonstrated. Here, embedding the base substrate material with antibody-conjugated microchambers enabled colorimetric signal generation (Figure 9e).[86] Effective detection of target exosomes within the tears of tested subjects confirmed the potential of the sensor toward non-invasive cancer prescreening and diagnostics (Figure 9f). Looking forward, future works in the tear sensing space will likely seek to address challenges related to low tear volume and tear composition variability among individuals.

5. Conclusion and Outlook

5.1. Situational Assessment

Wearable photonic sensors have the potential to transform modern personalized precision healthcare, enabling real-time, non-invasive, intuitive monitoring of versatile stimuli, including both physical and chemical signals through advanced optical technologies. Key advancements in photonic sensing principles, functional materials, fabrication strategies, and power management have paved the way for impactful healthcare applications.

Various photonic approaches have been employed in the wearable sensing space. The broad capabilities they collectively offer has enabled diverse sensor design strategies, inspiring new objectives and applications. The integration of these approaches into wearable formats has been realized using diverse functional materials. Here, light-emitting components such as OLEDs and LEDs provide wavelength-specific illumination, with OLEDs offering advantages in flexibility and tunability, while LEDs deliver higher brightness and cost-effectiveness.[72,73]Light-responsive materials, including photochromic, photophysical, photoconductive, and photothermal agents, provide the solutions to addressing the challenge of in-situ data processing in wearable devices by playing roles in sensing and signal transduction by exhibiting optical, electrical, or thermal changes upon light exposure.[10,61,74,75]

To address the challenge of enabling optical sensors to work on conformal surfaces under dynamic conditions, the developments of flexible, stretchable, stable, and biocompatible substrate materials pave the way for this. Widely used conventional substrates like PDMS and PET have maturely integrated wearable technologies such as microfluidics and paper-fluidics to solve the real-time in-situ analysis of biofluids.[61,82,83] Hydrogels provide good optical compatibility with transparency, tunable refractive indices, and biofluid permeability, enabling efficient in-situ collection for biomarkers.[86–89] Textiles provide flexibility, durability, and seamless integration into daily life cloths, demonstrating the great potential and value of technology transfer. Paper substrates stand out for their biodegradability, cost-effectiveness, and ability to handle biofluids through capillary-driven transport.[63,101] The choice of substrate depends on the application and balancing factors like optical properties, biocompatibility, and environmental

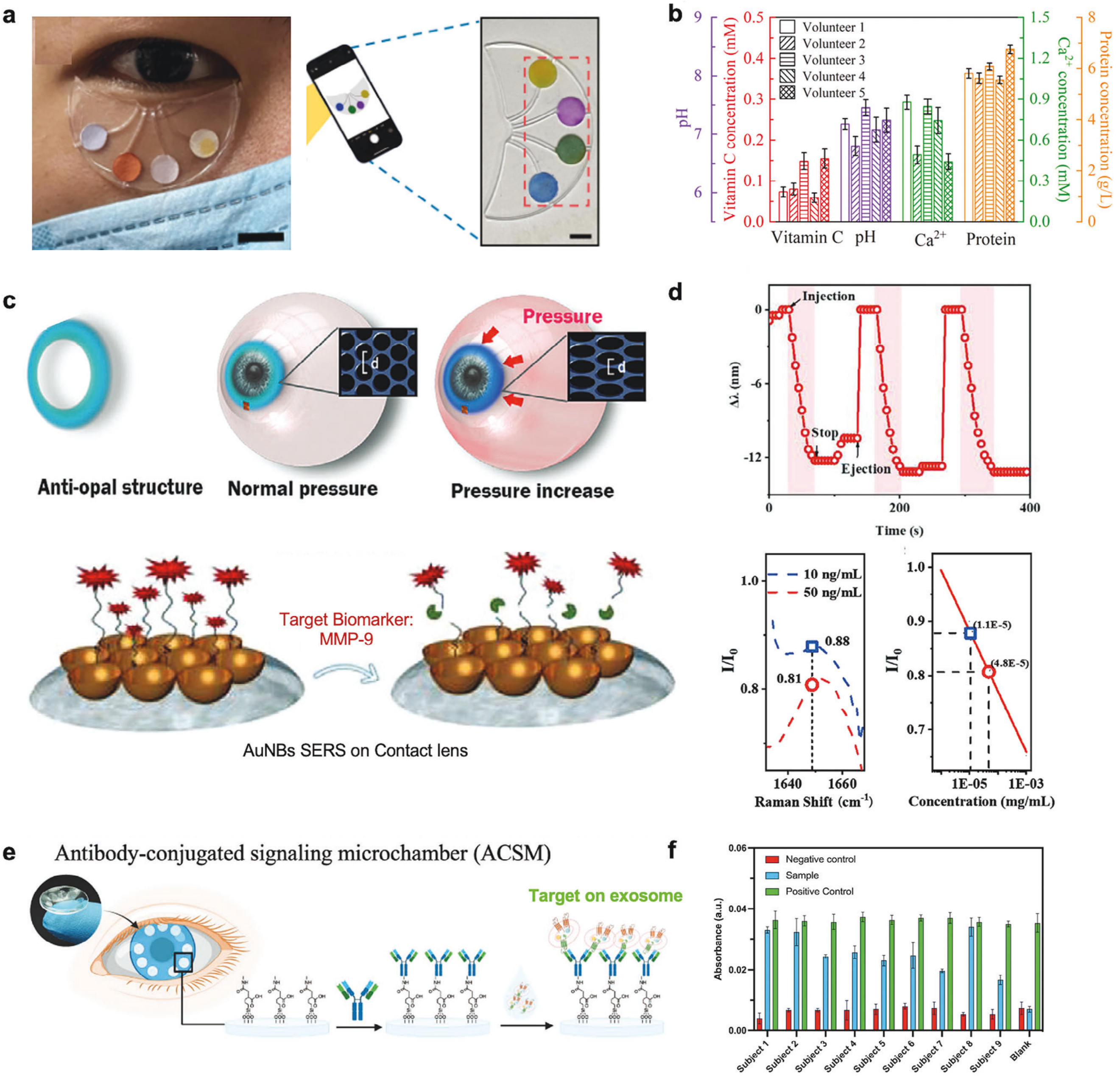

Figure 9. Applications of the wearable photonic sensing device in tears monitoring. a) Colorimetric tear patch: Diagram illustrating an epidermal microfluidic patch integrated with multiplexed colorimetric sensing modules for detecting tear biomarkers, including pH, vitamin C, calcium, and protein, with smartphone-based readout capabilities. b) On-body working performance validation: in vivo colorimetric results of the epidermal colorimetric tear patch on multiplex sensing (Vitamin C, pH, Ca^{2+}, Protein), validated through smartphone imaging and AI-assisted deep learning modules for accurate data interpretation. a,b) Reproduced under the terms of the CC-BY-4.0 license[250] Copyright 2019, The Authors. Published by Springer Nature. c) Smart contact lens with dual-sensing platform: Schematic representation of a dual-function contact lens designed for simultaneous intraocular pressure (IOP) monitoring using antiopal structural color and matrix metalloproteinase-9 (MMP-9) detection via peptide-modified gold nanobowl SERS substrates. d) In vivo validation of dual-sensing platform: Demonstration of cyclic real-time IOP monitoring and effective MMP-9 detection in rabbit tear samples, highlighting the lens's potential for ocular health management. c-d) Reproduced under the terms of the CC-BY-4.0 license.[251] Copyright 2022, The Authors. Published by Wiley-VCH GmbHe. e) Microchamber-enabled contact lens for tear exosome detection: Schematic illustrating a contact lens embedded with antibody-conjugated microchambers for non-invasive detection of tear exosomes, targeting biomarkers for cancer prescreening and diagnostics. f) Clinical validation of exosome detection: Validation of the lens's capability to detect exosomes in human tears, showcasing its potential for early cancer diagnostics and other systemic disease monitoring. e,f) Reproduced with permission.[86] Copyright 2022, Wiley-VCH GmbHe.

stability. Combining functional materials with suitable substrates ensures the development of efficient, scalable, wearable photonic sensors.

The fabrication methods highlight the diversity of approaches available for producing wearable photonic components, such as nanopatterning,[104–123] roll-to-roll printing,[119,124–130] and additive 3D printing.[131–134] Nanopatterning offers excellent precision, which is crucial for high-resolution photonic structures, but it often has high costs and limited scalability.[104–123] In contrast, roll-to-roll printing provides high scalability and cost-efficiency but may struggle to achieve the same level of precision.[119,124–130] Additive 3D printing, meanwhile, offers design flexibility and rapid prototyping but faces challenges with achieving nanoscale accuracy.[131–134] To move toward commercialization, future research should focus on improving the scalability of nanopatterning, enhancing the precision of transfer methods, and expanding material choices in 3D printing—all while reducing production costs.

Power management strategies reveal both the strengths and challenges of different power solutions for wearable photonic sensors. Battery-powered systems[148–151] provide stable energy but often introduce size and weight limitations, while wireless power transfer[155–158,80,159] via NFC addresses these limitations but depends on proximity to power sources. Self-powered sensors, using energy harvesting from solar or motion, promise sustainability but are affected by environmental conditions.[174–182] Hybrid approaches that combine these strategies could potentially improve the power stability and flexibility required for commercialization. In particular, one biomimetic fiber fabrication approach inspired by spider silk spinning introduces a low-energy, ambient-temperature technique using a polyacrylonitrile-silver ion polymer solution. This innovative work provides inspiring insight for smart low-power management in wearable photonic sensors, enabling applications like smart gloves and haptic systems in healthcare.[252] Furthermore, ensuring cost-effective, reliable power management solutions is key for future widespread adoption of wearable photonic sensors in healthcare.

Physical signal monitoring of wearable photonic sensors, focusing on cardiovascular, tactile, and temperature sensors. Cardiovascular sensors represent the most common wearable photonic sensor used for physical signal monitoring, capable of measuring multiple parameters such as heart rate, blood pressure, and respiratory rate from a single sensor by correlating various signals.[148,155–157,183,186–189] These sensors have seen significant clinical applications, providing valuable data for patient monitoring. Meanwhile, the development of advanced tactile sensors utilizing auxetic structures and optical fiber-based strain sensing has paved the way for precise and adaptable wearable applications, crucial for fields like prosthetics and rehabilitation.[59,190–196,90,197–202,253] Temperature sensors, including Fiber Bragg Grating and photoluminescence-based systems, offer high accuracy, while colorimetric sensors provide ease of use at the expense of precision.[41,59,142,195,202,205–218,254]

Wearable photonic sensors have been applied mainly to chemical signals for three alternative biofluids: sweat, interstitial fluid, and tears. A relatively poor number of reports on wearable sensors for analyzing biomarkers in saliva, wound fluids, and exhaled breath indicate there are new development opportunities for wearable photonics sensing.[2,7,80,204,255,256] The challenge is the effective in situ sampling of alternative biofluids, which aims to avoid cross-contamination and collect micro-volume quantities efficiently.[257–259] Among the reported applications in chemical signals, colorimetry has been the most widely used due to its simplicity and intuitively visible to users. However, another challenge is to achieve sufficient sensitivity to detect trace-level biomarkers, which makes fluorescent and SERS the ideal choices for ultra-sensitivity. Current works in wearable photonic sensors are largely focusing on the detection of a limited choices of biomarkers including electrolytes (e.g., Na^+, Cl^-, pH) and metabolites (e.g., glucose and lactate). We believe that in the future, it will be critical to target some other more clinically valuable biomarkers that have not yet been thoroughly explored yet. However, these biomarkers are likely to be trace amounts, which places high demands on the detection limit of the device.

5.2. Outlook

Wearable photonic sensors face several limitations that must be addressed to realize their full potential in healthcare. One primary concern is the accuracy of data collection while we utilize wearable sensors to conduct real-time monitoring. Optical signals are susceptible to environmental interference due to the dependence on ambient light conditions. In our opinion, ambient sunlight, artificial lighting, or the reflection change on the target surface can alter the intensity of the target signal. Meanwhile, motion artifacts can also influence the data output on the target. Considering wearable photonic sensors are often used in dynamic conditions (e.g., exercise), users' movement can change the angle of incidence or alignment of light with respect to the sensor, resulting in data collection variability. Hence, we speculate that future work can focus on mitigating environmental interference by implementing real-time filtering algorithms to distinguish target signals from noise and using machine learning models to compensate for motion artifacts and ambient light variations.[250] Another possible way might be to modify the design of the photonic sensor by considering multi-wavelength for compensation and calibration and narrowband filters and shields to minimize ambient light interference. Moreover, since the blood test has been considered the gold standard for traditional diagnostics in hospitals, correlating level of biomarkers between alternative biofluids (e.g., sweat, saliva, tears, and interstitial fluid) and blood serum can be a crucial factor that may influence the future development of wearable photonic biosensors. One possible future solution is to incorporate advanced machine learning algorithms to model user-specific parameters like sweat rate, skin hydration, temperature, and so on to refine correlations. We can also focus on some other alternative biofluids that have a stronger correlation with blood serum, such as interstitial fluids, if the scenario desires a strong correlation.

Both now and in the future, the translational market of wearable healthcare biosensors will likely experience significant growth, driven by increasing demand for its non-invasive health monitoring. Following the trend, we believe wearable photonic sensors show great potential for being translated from research prototypes to commercially available products. One point worth noting is that the current majority of commercialized wearable photonic sensors are PPG, electrocardiogram (ECG) sensors, and infrared photonic sensors to target physical signals, such as heart rate, blood oxygen level, sleep patterns, and skin temperature. The current market reflects a growing adoption of these three wearable photonic sensors, particularly with several notable products from leading industry companies, such as the Apple watch series (Apple Inc), Fitbit devices (Google LLC), and Oura ring (Oura Health Ltd.). Besides those notable products in physical signals that mainly occupy the current market rate of wearable photonic biosensors, commercialization of wearable photonic sensors in chemical signal monitoring is relatively limited, which may remain a future growing chance in the translational market. Currently, commercial wearable biosensors on chemical signals almost focus on sweat(electrolytes) and interstitial fluids(glucose), with limited reports in saliva and tears. For example, the Gx sweat patch from Epicore Biosystems is one commercial product that can real-time monitor sweat loss rate and electrolytes (chloride) concentrations by colorimetric sensing, which aims to provide early warning on dehydration status during daily activities. KnowU™ is one new product released in February 2024, which employs a form of radiofrequency spectroscopy to non-invasively measure blood glucose levels by rapidly scanning a large range of RF frequencies. Compared with other commercial wearable biosensors in glucose monitoring, such as Abbott FreeStyle Libre 3 and Dexcom G7, which utilize electrochemical signals to monitor glucose in interstitial fluidics mini-invasively, the photonic sensing product KnowU™ shows its advantages in non-invasive detections. Another notable product in the wearable photonic space is the DermaSensor, which is a handheld device using optical spectroscopy to analyze skin lesions for potential cancerous changes. It can simplify skin cancer detection for primary care physicians.

Based on the progress of commercialization above, we have confidence in its future development in translational markets, and we speculate on several key aspects that should be emphasized for future commercialization: 1) Expanding the library of detectable biomarkers of significant clinical value; 2) Integrating AI-driven machine learning for data analysis to and environmental interference mitigation;[260] 3) Developing solutions for continuous and multiplex biomarker monitoring; 4) Achieving long-term stability in dynamic wearable conditions; 5) Ensuring cost-effectiveness for scalable production. We envision wearable photonic sensors playing a transformative role in precision healthcare, bridging academic research and commercial applications to advance personalized medicine and improve patient outcomes.

Acknowledgements

R.S., S.C., and S.K. contributed equally to this work. This project was supported by the National Science Foundation grants 2145802 and 2444815, National Institutes of Health grants R01HL155815 and R01DC021461, Army Research Office grant W911NF-23-1-0041, US Army Medical Research Acquisition Activity grant HT9425-24-1-0249, Heritage Medical Research Institute, and National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2021R1A2C3008742).

Conflict of Interest

W.G. is a co-founder and advisor for Persperity Health.

Keywords

photonic sensor, wearables, personalized medicine, non-invasive sensing, health monitoring

Received: December 6, 2024
Revised: January 13, 2025
Published online:

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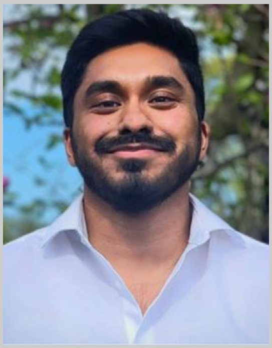

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