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Research Progress of Ultrathin Flexible Wearable Pressure Sensors

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Abstract. Wearable electronics are evolving from simple motion-recording devices toward skin-conformal, textile-integrated, and continuously operating sensing systems. Pressure is a fundamental mechanical signal for pulse and respiration monitoring, plantar-force analysis, motion assessment, human-machine interaction, and electronic skin. Ultrathin flexible pressure sensors combine compliant substrates, micro/nanostructured sensing layers, and lightweight electrodes to maintain mechanical conformity while providing useful pressure responses. This review summarizes four major sensing mechanisms - piezoresistive, capacitive, piezoelectric, and triboelectric sensing - and integrates their material and structural design strategies into a unified comparison. Conductive composite networks, porous aerogels, bioinspired microstructures, nanofibrous films, PVDF-based piezoelectric materials, and self-powered triboelectric structures are highlighted as representative routes for improving electromechanical conversion. Typical wearable applications in physiological monitoring, gait and motion analysis, human-machine interfaces, and electronic skin are then discussed. Finally, the review summarizes remaining limitations in sensitivity-range trade-offs, long-term stability, multimodal signal decoupling, scalable manufacturing, and system integration, and outlines directions toward reliable and practical wearable sensing systems.

Keywords: wearable electronics, ultrathin flexible pressure sensor, pressure sensing, health monitoring, electronic skin

1. Introduction

Flexible wearable devices are increasingly used in mobile health, rehabilitation, sports science, intelligent prostheses, and human-machine interaction. Among the signals collected at the human-machine interface, pressure is especially important because finger touch, joint motion, plantar loading, respiration, pulse, and external contact can all be converted into mechanical deformation. Pressure sensors therefore act not only as measurement devices but also as interfaces that connect the body, machines, and the surrounding environment [1, 2].

Conventional pressure sensors based on rigid silicon, ceramic, or metallic structures offer mature fabrication processes and high accuracy, but their stiffness limits conformal contact with skin and other deformable surfaces. For wearable use, thickness, elastic modulus, breathability, and interfacial adhesion directly affect signal quality. Mechanical mismatch can change the contact

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condition during small body motions and may cause baseline drift, hysteresis, or false responses. Consequently, flexibility, low thickness, and conformability have become central design requirements for wearable pressure sensing [3].

Recent progress is not simply a replacement of rigid substrates with soft materials. Instead, sensing mechanisms, functional materials, microstructures, and interfaces are being co-designed. Piezoresistive sensors exploit changes in conductive pathways; capacitive sensors rely on variations in electrode spacing or effective permittivity; piezoelectric sensors directly generate electrical charge under dynamic deformation; and triboelectric sensors combine contact electrification with electrostatic induction. At the same time, MXene, carbon nanotubes, graphene, silver nanowires, conductive polymers, poly(vinylidene fluoride) (PVDF)-based polymers, porous aerogels, nanofibrous films, and hydrogels have expanded the available design space [4, 5].

The main design objective has therefore shifted from maximizing a single metric toward balancing sensitivity, measurement range, response speed, bending tolerance, cyclic durability, and integration with wearable systems. This paper provides a concise review organized around sensing mechanism and material/structural strategy, followed by representative wearable applications and the major barriers to practical deployment. The aim is to clarify why different sensing mechanisms favor different structures and use conditions, rather than to list individual sensor demonstrations.

2. Sensing mechanisms and material-structural strategies

The performance of a flexible pressure sensor is commonly described by sensitivity, operating range, response and recovery time, detection limit, hysteresis, cyclic stability, stretchability, and, for long-term wear, breathability and environmental stability. These parameters are coupled to the transduction principle, and the same material may behave very differently when arranged as a dense film, a porous network, a microstructured surface, or a fibrous membrane. Table 1 summarizes the main characteristics of the four mechanisms considered in this review.

Table 1. Comparison of major flexible pressure-sensing mechanisms

Mechanism	Materials/structures	Strengths	Limitations	Applications
Piezoresistive	Carbon materials, MXene, silver nanowires; porous layers	Simple readout; high low-pressure sensitivity	Drift, hysteresis, saturation, network fatigue	Pulse, touch, motion, tactile sensing
Capacitive	Soft electrodes; porous elastomer or ion-gel dielectrics	Low static power; array-friendly	Parasitic capacitance; packaging sensitivity	Gait, physiological pressure, touch arrays
Piezoelectric	PVDF-family polymers; functional composites	Self-generated dynamic signal; fast response	Weak static response; charge leakage; rate dependence	Motion, impact, vibration, pulse dynamics
Triboelectric	Silicone/fluoropolymers; textiles; microstructured pairs	Self-powered operation; simple event detection	Humidity/frequency dependence; wear	Gait, tapping, joint motion, wearable interfaces

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2.1. Piezoresistive sensors

Piezoresistive pressure sensors use conductive composites, thin films, or porous conductive frameworks as the sensitive layer. External pressure changes particle contact, tunneling distance, or the effective number of conductive pathways, which appears macroscopically as a resistance change. Their simple electrical readout and large design freedom make them one of the most widely used approaches in wearable pressure sensing [1, 3].

A key design issue is the initial state of the conductive network. An overly dense network gives limited relative resistance change, whereas a very sparse network may show strong low-pressure sensitivity but saturate quickly or lose repeatability. Recent studies therefore use wrinkled layers, porous fibers, paper networks, aerogels, and bioinspired multilevel structures to create gradually evolving contact pathways. Wrinkled piezoresistive layers have been used to improve low-pressure response and response speed [6], while bioinspired cocklebur-shell microstructures were reported to widen the useful detection range [7]. MXene-based paper sensors similarly exploit the natural porosity of fibrous substrates to extend pressure response [8].

For ultrathin designs, nanofibrous membranes are attractive because they provide a light, compliant support for conductive coatings. Jin et al. reported a microbead-embedded nanofibrous pressure sensor with a thickness below 100 micrometers, using electrospun films and coated electrodes to reduce bending stiffness while maintaining pressure responsiveness [9]. However, wearable piezoresistive sensors still need improved resistance to sweat, friction, repeated compression, and long-term conductive-network rearrangement.

2.2. Capacitive sensors

Capacitive pressure sensors generally consist of two flexible electrodes separated by a compliant dielectric layer. Under pressure, the electrode spacing decreases and/or the effective dielectric constant changes, leading to a measurable capacitance variation. Compared with piezoresistive devices, capacitive sensors are attractive for low-power and array-based measurements, but small capacitance changes are sensitive to parasitic effects, external electromagnetic noise, and packaging conditions [1].

Performance improvement is mainly achieved by engineering the dielectric layer and the electrode interface. Porous polydimethylsiloxane (PDMS), soft dielectric elastomers, ion gels, and nanocomposite dielectrics increase compressibility or interfacial polarization under load. Park et al. developed a flexible insole-type capacitive pressure sensor with porous PDMS and carbon-nanotube/conductive-polymer composite electrodes for continuous gait-signal analysis [10]. A flexible PDMS/polyethylene terephthalate capacitive device was also applied to blood-pressure-related oscillation monitoring [11]. These studies show that capacitive sensors are particularly suitable when low-power continuous measurement and spatial arrays are more important than extreme low-pressure sensitivity.

2.3. Piezoelectric sensors

Piezoelectric sensors convert mechanical deformation directly into electrical charge or potential. Flexible systems commonly use PVDF and related copolymers and composites because they combine polymer flexibility with piezoelectric activity [12, 13]. Since no continuous external excitation is required for signal generation, these devices are well suited to dynamic pressure, gait, impact, vibration, and pulsatile signals.

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Their main limitation is the decay of charge under static load, which makes stable low-frequency or quasi-static pressure measurement difficult. Recent strategies introduce metal-organic frameworks, MXene, or inorganic nanofillers to promote electroactive phase formation and improve interfacial polarization. For example, UIO-66-NO2/MXene/PVDF-based composite fibers were used to enhance piezoelectric output through combined structural and interfacial effects [13]. For practical wearables, however, signal-conditioning circuits, encapsulation, and resistance to humidity are as important as the peak piezoelectric output.

2.4. Triboelectric sensors

Triboelectric pressure sensors operate through contact electrification and electrostatic induction. Repeated contact-separation or sliding between materials with different electron affinities produces voltage or current, making the mechanism attractive for self-powered sensing. Flexible triboelectric structures are therefore often used in shoes, gloves, joints, and textile patches where periodic motion is naturally available [14].

Output depends strongly on contact area, surface roughness, humidity, loading frequency, and charge retention. Microstructured and textile interfaces can enlarge the effective contact area at low pressure, while conductive two-dimensional materials can assist charge collection. A 2026 study reported a bioinspired flexible pressure sensor using MXene and a naturally templated textile microstructure for self-powered gait monitoring [14]. Despite the advantage of reduced battery dependence, long-term wear, humidity sensitivity, and unstable output during slow or weak motions remain important obstacles.

3. Wearable applications

3.1. Physiological and health monitoring

Physiological monitoring is a direct use case for ultrathin pressure sensors because pulse, respiration, swallowing, speech, and local contact pressures generate low-amplitude mechanical signals at the body surface. Flexible capacitive sensors have been used to acquire blood-pressure-related oscillation waveforms [11], while piezoelectric devices have demonstrated dynamic pressure measurement and health-monitoring potential [12]. Breathable all-nanofiber iontronic pressure sensors further illustrate the growing emphasis on wearing comfort, ultraviolet shielding, and antibacterial performance for prolonged skin contact [15].

For medical or rehabilitation use, the main requirement is not simply to detect a signal in a short laboratory demonstration. Long-term reliability is affected by attachment position, motion artefacts, sweat, temperature, and individual differences. Accordingly, future wearable health systems need stable calibration, multi-channel sensing, and signal processing that can separate physiological information from environmental and motion-induced disturbances.

3.2. Motion and gait monitoring

Motion monitoring involves larger deformation and a wider pressure range than pulse sensing. Typical targets include knees, elbows, wrists, fingers, and plantar loading. Flexible pressure or strain sensors can capture joint movement, gait cycles, landing impact, and posture changes, providing information that is difficult to obtain continuously with laboratory-only equipment. Recent work in

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orthopaedic sports medicine has highlighted their value for real-time biomechanical assessment outside conventional test facilities [16].

Plantar pressure and gait recognition are representative examples. Insole-type capacitive devices support continuous pressure-distribution recording [10], triboelectric systems can exploit walking motion for self-powered output [14], and MXene paper-based sensors provide a broad pressure-response range for human-motion detection [8]. In these applications, wide range, impact resistance, repeated-bending durability, sweat resistance, and signal consistency are usually more important than achieving the lowest possible detection threshold.

3.3. Human-machine interaction and electronic skin

In human-machine interaction, flexible pressure sensors function as touch inputs, gesture interfaces, tactile feedback elements, and spatial pressure arrays. MXene-based composite fibers and films have been used for tactile detection and pressure visualization, demonstrating the feasibility of low-mass flexible interfaces [17]. More broadly, electronic skin seeks to combine pressure with temperature, strain, humidity, magnetic field, or other stimuli so that a deformable surface can perceive multiple aspects of contact.

This integration creates a new difficulty: signal coupling. Temperature can change hydrogel resistance and dielectric properties, stretching shifts a pressure-sensor baseline, and humidity affects triboelectric output. A conductive hydrogel with temperature- and pressure-responsive, healable, adhesive, and biocompatible properties illustrates the move toward multifunctional soft materials [18]. The practical challenge is to integrate these functions without losing signal interpretability, mechanical softness, and repeatability.

4. Challenges and future directions

Several issues continue to limit the transition from laboratory prototypes to dependable wearable systems. First, sensitivity and operating range are often in tension. Highly deformable microstructures or sparse conductive networks can strongly amplify low-pressure response, but they may saturate early or show irreversible rearrangement. A more useful design target is therefore a controlled multiscale structure that provides progressive deformation over the required pressure range rather than maximizing sensitivity at a single point [5-7].

Second, long-term stability under real wearing conditions remains insufficiently demonstrated. Sweat, humidity, temperature changes, repeated bending, friction, and local delamination can all change the electrical baseline and mechanical contact. Self-healing conductive hydrogels offer a possible route to improved conformability and damage tolerance [16], but device-level durability also depends on electrodes, interconnects, encapsulation, and skin attachment.

Third, multimodal sensing introduces cross-sensitivity. Pressure, strain, temperature, and humidity are often coupled through the same soft material. Reliable wearable systems will require either structural decoupling, differential reference channels, calibrated physical models, or data-driven compensation. The objective should be not only high classification accuracy but also stable interpretation when the sensor is moved between users or exposed to different environmental conditions.

Fourth, scalable fabrication and system integration remain major engineering barriers. Laboratory processes that rely on carefully prepared microstructures or nanomaterial dispersions may suffer from unit-to-unit variation when scaled. At the same time, a complete wearable system requires flexible interconnects, low-noise front-end electronics, power management, wireless transmission,

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and local processing. Future progress should therefore evaluate the sensor as part of a complete platform rather than as an isolated material sample.

Finally, standardized testing is needed. Reported sensitivities and cycling results are often obtained under different loading rates, pressure ranges, bending states, and environmental conditions, making direct comparison difficult. Application-oriented protocols that include bending, stretching, sweat exposure, temperature/humidity variation, and long-duration cycling would make performance claims more comparable and help distinguish promising prototypes from wearable systems with practical reliability.

5. Conclusion

Ultrathin flexible pressure sensors have developed from simple thin-film devices toward porous, microstructured, fibrous, hydrogel-based, and multifunctional wearable platforms. Piezoresistive sensing remains attractive for its simple readout and strong low-pressure response; capacitive sensing is suitable for low-power continuous and arrayed measurements; and piezoelectric and triboelectric approaches provide advantages for dynamic and self-powered sensing. Across these mechanisms, material selection alone is not sufficient: pressure response is jointly determined by microstructure, conductive or dielectric networks, interfaces, electrodes, and packaging. Future work should focus on balanced sensitivity and range, long-term environmental stability, interpretable multimodal sensing, scalable fabrication, and system-level integration. Progress in these areas is essential for moving flexible pressure sensors from short laboratory demonstrations toward reliable use in health monitoring, motion assessment, human-machine interaction, and electronic skin.

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