Recent Advances in 3-D Printed, Wearable Pressure Sensors for Plantar Pressure Monitoring: A Review

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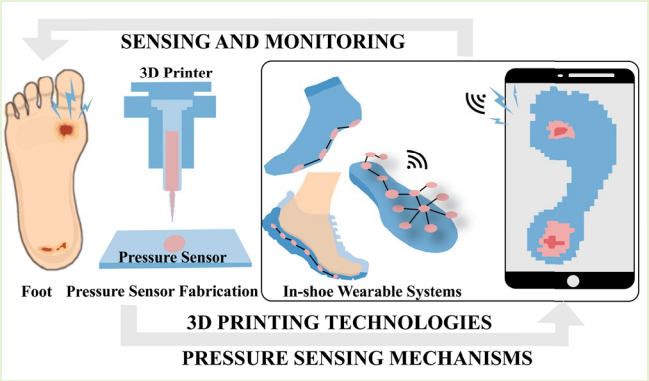
Abstract **—Plantar pressure has attracted extensive research interest as a crucial parameter in the assessment of foot and ankle functions during physical activities and in the monitoring and prevention of pressure-related foot diseases. The utilization of 3-D printed pressure sensors, known for their customization, exceptional precision, and flexibility, holds immense potential in wearable in-shoe systems. However, a comprehensive summary and comparison of these 3-D printed, wearable pressure sensors in terms of their printing methods, sensing mechanisms, materials, and structures is still lacking. This article aims to summarize recent research developments and provide insights into the theoretical foundations and essential aspects of 3-D printed pressure sensors dedicated to plantar pressure monitoring. First, typical 3-D printing methods for pressure sensor fabrication are introduced. Second, pressure-sensing mechanisms are summarized from the perspectives of their working principles, 3-D printing materials, and structures. Third, case studies of practical applications in various fields are discussed. Next, the challenges and suggestions for the development of printed pressure sensors for future improvements are addressed. Finally, a conclusion is drawn, offering an outlook on future research directions.**



Index Terms**— 3-D printing, in-shoe systems, plantar pressure monitoring, pressure sensors, wearable sensors.**

I. Introduction

PLANTAR pressure measurement encompasses the magnitude and distribution of force that is applied to the plantar surface of the foot [1]. It holds paramount significance across diverse domains, from the field of basic gait analysis [2], [3] and athletic performance [4], [5], to the clinical diagnosis and setup of rehabilitation strategies [6], [7], which proactively address injury or disease prevention [8], [9], [10]. In recent years, there has been substantial exploration into wearable pressure sensors known for their excellent flexibility, lightweight design, and comfortable seamless integration into footwear systems.

A. Systems for Plantar Pressure Monitoring

Plantar pressure monitoring systems typically fall into two categories. The first type consists of barefoot pressure platforms, such as footprints, mats, and plates [11]. Subjects can either walk over these platforms [12] or place their foot on them [13] [Fig. 1(a)]. While these platforms offer specific pressure data for the foot, they are restricted to measuring pressure only when subjects are barefoot. In contrast, the second category consists of smart wearable in-shoe pressure assessment systems, which provide insights into the mechanical stresses on the foot's plantar surface during activities such as walking, running, or jumping [14]. These systems incorpo-

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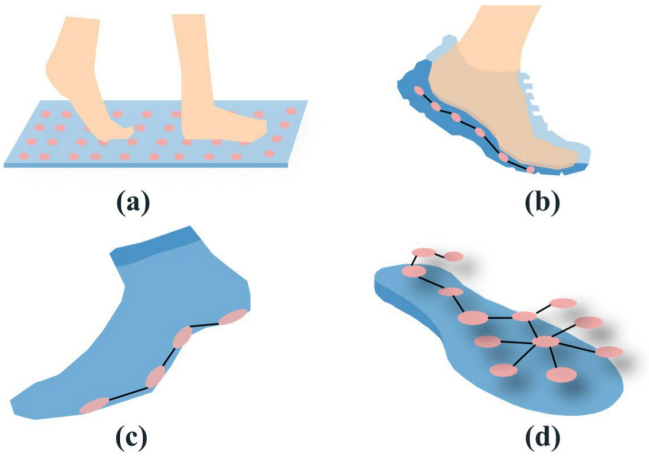

Fig. 1. Plantar pressure monitoring systems. (a) Barefoot platform. Typical in-shoe wearable systems. (b) Shoe, (c) sock, and (d) insole systems.

rate sensing technologies, coupled with data acquisition and transmission modules, alongside wired or wireless communication protocols and user interfaces for processing sensor signals and visualizing analyzed data [15], [16]. Unlike traditional pressure monitoring platforms, in-shoe systems allow for direct measurements at the skin–foot interface and enable the convenient collection of long-term data through daily monitoring. This capability enhances statistical robustness and expands the scope of activities studied, including stair climbing and various sports [17]. However, in-shoe pressure measurements are technically more demanding than external platforms due to the dynamic, curved surfaces inside shoes during movement [18]. This review article specifically focuses on in-shoe pressure assessment, excluding the consideration of barefoot platforms.

Wearable plantar pressure monitoring systems are generally classified into three types based on their placement: shoe, sock, and insole systems [Fig. 1(b)–(d)].

Shoe systems are designed for daily wear, providing significant advantages for various user groups. First, these shoes are beneficial for athletes by tracking foot pressure during physical activities, thereby enhancing performance and reducing injury risk. Second, individuals with foot ulcers can benefit from smart shoes constructed from soft leather or composite materials, which are designed to accommodate toe deformities and volume fluctuations [17]. These systems not only redistribute plantar pressure but also monitor various parameters, such as pressure, humidity, and temperature.

Sock systems, recognized for their high elasticity and integration of multiple sensors, provide comfort to patients and are well suited for indoor use [19], [20]. However, these systems have certain limitations, such as being difficult to wash, which confines their application to short-term monitoring [21]. Moreover, while a snug fit can enhance sensor performance, it may also result in increased noise and decreased durability.

Insole-based plantar pressure monitoring systems are experiencing rapid expansion, driven by their lightweight design, customizable features, and compatibility with various types of footwear [22], [23]. A notable concern, however, is their limited durability. Insoles can deteriorate quickly due to their direct contact with the foot and the repetitive stresses endured during walking and other weight-bearing activities.



Fig. 2. Commercial plantar pressure monitoring systems. (a) Sensoria sock system [25]. (b) F-Scan insole system. (c) F-Scan insole [26].

1) Commercial Systems: Various commercial wearable devices equipped with pressure sensors are available for plantar pressure monitoring. Altra Running (Logan, UT, USA), for instance, offers smart shoes that integrate pressure sensors, a battery, and a microchip in the midsole [24]. These shoes interface with a smartphone via Bluetooth, facilitating the collection of data on impact force, contact time, and cadence to improve running efficiency. Similarly, Sensoria (Redmond, WA, USA) has developed smart socks [Fig. 2(a)] embedded with textile pressure sensors, providing real-time feedback on foot strike patterns to optimize running form [25].

Moreover, Novel GmbH (Munich, Germany) manufactures the Pedar insole system, which integrates up to 99 capacitive sensors capable of detecting pressures ranging from 15 to 600 kPa [27]. This system is utilized to analyze foot–shoe interactions in both clinical and sports applications. In addition, Medilogic GmBH (Schönefeld, Germany) produces insoles that incorporate up to 240 resistive sensors, capable of measuring pressures up to 640 kPa with a sampling rate of 400 Hz, thereby offering high-resolution biomechanical data [28]. Furthermore, Moticon's OpenGo (Munich, Germany) insoles are equipped with 16 capacitive pressure sensors and a six-axis inertial measurement unit (IMU), providing low hysteresis and a high-pressure range (up to 500 kPa) for comprehensive gait analysis [29]. XSensor (Calgary, AB, Canada) offers intelligent insoles incorporating 235 capacitive sensors and an IMU, which capture lab-quality biomechanical data suitable for both athletic and clinical use [30]. In addition, Tekscan (Norwood, MA, USA) provides an advanced F-Scan insole system with a polyester substrate, maintaining a thin profile of 0.28 mm for precise pressure mapping [Fig. 2(b) and (c)] [26]. These devices collectively enable detailed plantar pressure and gait analysis, thereby enhancing athletic performance and clinical diagnostics.

2) Academic Systems: Commercial plantar pressure monitoring devices encounter several significant challenges that hinder their widespread adoption and long-term reliability.

1) One of the primary barriers is the high cost of these devices, which restricts accessibility for end users [31].
2) Standardized shoes available on the market may not fit all foot shapes, particularly for patients with Parkinson's or diabetic feet [18], [32].
3) Ensuring stability in long-term measurements is another critical concern, as many commercial pressure sensors

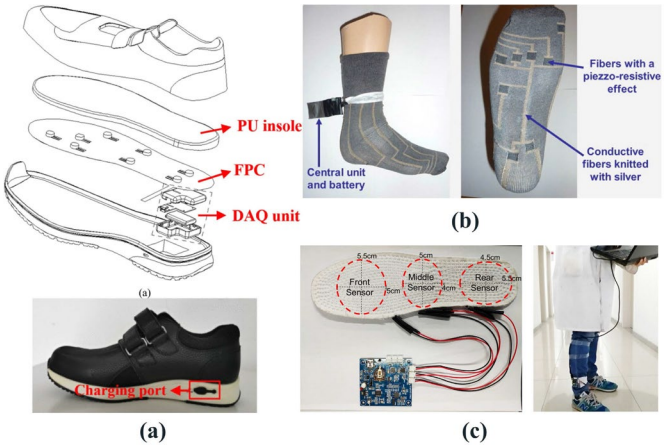

Fig. 3. Academic plantar pressure monitoring systems. (a) Low-cost shoe system for daily monitoring of plantar pressure in diabetics [32]. (b) Sock system for foot ulcer detection [20]. (c) Low-cost insole system with capacitive pressure sensors [33].

exhibit a limited lifespan during extended use, especially in running applications [11].

4) Data accuracy is frequently compromised due to calibration issues, improper sensor placement, and interuser variability, leading to inconsistent results [17].

To address these issues, researchers are developing innovative wearable devices that leverage advanced sensor technologies. Wang et al. [32] introduced an innovative, low-cost system designed for daily monitoring of plantar pressure in diabetic patients. This system includes an insole embedded with a pressure sensor array that continuously tracks plantar pressure, displaying real-time changes on a mobile phone, and providing early warnings for those at high risk of diabetic foot complications [Fig. 3(a)]. The pressure sensor, which utilizes copper and carbon black (CB) as the electrode and conductive filler, respectively, is designed for mass production at a low cost. The sensor is soft and bendable, making it well suited for the demands of daily plantar pressure monitoring.

Perrier et al. [20] developed a prototype of smart diabetic socks using piezoresistive textiles capable of detecting external foot pressures [Fig. 3(b)]. These socks are designed to assess the risk of foot pressure ulcers. Zhang et al. [33] developed a simple, low-cost, and highly integrated textile-based sensing insole with capacitive pressure sensors [Fig. 3(c)]. The sensors' elasticity and flexibility are well matched to the insole, ensuring close integration without sacrificing comfort. These sensors also exhibit rapid response times, minimal hysteresis, and high sensitivity (0.947 MPa^{-1}).

B. State-of-the-Art 3-D Printing Technique

Three-dimensional printing is an additive manufacturing process that represents a revolutionary and rapidly evolving technology across diverse industries [34], [35]. Its impact spans various sectors. In architecture, innovations, such as 3-D printed concrete structures, are reshaping construction practices [36]. In gastronomy, 3-D printing enables the creation of intricately designed, customizable food products [37]. In the medical field, it is considered a game changer, with applications ranging from personalized implants to drug delivery systems [38], [39]. Furthermore, 3-D printing plays a crucial role in environmental sustainability by reducing waste, energy demand, and carbon emissions [40]. The electronics manufacturing sector also benefits from this technology, particularly in producing intricate multilayered components [41].

As for wearable sensor fabrication, traditional manufacturing processes have been prevalent over the past decades. These include screen printing [42], roll-to-roll gravure printing [43], stamp contact printing [44], bar coating [45], and spin coating [46]. With the advent of 3-D printing techniques, researchers have begun utilizing 3-D printing to fabricate wearable pressure sensors. Compared to traditional methods such as screen printing, bar coating, and spin coating, 3-D printing offers distinct advantages in terms of material efficiency and waste reduction. Furthermore, 3-D printing excels in structure building, customization, and repeatability, providing designers and innovators with unprecedented freedom to rapidly create sensor prototypes. In addition, 3-D printing allows for the fabrication of flexible, bendable, and low-cost wearable sensors at a fast speed, enhancing the overall efficiency of the production process.

C. Highlights of This Review Article

In recent years, the field of plantar pressure monitoring has been extensively reviewed with a focus on specific niches, including dedicated sensors for diabetic foot ulcers [47], [48], identification of gait disorders [49], and clinical applications [50], [51], [52]. Concurrently, broader reviews have explored the versatile landscape of 3-D printed sensors across various domains, spanning biomedical applications [53], electrochemical sensing [54], and diverse sensor types [55], [56]. However, the realm of 3-D printed pressure sensors tailored explicitly for plantar pressure monitoring has received limited attention in the current literature.

This review article focuses on two main aspects. First, it systematically discusses widely used 3-D printing techniques for wearable pressure sensors, highlighting their advantages and limitations. Second, it focuses on three common pressure-sensing mechanisms—piezoresistive, capacitive, and piezoelectric—along with two emerging trends: triboelectric and optical fiber Bragg grating (FBG) sensors. It provides a comprehensive summary of the 3-D printing techniques, materials, and sensor structures involved in these mechanisms. Thus, this review explores the current landscape of 3-D printed pressure sensors specifically designed to monitor plantar pressure.

This article unfolds as follows. Section II comprehensively summarizes the predominantly used 3-D printing techniques. Section III details diverse sensing mechanisms and materials, elucidating the structures incorporated in printed pressure sensors. Section IV presents an analysis of case studies and practical applications, demonstrating the utility of these sensors in various domains. In Section V, this article addresses the prevailing challenges and presents insightful suggestions. Finally, Section VI concludes the review and outlines future perspectives for this evolving field.

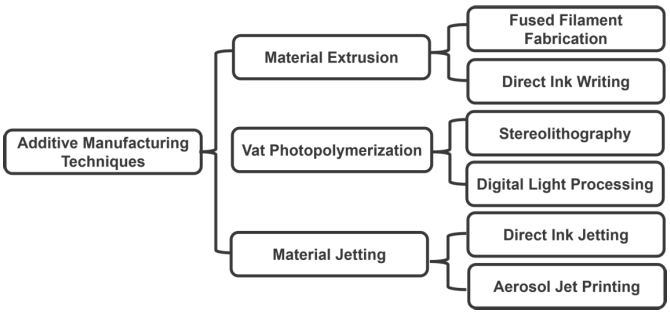

Fig. 4. Commonly used 3-D printing techniques for pressure sensor fabrication.

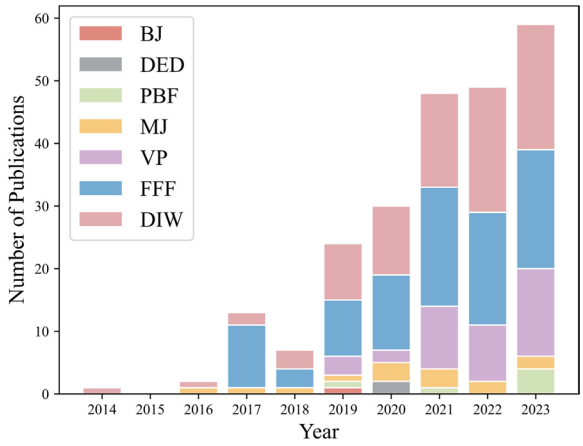

Fig. 5. Publication trend of different 3-D printing techniques for pressure sensor fabrication. (Source: Web of Science, keywords: "3-D printing" and "pressure sensor" in title, abstract, or keywords, January 2024.)

II. Main 3-D Printing Techniques for Fabrication of Pressure Sensors

The International Organization for Standardization (ISO) and the American Society for Testing and Materials (ASTM) categorize 3-D printing processes into seven distinct classifications [57]. These encompass material extrusion (ME), vat photopolymerization (VP), material jetting (MJ), sheet lamination (SL), direct energy deposition (DED), binder jetting (BJ), and powder bed fusion (PBF). Fig. 4 visually illustrates various 3-D printing techniques employed in the creation of pressure sensors. Representative ME methods include fused filament fabrication (FFF) and direct ink writing (DIW). Notably, ink jetting printing, a prevalent MJ technique, is frequently applied in the construction of pressure sensors. Within the VP method, diverse techniques, such as digital light processing (DLP) and stereolithography (SLA), contribute to the versatility of this category [58]. The four most utilized techniques in the fabrication of 3-D printed pressure sensors in the research field include FFF, DIW, MJ, and VP (Fig. 5).

A. Fused Filament Fabrication

FFF, commonly known as fused deposition modeling (FDM), is a widely utilized additive manufacturing technique across various scientific and industrial sectors. Its operation relies on a sophisticated slicing computer program, intricately managing the segmentation of digital models into discrete layers to enable precise fabrication. The FFF process initiates with the extraction of a thermoplastic filament from a spool, guided through the system for subsequent processing [Fig. 6(a)]. Upon reaching the heated extruder head, the filament undergoes a transformative phase, transitioning from a solid state to a molten form. The heated nozzle then follows a predetermined trajectory, executing a planar motion to delineate each layer of the model accurately. Subsequently, the rapid cooling of the extruded filament upon deposition facilitates the gradual solidification of the material, fostering adhesion with the build plate or previously deposited layers.

In the domain of pressure sensor fabrication, researchers utilize FFF for the creation of molds that define the sensor's structural form, as evidenced in studies by Zhuo et al. [59] and Lin et al. [60]. The adaptability of FFF enables the production of microstructured molds featuring designs that are not only environmentally sustainable but also innovative. Two primary methodologies are employed with these molds: immersing them into conductive or elastic materials to confer functionality [61], [62] or employing them as containers and subsequently adding materials to achieve the desired structure [63], [64]. In addition, some research groups integrate conductive materials into the filaments themselves. For example, Liu et al. [65] reported the fabrication of a force-sensing device using a graphene-doped electrically conductive polylactic acid (PLA) polymer for the electrodes and interconnections.

FFF offers several notable advantages, including its simplicity and affordability in terms of equipment, which make it an appealing option for 3-D printing enthusiasts. The widespread availability of polymer filaments further enhances its appeal by providing a diverse range of materials. However, FFF has limitations. It is restricted to the use of thermoplastics, which limits the range of printable materials. The surface finish of printed models may not always meet the desired smoothness standards, impacting the final esthetic quality. Another challenge is the potential nozzle clogging, which can lead to material wastage and disrupt the printing process.

B. Direct Ink Writing

DIW stands out as a remarkably versatile 3-D printing method, particularly in material development. It empowers the creation of intricate 3-D shapes using virtually any material through the formulation of a paste with adequate rheology [66]. In this process, the functional ink, usually housed in a syringe container, is extruded under pressure from a needle-like nozzle and deposited onto a substrate or a previously laid layer [Fig. 6(b)]. The pressure is generated on the piston either through a pneumatic gas pump or a motor-driven screw mechanism.

Materials utilized in DIW can either be low-viscosity inks that smoothly flow through the nozzle or thinning pastes, which necessitate a more substantial driving force. When low-viscosity inks are employed, postprocessing steps for solidification typically involve a curing system (e.g., ultraviolet (UV) light and heating plate) to instantly solidify the extruded filament [67], [68].

The pivotal aspect of manufacturing pressure sensors through DIW technology revolves around formulating an ink with a stable composition, ensuring optimal fluidity and appropriate viscosity [68]. Recent research in this field has delved

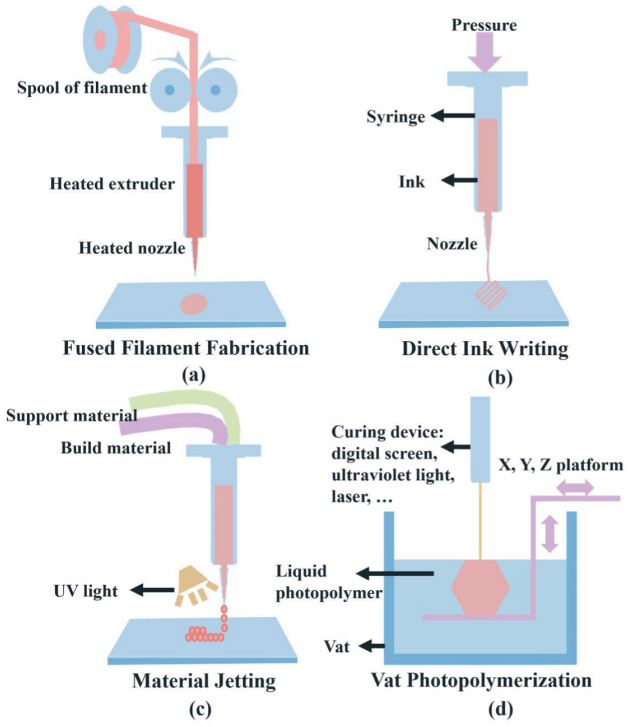

Fig. 6. Typical 3-D printing techniques for 3-D printed pressure sensors. (a) Fused filament fabrication. (b) Direct ink writing. (c) Material jetting. (d) Vat photopolymerization.

into a variety of functional materials for 3-D printed pressure sensors, spanning polymers [69], metals [70], and biological inks [71]. DIW's exceptional versatility accommodates a broad spectrum of materials, facilitating diverse pressure sensor designs. Moreover, its capability for simultaneous printing of multiple materials or material combinations allows for the creation of composite structures in pressure sensors. The use of small-diameter nozzles in DIW contributes to achieving high printing resolutions, making it particularly suitable for applications demanding fine details and precision. Despite its advantages, DIW does present certain challenges. The printing process can be comparatively slow, potentially limiting its efficiency for large-scale production. In addition, depending on the materials employed, DIW may necessitate postprocessing steps such as curing or sintering to attain the desired material properties, introducing complexity to the fabrication process. Furthermore, intricate geometries in the printing process may require support structures, which can be time-consuming to remove and may impact the surface finish of the final pressure sensor product. These considerations highlight the importance of carefully balancing the advantages and limitations of DIW in the context of pressure sensor manufacturing.

C. Material Jetting

MJ technology is an additive manufacturing method that selectively cures liquid photopolymer to build functional parts. Direct ink jetting and aerosol ink jetting are two typical MJ printing methods; the former uses liquid material such as photopolymer resin, jetted through a nozzle directly onto the build platform, and the latter involves atomizing liquid material into a fine aerosol mist, then jetting the material through a nozzle using a carrier gas [72]. The material is then solidified or cured layer by layer using a UV light source. Although MJ printing designs may vary slightly from one manufacturer to another, a general schematic representation of the MJ process is illustrated in Fig. 6(c).

Compared to DIW, MJ is renowned for its high resolution and accuracy, enabling the fabrication of intricate and detailed components, particularly in electronics and biomedical devices. MJ inks can be classified into four main categories, metal inks, carbon-based inks, polymer inks, and ceramic inks [73]. Silver (Ag), gold (Au), and copper (Cu) inks are typically used to print the electrodes due to their excellent electrical conductivity and stability [74], [75], which are crucial for accurate signal transmission. Carbon-based inks, such as graphene and carbon nanotubes (CNTs), are often utilized to form the sensing elements because of their high sensitivity to pressure changes and superior mechanical properties. These inks enhance the performance and durability of the sensors. In addition, piezoresistive and piezoelectric materials, which change their electrical resistance or generate electric charges in response to mechanical stress, are incorporated to improve the sensor's responsiveness and accuracy. Elastomeric inks, such as polydimethylsiloxane (PDMS) [76], provide flexibility and stretchability, making the sensors suitable for wearable applications. Photopolymer resins are also used to create precise and detailed microstructures that enhance the overall functionality of the sensors. This diverse range of inks and materials enables the fabrication of highly specialized and efficient pressure sensors for various applications, from healthcare to industrial monitoring.

The MJ technique offers several key advantages, particularly for high-integration devices such as transistors in 3-D printed electronics. These benefits include the ability to work with various substrates, minimal waste production, easy application of low-viscosity solutions, and, notably, high printing resolution. This high resolution is crucial for achieving intricate details in electronic components, which enhance their overall performance [77]. Compared to FFF and DIW, MJ excels in producing superior surface finishes through the use of microdroplets [78]. However, MJ has certain drawbacks. There is a significant risk of nozzle clogging, especially with high-viscosity inks, which can limit the range of ink formulations and impact the submicrometer quality of printed features. Moreover, achieving high-speed printing often requires complex and costly microelectromechanical multinozzle systems [35]. These challenges underscore the ongoing need for advancements in ink formulation and printing technology to fully harness the potential of MJ in the field of sensor printing.

D. Vat Photopolymerization

VP, characterized by its utilization of a vat containing liquid photopolymer resin, orchestrates the additive manufacturing process by fabricating models layer by layer. The curing process, facilitated by an array of devices, including digital screens, UV light, and lasers, selectively solidifies the resin at predetermined locations. Concurrently, a platform incrementally descends following the completion of each layer, ensuring the progressive realization of the desired structure [57] [Fig. 6(d)].

Within the domain of pressure sensor fabrication, VP emerges as a seminal technique for producing elaborate structures tailored to enhance sensor performance [79]. Researchers leverage VP to achieve high sensitivity through the integration of specialized microstructures. For instance, Xia et al. [80] exemplified the creation of flexible piezoresistive sensors via SLA printing, ingeniously incorporating hollow microstructures. Similarly, Zhang et al. [81] utilized SLA to engineer a flexible pressure sensor boasting exceptional sensitivity, crafted from a printable photosensitive resin. Moreover, Xia et al. [82] developed a flexible pressure sensor with superior strain stability through the utilization of DLP technology. Their methodological fusion of structural design principles with DLP printing techniques presents a novel paradigm for the enhancement of bulk-structured flexible pressure sensors. These advancements highlight the broad applicability and transformative potential of VP in the field of pressure sensor innovation.

VP stands out for its capacity to deliver exceptional resolution and accuracy, making it particularly well suited for the fabrication of intricately designed components. The process is highly efficient, characterized by swift production cycles and minimal material wastage. However, one notable limitation is the need for precise control over the curing process, which can introduce complexity in achieving consistent material properties and avoiding defects [83]. In addition, the postprocessing phase requires meticulous handling to prevent premature curing, adding another layer of complexity. Furthermore, the initial investment in VP equipment can be substantial, posing a significant barrier to entry for potential adopters [84].

III. Sensing Mechanisms: 3-D Printing Material Selection and Structure Design

Numerous sensing techniques have been proposed for quantifying load distribution at the plantar surface, frequently employed in academic research settings. These methodologies include piezoresistive, capacitive, inductive, piezoelectric, triboelectric, and optical fiber technologies. Among these, piezoresistive, capacitive, piezoelectric, triboelectric, and optical fiber sensors, in conjunction with 3-D printing, are particularly prevalent for integration into wearable devices due to their sensitivity and adaptability. This section provides a comprehensive overview of these sensing methods, detailing the specific 3-D printing materials and structural designs utilized in their implementation, thereby highlighting their respective advantages and potential applications in wearable foot pressure sensor fabrication.

A. Target Pressure Sensor Requirements

Plantar pressure sensors serve the purpose of measuring pressure distribution and forces applied to the feet during various activities. To ensure accurate and reliable data collection, these sensors must meet specific requirements. The following outlines the fundamental requirements for materials and device architectures utilized in plantar pressure detection.

1) *Pressure Range:* It is the key parameter for foot locomotion monitoring. Different activities involving the foot have different operating pressures. It has been reported that healthy young people's foot pressure range is between 150 and 310 kPa [85] when standing, whereas diabetic patients' standing pressure can amount to 600 kPa or larger. People with foot ulcers have a larger foot pressure range than healthy people, and the average pressure can even reach 800 kPa during walking [86]. Studies show that a pressure range within 1 MPa is suitable to detect most of the foot activities [87].
2) *Sensor Size:* The size of pressure sensors used for assessing plantar pressures plays a crucial role in determining the accuracy of pressure measurements. Typically, these sensors have finite areas, and the ability to accurately measure the true maximum pressure is contingent upon their size [88]. The pressure recorded by such sensors often represents an average value across their respective areas, rather than capturing the actual peak pressure experienced. Consequently, the true peaks in the pressure profile tend to be underestimated [89]. Lord [90] introduced a theoretical prediction regarding the averaging effect of a pressure cell relative to its area. Their findings suggest that peak pressure is consistently underestimated, with the extent of underestimation potentially reaching up to a third for a square cell with a width of 10 mm under a barefoot record. Moreover, different in-shoe systems necessitate sensors to be placed on diverse substrates with varying upper and bottom surfaces. This requirement often calls for adjustments in sensor sizes to ensure the optimal performance [91].
3) *Sensitivity:* The sensitivity of a pressure sensor indicates its capability to detect small alterations in pressure and translate them into a measurable output. It is commonly quantified as the ratio of the change in the output signal (e.g., resistance, current, or voltage) to the corresponding change in pressure input. The sensor must possess sufficient sensitivity to accurately detect variations in pressure, especially in applications where subtle changes in foot pressure are crucial. Typically, a pressure resolution below 10 kPa is considered a standard criterion for applications in footwear [52].
4) *Flexibility:* It is paramount in footwear devices, particularly for pressure sensors required to conform to curved or soft surfaces within shoes. This characteristic ensures accurate pressure measurements, as flexible sensors can adapt to the foot's contours, even during dynamic movements.
5) *Durability/Stability:* The sensor should be robust and durable enough to withstand the repetitive stresses associated with foot movements, ensuring a long lifespan. It should also have the ability to provide consistent measurements under the same conditions over time, even after enduring numerous loading cycles.
6) *Linearity:* The sensor's response to applied pressure, when plotted, demonstrates its linearity, reflecting the intricacy of the required signal processing and calibration. Linear pressure sensors are favored for their straightforwardness. However, many pressure sensors exhibit limited linearity across wide pressure ranges due

to material characteristics. Recent research [92], [93] has concentrated on enhancing linearity and sensitivity for wide-range pressure detection, which is advantageous for the development of plantar pressure measurement applications.

7) *Hysteresis:* This phenomenon is assessed by analyzing the output signal as the sensor undergoes loading and unloading. Two distinct responses are observed when pressure is increased through loading or decreased through unloading. Hysteresis often stems from elastic aftereffects linked with viscoelasticity, creep, and internal friction [94]. Utilizing appropriate materials and structures can help minimize hysteresis.
8) *Temperature Sensitivity:* The pressure readings of sensors may vary with fluctuations in ambient temperature. This variability is often attributed to the materials used in the sensor body, which respond differently to temperature changes. Sensors with low-temperature sensitivity within the body temperature range are preferred for footwear devices.
9) *Response Time:* It pertains to the duration required for a sensor to detect a variation in pressure and provide an accurate measurement. Typical response times span from milliseconds to several tens of milliseconds, enabling sensors to capture swift alterations in pressure distribution during various foot activities. This attribute is influenced by factors such as the sensor's materials, structures, and operational mechanisms. The operating frequency of wearable systems denotes the rate at which each sensor measures samples per second, usually quantified in hertz. This parameter is selected based on the sensors' response time. Studies have indicated that sampling frequencies ranging from 45 to 100 Hz are sufficient for walking activities [1], [94]. Commercially available systems, such as the F-Scan system, commonly offer sampling rates within the range of 50–100 Hz. However, sensors should possess a sampling capability of at least 200 Hz to accurately measure foot plantar pressure during running activities [95]. This frequency is generally deemed sufficient for capturing most foot movements.

Various 3-D printed pressure sensors are utilized in wearable devices, but plantar pressure sensors exhibit distinct characteristics compared to other wearable pressure sensors (Table I) such as those used in pulse detection [97] and blood pressure monitoring [98]. Specifically, plantar pressure sensors are engineered to accommodate a broader pressure range, enhanced flexibility, extended durability, and particular response times tailored for foot-related activities.

B. Piezoresistive Pressure Sensor

A piezoresistive pressure sensor detects changes in electrical resistance within certain materials when subjected to mechanical stress or pressure [Fig. 7(a)]. Materials with piezoresistive properties, such as silicon semiconductors, exhibit measurable resistance changes under stress. This principle is harnessed to measure applied pressure.

TABLE I
COMPARISON OF FOOT WEARABLE PRESSURE SENSORS WITH OTHER WEARABLE PRESSURE SENSORS

Property	Foot pressure sensors	Other wearable pressure sensors
Placement	Embedded in shoes, insoles, and socks	Various body parts such as wrist, back, chest, etc.
Pressure range	high pressure range: 0-1 MPa [87]	Normally < 100 kPa [96]
Flexibility	Flexible, thin	Rigid or flexible depending on body part
Durability	Durable for repeated foot strikes and weigh	Less durability
Response time	Typically 1-100 ms	<100 ms to several seconds

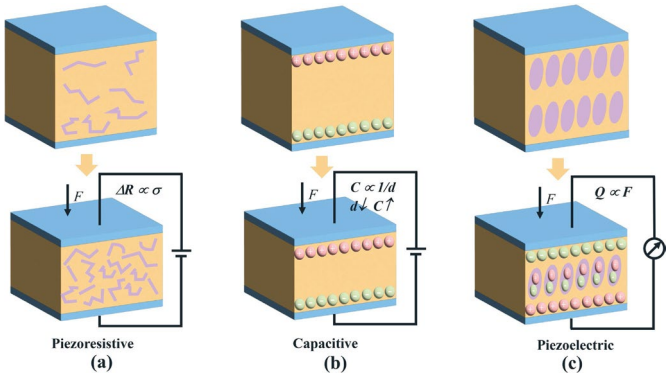

Fig. 7. Typical sensing techniques used for 3-D printed pressure sensors. (a) Piezoresistive. (b) Capacitive. (c) Piezoelectric.

Typically, piezoresistive sensors are crafted with a flexible substrate, conductive fillers, a contact layer, and electrodes. These sensors offer numerous advantages for plantar load sensing, including affordability, minimal interface electronics requirements, and low susceptibility to electromagnetic interference. Despite their benefits, challenges, such as low repeatability and limited sensitivity across the pressure range, have been observed. Recent research highlights various examples of 3-D printed piezoresistive pressure sensors, as presented in Table II. It shows that: 1) FFF and DIW are two prevalent methods for fabricating piezoresistive pressure sensors; 2) the utilization of elastic materials such as PDMS, hydrogel, and thermoplastic polyurethane (TPU) can enhance sensitivity and stability; and 3) the preference for materials such as graphene, reduced graphene oxide (rGO), CNTs, multiwalled CNTs (MWCNTs), poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS), MXene, and CB as fillers, owing to their exceptional mechanical, electrical, and thermal properties (Table III).

To enhance piezoresistive sensing performance, the method of utilizing nanocomposite or adding nanostructure has raised researchers' interest. CNTs [61], [62] and PDMS [93], [101] stand out as popular choices in the domain of human–machine interaction due to their robustness, flexibility, and ability to detect a wide range of pressures. FFF and VP printing methods are commonly employed to fabricate diverse sensor structures. In addition, methods, such as dipping, are utilized to impart piezoresistive properties to sensors [64], [93], [107], [108]. Yin et al. [62] introduced a lattice structure pressure sensor

TABLE II
EXAMPLES OF 3-D PRINTED PIEZORESISTIVE PRESSURE SENSORS

Printing Method	Key Materials	Sensitivity	Pressure Range (kPa)	Hysteresis	Stability (cycles)	Response Time	Ref.
FFF	CNTs/TPU	2.68 MPa^{-1}	< 1450	Some elastic hysteresis	1000@200 kPa	74 ms	[61]
FFF	CB/TPU	0.7145 kPa^{-1}@0.5 kPa	0.1-200	Negligible	10@50 kPa	8.04 s@1 kPa	[99]
FFF	PLA/MWCNTs/ DCM	2.689×10^{-4} kPa^{-1} @2.2 kPa	< 30	/	50@5 N	100 ms	[63]
FFF	Liquid metal	0.158 kPa^{-1}@50 kPa	< 600	Negligible	12000@0-30 kPa	77 ms	[64]
DIW	Hydrogel	0.0013 kPa^{-1}@5 kPa-250 kPa, 0.00048 kPa^{-1}@250 kPa-600 kPa	< 10300	Small	600	960–1840 ms @600 Pa	[100]
DIW	CB/PDMS	0.0048 kPa^{-1}@0-500 kPa	0-500	Obvious	500 (50% strain)	/	[93]
DIW	PDMS/CB/ MWCNT/Cu	124 kPa^{-1}@50–163 kPa, 212 kPa^{-1}@163–262 kPa	0-396	/	5000	32 ms	[101]
DIW	CNTs/SiNPs	0.097 kPa^{-1}	< 175	/	10000	0.2-0.4 s	[102]
DIW	PEDOT:PSS/ Graphene	0.49 kPa^{-1}@0-4 kPa	< 25	/	1000@25 kPa	51 ms	[103]
DIW	MXene	3.15 kPa^{-1}@0–15 kPa, 6.31 kPa^{-1}@15–150 kPa	< 150	Negligible	2000@260 g	300 ms	[104]
DIW	Graphene	3.22 kPa^{-1}@0-10 kPa, 0.47 kPa^{-1}@10-98 kPa	< 98	/	1500@10 kPa	130 ms	[105]
DIW	rGO/MXene	0.29 kPa^{-1}@0-1.6 kPa, 0.03 kPa^{-1}@1.6-7.8 kPa, 0.0033 kPa^{-1}@7.8-70 kPa	< 80	/	1000@20-25 kPa	40 ms	[106]
DLP	CNTs/TPU	1.02 kPa^{-1}@0-130 kPa	< 160	/	60000@10 kPa	65 ms@1 kPa	[62]

using a bottom-up DLP 3-D printing technique, enabling the 30-min rapid production of 55 high-fidelity lattice models. The sensor exhibits remarkable sensitivity (1.02 kPa^{-1}) and exceptional linearity across a wide pressure range (0.7 Pa–160 kPa). Through adjustments to design parameters such as lattice type and layer thickness, precise control over both electrical sensitivities and mechanical properties of the pressure sensor can be achieved. Moreover, the sensor demonstrates outstanding durability, enduring up to 60 000 compression cycles at 10 kPa without any significant degradation in the electrical signal. Kamat and Kottapalli [79] utilized SLA to fabricate an elastomeric body-centered cubic lattice structure with a relative density of 21% and an elastic modulus of 31.5 kPa. They subsequently coated the lattice in graphene nanoplatelets via dipping, resulting in a piezoresistive pressure sensor with an exceptional sensitivity of 0.1 kPa^{-1} and excellent repeatability over 120 cycles, fully restoring its original resistance afterward. Similarly, Kim et al. [61] developed a piezoresistive pressure sensor based on a gyroid structure with a conformal coating of CNTs. Utilizing the FFF printing method with TPU, the gyroid structures exhibited mechanical robustness even at low-pressure ranges. This sensor demonstrated a wide sensing range of up to 1.45 MPa and a high sensitivity of 2.68 MPa^{-1}. The sensor can be seamlessly integrated into a shoe for wearable applications, demonstrating its mechanical resilience and potential for monitoring human stance and motion [Fig. 8(a)]. Furthermore, employing FFF printing, Kim et al. [63] showcased a hollow-structure piezoresistive pressure with multiple axes [Fig. 8(c)]. Notably, they utilized an innovative solution casting method with PLA, MWCNTs, and dichloromethane (DCM) solvent, which was transformed into filament for printing.

For DIW-printed piezoresistive sensors, electrodes typically consist of metal nanoparticle inks, such as silver or copper inks [103], [105], [119]. Flexible substrates commonly employ materials such as PDMS [120], [121], polyethylene glycol terephthalate (PET) [122], and cellulose nanocrystals (CNCs) [123]. As for conductive fillers, also known as active layers, they typically comprise carbon nanomaterials and conductive polymers. Tang et al. [102] fabricated a piezoresistive pressure sensor using CNTs and fumed silica nanoparticles (SiNPs) as a conductive filler and rheology modifier, respectively. They converted a viscoelastic silicone rubber solution into a printable gel ink and directly printed soft and porous composites at room temperature [Fig. 8(e)]. Through optimizing the density of the CNTs conductive network with the matrix, positive piezoresistive sensitivity (+0.096 kPa^{-1}) and a large linear sensing range (0–175 kPa) were obtained.

C. Capacitive Pressure Sensor

Capacitive pressure sensors typically comprise two conductive plates separated by a dielectric material. These sensors operate by modulating the distance between the upper and lower electrodes in response to external forces, allowing for the detection and measurement of pressure variations [Fig. 7(b)]. Benefiting from this mechanism, capacitive pressure sensors often have lower power consumption and wider pressure detection range compared to piezoresistive sensors.

Two methods are usually employed to enhance the sensitivity of capacitive pressure sensors: 1) utilizing a dielectric material with a high dielectric constant [133] and 2) optimizing the layers' microstructure [134]. Selected recent papers regarding 3-D printed capacitive pressure sensors are listed in Table IV. It is evident that in comparison to 3-D printed piezoresistive pressure sensors, most 3-D printed capacitive pressure sensors exhibit lower sensitivity and higher hysteresis. Furthermore, capacitive pressure sensors fabricated via FFF tend to exhibit lower sensitivity but higher durability compared

TABLE III
PHYSICAL PROPERTIES OF SELECTED PIEZORESISTIVE SENSOR FILLER MATERIALS

Property	Graphene	rGO	CNTs	PEDOT:PSS	MXene
Charge carrier mobility ($cm^2/V \cdot s$)	10000-200000	1000-3000	Up to 100000	1-10	10-50
Thermal conductivity (W/mK)	3000-5000	100-200	3000-6000	0.1-0.5	10-20
Specific surface area (m^2/g)	2630 for a monolayer	500-1000	1000-1400	/	300-2000
Young's modulus (GPa)	1000	100-300	1-1000	1-4	10-100
Tensile strength	130 GPa	20-40 MPa	100 GPa	10-20 MPa	20-100 MPa
Band gap (eV)	0	0.1-1.5	Can have a small band gap depending on type	0.6-0.8	0.5-3.0
Specific density (g/cm^3)	2.26	1.9-2.1	1.2-2.6	1.3-1.45	Varies based on composition
Resistivity ($\Omega \cdot cm$)	2.26×10^{-6}	10^{-2}-10^{-4}	10^{-3}-10^{-6}	10^{-2}-10^{-4}	10^{-2}-10^{-4}
Ref.	[109], [110]	[111], [112]	[113], [114]	[115], [116]	[117], [118]

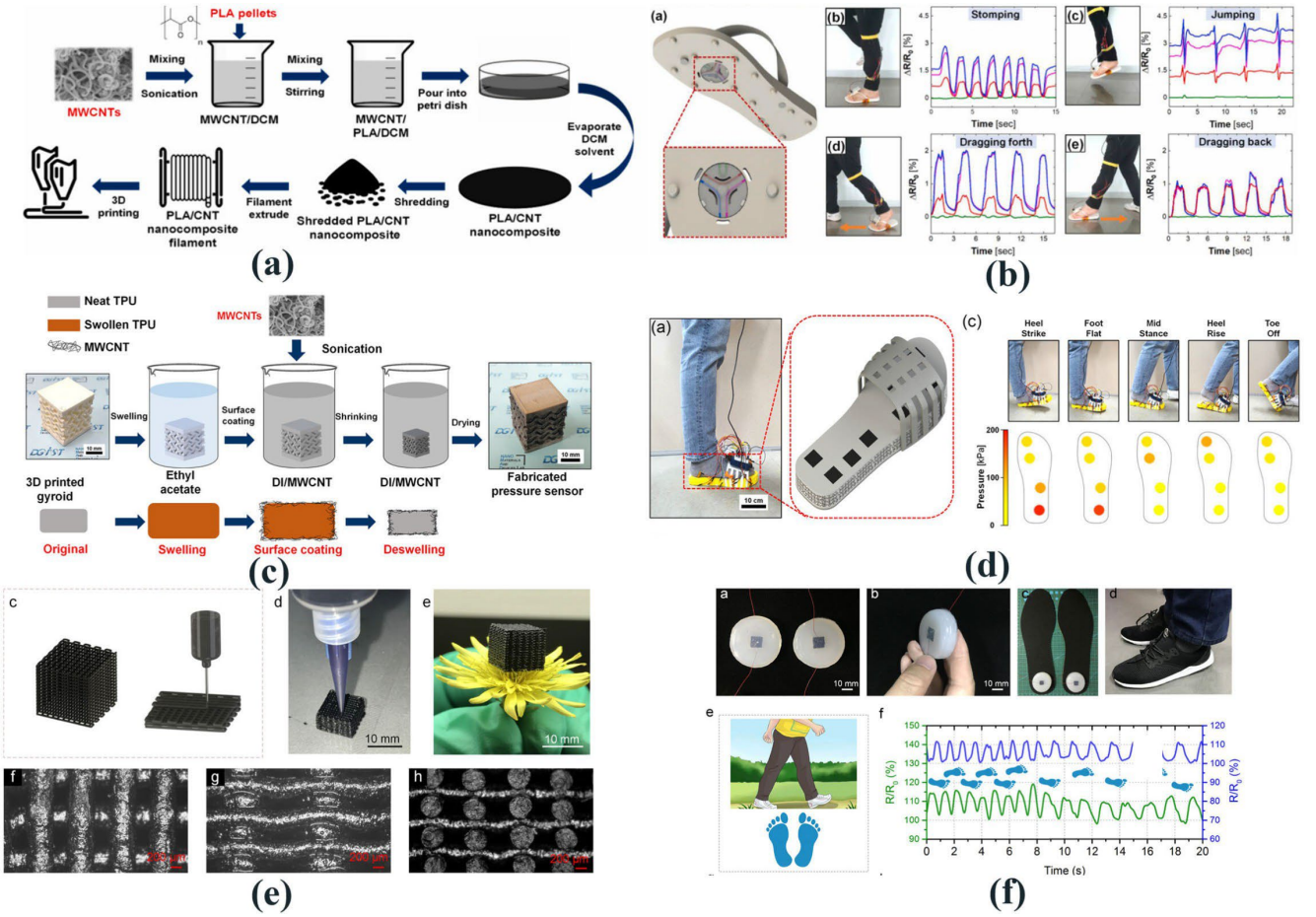

Fig. 8. 3-D printing techniques for piezoresistive pressure sensor fabrication. (a) Process of composite filaments for FFF fabrication and (b) sensing performance of the filament-made pressure sensor embedded flip-flop [63]. (c) Schematic of a 3-D printed gyroid structured pressure sensor and (d) schematic of the pressure sensor integrated with a sandal, capable of distinguishing different walking gaits [61]. (e) Schematic of the fabrication of DIW-printed pressure sensors and (f) optical image of the fabricated smart insoles with the pressure sensors and their performance [102].

to those fabricated using DIW [131]. Samarentsis et al. [125] presented a smart insole system integrated with 16 FFF-printed capacitive pressure sensors with PLA electrodes and TPU dielectric layers. Their study showcased remarkable sensor capabilities, including a high sensitivity of 1.19 MPa^{-1}, a wide working pressure range of up to 872.4 kPa, excellent stability and durability for at least 2280 cycles, and minimal hysteresis. Gothard Anton [135] and Gothard et al. [136] focused on the development and dynamic characterization of fully 3-D printed capacitive sensors using flexible TPU filament as the dielectric

TABLE IV
EXAMPLES OF 3-D PRINTED CAPACITIVE PRESSURE SENSORS

Printing Method	Key Materials		Sensitivity	Pressure Range (kPa)	Hysteresis	Stability	Response Time (ms)	Ref.
	Electrode	Dielectric						
FFF	TPU/CB	EcoFlex	0.526 MPa^{-1} @60 kPa-300 kPa	< 300	9.57%	1000@30 kPa	3200	[124]
FFF	PLA	TPU	1.19 MPa^{-1}	< 872.4	10%	2280@872.4 kPa	142-160	[125]
FFF	TPU/CB	EcoFlex	0.0004 kPa^{-1}	< 35	/	/	/	[126]
DIW	AgNWs	UV resin /TPU/PDMS	0.01123 kPa^{-1} @300 Pa-44 kPa	300 Pa-44 kPa	Small hysteresis	1500@3.75 kPa	50	[127]
DIW	/	Graphene/PDMS	0.22 kPa^{-1} @1 Pa–400 kPa	< 400	/	10000@200 kPa	14.93	[128]
DIW	Copper/PI	PDMS	1.23 kPa^{-1}	< 10	/	100@0.4 kPa	200	[129]
DIW	PVA iongels	/	0.1 kPa^{-1}	< 10	Obvious hysteresis	5@200 kPa	/	[130]
DIW	AgNWs/CPI	PDMS	3.19 kPa^{-1} @50-400 kPa	< 400	Slight hysteresis	7300@500 Pa	43	[131]
DLP	PEDOT:PSS/CNs	PDMS	3.54×10^{-3} kPa^{-1}	< 22.2	1.41%	2000	/	[132]

layer and either conductive TPU or conductive PLA for the conductive plates. The study involved sinusoidal compressive tests conducted at various frequencies to simulate typical footbed environment pressures. The fully and continuously FFF 3-D printed capacitive sensors demonstrated their capability to accurately track dynamic pressure changes.

Ntagios et al. [126] developed a capacitive pressure sensor embedded in a shoe sole using FFF printing. They fabricated conductive flexible electrodes and utilized a two-part rubber with microbubbles as the dielectric layer to enhance sensitivity. Simultaneous FFF printing of the sensor and its packaging aimed to improve durability. Testing under static and dynamic conditions, with loads up to 30 kg, the sensors revealed an average sensitivity of 0.0004 kPa^{-1}. Yang et al. [129] devised flexible capacitive sensors exhibiting a high sensitivity of 1.23 kPa^{-1} within a low-pressure range of 0–10 kPa. They utilized an elastomeric dielectric layer of 3-D printed mesoporous PDMS sandwiched between two electrodes of electroless copper-plated polyimide (PI) films. The mesoporous structure of PDMS, printed via the DIW approach, enabled the 3-D printing of layers consisting of PDMS filaments, thereby enhancing sensitivity. Jia et al. [127] assembled capacitive flexible pressure sensors using various materials, including 3-D printed UV resin, 3-D printed TPU, flat PDMS, and air as the dielectric, along with qualitative filter paper as the substrate and silver nanowires (AgNWs) as the electrode material. The dielectric layer featured a grid structure prepared by 3-D printing, facilitating simplicity, ease of implementation, and mass production. With this design, the sensor achieved a high sensitivity of 0.01123 kPa^{-1} in the high-pressure range (from 3.95 kPa to 44 kPa), a wide detection range of 0.3–44 kPa, and good durability with 1500 cycles under 3.75 kPa and 0.5 Hz.

D. Piezoelectric Pressure Sensor

Piezoelectric pressure sensor utilizes the piezoelectric effect in crystals with asymmetrical structures, where mechanical stress triggers electric polarization within the material [137]. Under external pressure, the material deforms, segregating positive and negative charges within its structure [Fig. 7(c)]. These charges align in opposite directions on the material's surfaces, generating a potential difference. Analyzing these differences allows for the assessment of external force impacts.

Piezoelectricity is naturally present in specific crystals such as quartz and Rochelle salt, and it can be induced in polymers such as nylon as well as polyvinylidene fluoride (PVDF) with trifluoroethylene (TrFE) [141] or tetrafluoroethylene (TeFE) [51]. The primary piezoelectric materials employed for commercial sensing applications predominantly stem from synthetic polycrystalline ferroelectric ceramics, with lead zirconate titanate (PZT) as a notable example. In contrast to single crystals, ceramics offer significant advantages, including high strength and ease of fabrication, especially for intricate shapes and large-area pieces.

Piezoelectric pressure sensors typically adopt laminated configurations, which include electrodes and a piezoelectric film. The manufacturing process typically concludes with poling, a crucial step necessary for aligning molecular dipoles within the structure. Finally, the electrodes play a vital role in facilitating the conduction of electric charges between the piezoelectric material and an electrical circuit.

Poling is a critical step in the fabrication of piezoelectric devices, involving the alignment of molecular dipoles in a single global direction within the sensor material. Among various poling techniques, electrical poling stands out as the most prevalent and effective method, entailing the application of a strong electric field to align the dipoles as desired. Piezoelectric sensors resulting from this process exhibit several desirable attributes, including low energy consumption, structural flexibility, heightened sensitivity, and a distinctive capacity for self-powered characterization [144], [145]. This unique combination of features has positioned piezoelectric sensors as a subject of increasing research attention.

Polarization has a notable effect on improving the output performance. However, challenges include imperfect alignment of the polarization orientation in piezoelectric materials, resulting in sensitivity to undesired force components [146]. Lee and Tarbutton [138], [147] pioneered

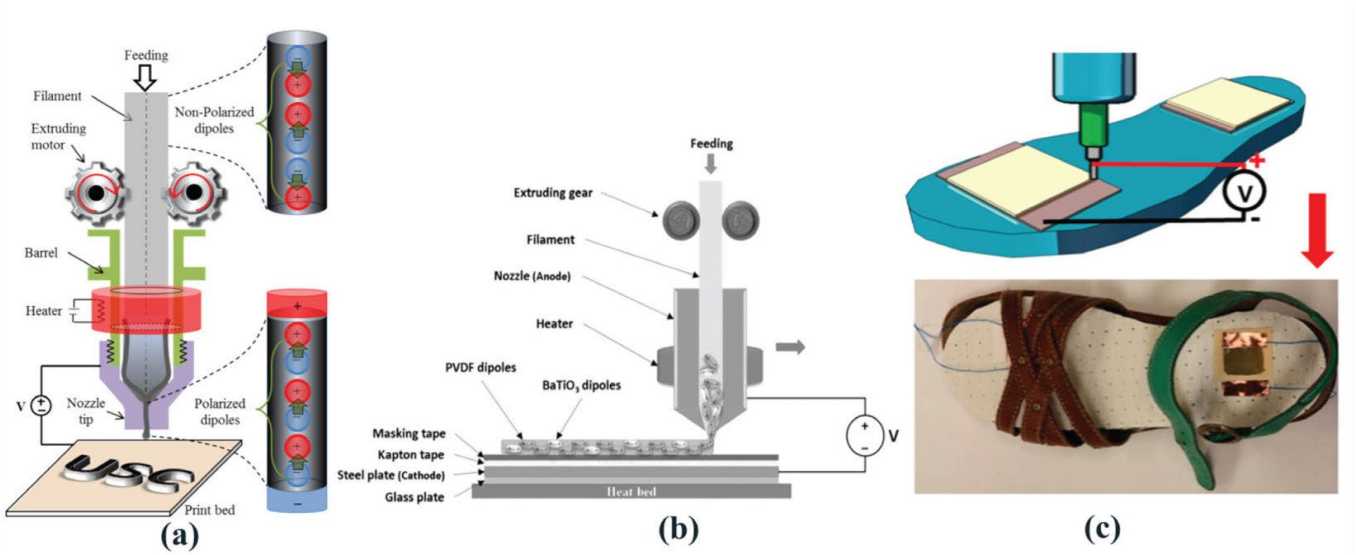

Fig. 9. Electric poling-assisted 3-D printing system development. (a) Schematic of electric poling-assisted 3-D printing process [138]. (b) Schematic of an in situ 3-D printing and dipole alignment of PVDF and barium titanate ($BaTiO_3$) filler [139]. (c) Schematic of an in situ poling setup for solvent evaporation 3-D printing [140].

the electric poling-assisted additive manufacturing (EPAM) process, enabling the printing of piezoelectric filaments by incorporating polarizing techniques, including mechanical stretching, heat press, and simultaneous electric field poling [Fig. 9(a)]. Subsequently, Kim et al. [139] proposed an advanced EPAM process that applies a higher electric field during the FFF process [Fig. 9(b)]. Their work involved fabricating PVDF-$BaTiO_3$ composites, leveraging $BaTiO_3$ ceramic filler in a PVDF matrix to enhance the piezoelectric response. The EPAM process underwent modifications to increase the maximum electric field capacity, facilitating improved polarization with an increasing number of layers while concurrently conducting in situ electric poling of PVDF-$BaTiO_3$ composites. Similarly, Bodkhe et al. [140] introduced a simultaneous approach integrating the DIW technique and in situ poling processes for manufacturing a piezoelectric pressure sensor using PVDF-$BaTiO_3$ nanocomposites directly on an insole [Fig. 9(c)]. Incorporating 10 wt% $BaTiO_3$ nanoparticles and applying an electric field of 1 MV $\cdot$ m^{-1} resulted in a remarkable 300% enhancement in piezoelectric charge output compared to printing unpoled neat PVDF. They also conducted tests demonstrating the fabrication of multilayer circular spiral, square spiral, and scaffold structures using both PVDF and its nanocomposite inks.

A DIW method is widely used in piezoelectric pressure sensor fabrication. Zhou et al. [148] developed a stretchable piezoelectric nanogenerator based on $BaTiO_3$ nanoparticles, PVDF-TrFE matrix, and silver flake-based electrode using the DIW method. Besides mounting on a sock and detecting different foot activities, the all-3-D printed device is demonstrated as a wearable energy harvester to harvest energy from body motion. Nassar et al. [149] presented a fully printed and packaged piezoelectric sensor using P(VDF-TrFE)-$BaTiO_3$ as the active material. The device exhibited a linear response in the working range of 0–60 kPa and remained stable under continuous operation for 2200 s. Using the DIW method, Pawar and Lim [150] employed PVDF and graphitic carbon nitrate composite to fabricate a printed sensor and nanogenerator, which demonstrated better performance without poling and generated a peak-to-peak high voltage. Using the FFF technique, Liu et al. [151] tested standard, cross, sandwich, and pyramid cells and finally achieved a 3-D printed piezoelectric sensor with fast response time, high sensitivity, and excellent linearity within a wide pressure range outperforming many 2-D film sensors. Numerous 3-D printed pressure sensors are used for plantar pressure detection (Fig. 10).

E. Other Pressure Sensors

In addition to the aforementioned commonly utilized mechanisms, advancements in 3-D printing techniques have facilitated the development of novel pressure-sensing technologies. Noteworthy examples include triboelectric sensors and FBG sensors.

1) Triboelectric Pressure Sensor: Triboelectric sensors exploit the triboelectric effect, generating an electric charge through contact electrification and electrostatic induction when materials come into frictional contact [Fig. 11(a)]. When two different materials make contact and then separate, electrons transfer from one material to the other, resulting in an electrostatic charge. The difference in charge generates a measurable voltage that corresponds to the applied pressure.

A variety of triboelectric materials, including polymers, metals, and dielectrics, can be utilized in different combinations. Zhu et al. [152] developed a 3-D printed triboelectric nanogenerator (TENG) comprising polytetrafluoroethylene (PTFE) film, nylon film, and a 3-D printed substrate. Utilizing the principles of friction electrification and electrostatic induction, this device effectively captures mechanical energy and monitors gait. A capacitor of 2 μF was charged to 1.92 V within 20 s, with voltage changes under different pressure conditions demonstrating its capability for weight monitoring. Rasel et al. [153] showcased a highly efficient method for

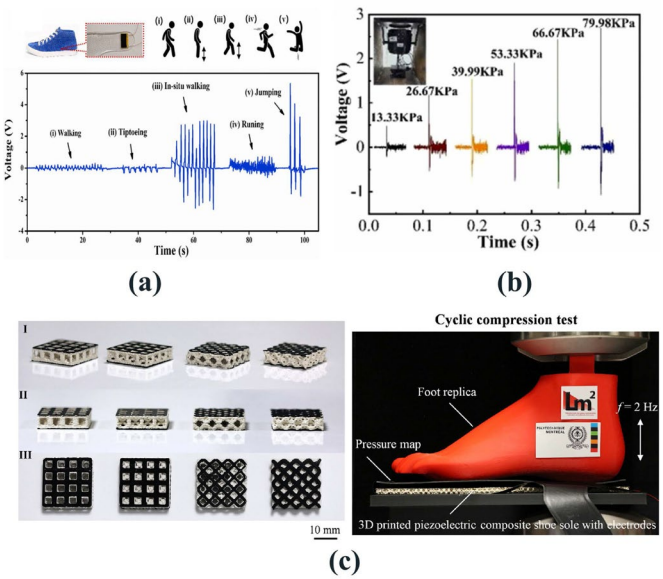

Fig. 10. 3-D printed piezoelectric pressure sensors for plantar pressure monitoring. (a) Photograph showing a four-layer pressure sensor integrated into an insole, with (i)–(v) representing different foot movement states and corresponding output voltages [142]. (b) Output signals of a pressure sensor under different excitation forces [143]. (c) Left: images depicting the investigated multimaterial 3-D printed piezoelectric nanocomposite lattices, including isometric, front, and top views. Right: cyclic compression test setup is shown, where a 3-D printed foot replica is clamped on the upper compressive head, the multimaterial piezoelectric nanocomposite shoe sole is placed on the bottom plate, and a pressure map captures the pressure distribution during the test [144].

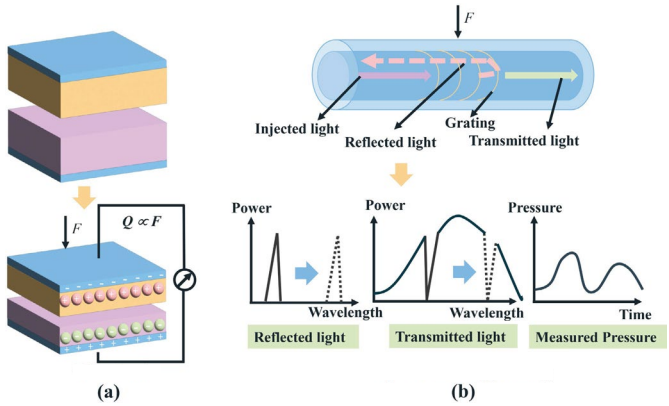

Fig. 11. Two other sensing mechanisms. (a) Triboelectric. (b) Optic: FBG.

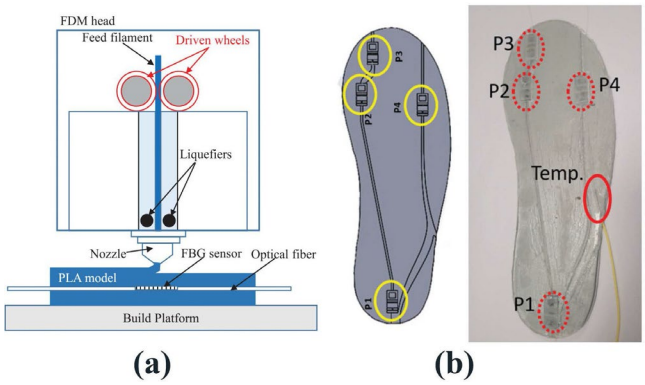

Fig. 12. 3-D printed FBG pressure sensors. (a) Schematic illustrating the use of the FFF method to embed an FBG sensor within a fused PLA model [157]. (b) Design of a PLA insole, featuring with four sensor cells and one temperature sensor [158].

detecting pressures ranging from 5 to 450 kPa, achieving a sensitivity of 0.51 V/kPa. Their FFF-printed structure maximizes the effective overlapping area between two horizontally aligned tribological layers by precisely positioning the top and bottom components, which contain the PDMS layer and PDMS-CNT nanocomposite layer, respectively. Integrated into a shoe insole, the sensor demonstrated potential for wearable foot pressure sensing across various human weights and walking motions.

2) Optic Pressure Sensor: FBG: In recent years, the development of optical pressure sensors has advanced significantly, driven by optical-based technology overcomes the problems of electromagnetic interference, hysteresis, and temperature drift, which are shared issues in the methods explained above [52]. These optical sensors operate by detecting variations in light properties, such as intensity, phase, or wavelength, induced by pressure changes [154].

FBG sensors, a notable subset of optical sensors, are particularly amenable to integration with 3-D printing technologies [155], [156]. The operational principle of FBG sensors involves injecting broadband light into an optical fiber that contains a periodic grating structure [Fig. 11(b)]. When pressure is applied to the FBG sensor, it induces a strain that alters the periodicity of the grating, resulting in a shift in the Bragg wavelength of the reflected light. This reflected light is analyzed to determine the pressure, whereas the remaining light continues to transmit through the fiber. The precise correlation between the shift in the reflected wavelength and the applied pressure allows for accurate and reliable pressure measurement.

The integration of FBG technology with the FFF 3-D printing method offers a powerful synergy, enabling the fabrication of customized, high-performance pressure sensors. Hong et al. [157], [159] demonstrated a method utilizing the FFF process to embed a simple FBG-based pressure sensor for monitoring vertical pressures [Fig. 12(a)]. The sensor, fabricated using PLA, was capable of measuring vertical pressures up to 800 kPa. The FFF process proved to be an effective and expedient encapsulation method, maintaining the FBG sensors' performance when embedded in melted PLA. These sensors were also applied to a platform for plantar pressure monitoring, showcasing their potential in wearable foot pressure applications [160]. Due to the flexible structure design of the FFF printing technique, Tavares et al. [158] presented an FBG-based sensing insole, which was capable of simultaneously measuring plantar force and shear force. The sensor cell, constructed from PLA and coated with an epoxy resin layer, incorporates an optical fiber with two inscribed FBGs. For the insole instrumentation, this sensor cell was replicated and strategically placed at four key points to analyze foot plantar forces [Fig. 12(b)]. This innovative approach is distinguished by its ability to simultaneously measure two directional forces with a high level of detail.

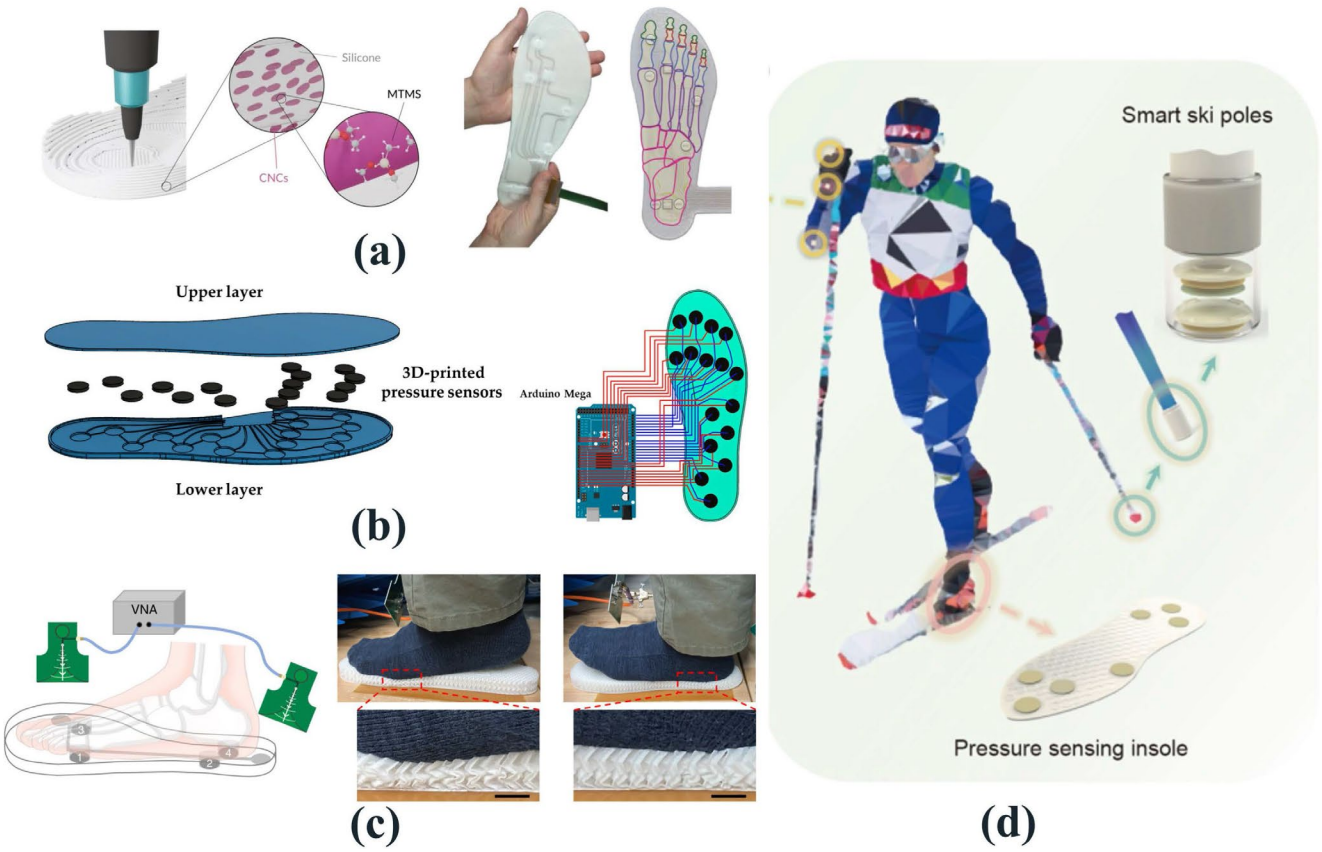

Fig. 13. Design and prototype of foot wearable devices using 3-D printed pressure sensors. (a) Schematic of the DIW printing process of the CNC-reinforced silicone resin used as structural ink and the fully 3-D printed insole with embedded sensors [123]. (b) Schematic of a 3-D printed smart insole with its general structure, electrical circuit, and image of the capacitive 3-D printed smart insole [125]. (c) Schematic for the experiment setup of the insole with four different locations of sensor blocks and two antennas connected to two ports of the insole device [161]. (d) Structure of a pressure-sensing insole and smart ski poles based on triboelectric sensors and their application in skiing sports monitoring [162].

IV. Case Studies and Practical Applications

The integration of 3-D printed sensors into plantar pressure monitoring has led to significant advancements in various fields, including clinical rehabilitation, sports science, and orthotic development. These technologies leverage the precision and customizability of 3-D printing to enhance the monitoring and analysis of plantar pressure and gait dynamics.

A. Diabetic Foot Ulcer Prevention

Several studies have demonstrated the effectiveness of 3-D printed plantar pressure sensors in preventing diabetic foot ulcers. For instance, Binelli et al. [123] have pioneered a novel approach to the manufacturing of custom 3-D printed insoles incorporating integrated piezoresistive sensors for comprehensive gait analysis [Fig. 13(a)]. Their development focuses on the use of advanced functional inks to create insoles capable of monitoring both normal and shear pressures experienced during human gait. By strategically positioning these sensors at locations customized to the individual patient's needs, the system allows for precise measurement and assessment of gait parameters under real-world conditions. The manufacturing process utilizes readily available feedstock materials and operates at room temperature using a desktop DIW printer, which enhances the cost-effectiveness and scalability of the technology. This approach facilitates the in situ adaptation of the insoles by healthcare professionals, making it feasible to integrate this technology into orthopedic practice. In addition, the use of biocompatible silicone in the ink formulations ensures that the resulting materials are safe for prolonged skin contact, offering flexibility and durability suitable for everyday use.

B. Clinical Rehabilitation

Three-dimensional printed pressure sensors have been effectively used in postsurgical rehabilitation to ensure proper healing and facilitate patient recovery. Samarentsis et al. [125], as discussed in Section III, developed a 3-D printed capacitive smart insole for measuring plantar pressure, and this was done by fabricating a novel FFF 3-D printed capacitive sensor array and evaluating its performance. The insole was tested and it has shown great results in differentiating between several gait phases. The insole is simply manufactured and cost-effective, and it has great potential in person-centered applications [Fig. 13(b)]. The data collected from the sensors enabled clinicians to tailor rehabilitation exercises and make necessary orthotic adjustments, leading to improved patient outcomes and faster recovery times.

C. Sports Performance Analysis

In sports, 3-D printed plantar pressure sensors have been employed to optimize athletic performance and reduce injury

risk. Kim et al. [161] developed a battery-free wireless pressure sensor using an origami structure. This platform, integrated with a 3-D printed smart insole, utilized inductor–capacitor sensors and a monopole antenna. The sensors, 3-D printed alongside the insole, achieved tunable sensitivity from 15.7 to 2.1 MHz/kPa for pressure ranges of 0–9 kPa and 10–40 kPa. Fabricated using FFF technology for the insole and DIW for the sensors, the final design is applicable in fields such as orthotics, prosthetics, and sports equipment [Fig. 13(c)]. The detailed pressure maps generated by this system provided insights for personalized training, improving running efficiency and reducing injury risk, demonstrating the potential of 3-D printed sensors in enhancing athletic performance through precise biomechanical analysis. Similarly, Yang et al. [162] developed a 3-D printed TPU-based flexible TENG with a personalized spatial structure, showing a strong correlation to external pressure. This device exhibited high sensitivity to joint-bending motions of the finger, wrist, or elbow. In addition, a pressure-sensing insole and a smart ski pole based on TENG were developed to create a comprehensive sports monitoring system, transmitting athletes' motion information from feet and hands via plantar pressure distribution and ski pole action [Fig. 13(d)].

V. Challenges and Suggestions

Even though remarkable research outcomes have reported various 3-D printing techniques for plantar pressure sensor design, customizable footwear systems based on 3-D printed pressure sensors have not been widely applied in daily practice yet. Some of the limitations of 3-D printed pressure sensors, along with the challenges, are discussed next.

1) *End-User Comfort:* In the current market, many pressure sensors lack the flexibility needed to accommodate curved foot interfaces. Three-dimensional printing technology utilizes additive manufacturing, building layer by layer. However, as the printing height and speed increase, the bond between layers weakens, leading to greater printing challenges, reduced accuracy, and weakened connections between printed parts. If some object models have complicated structures, their positions may require supporting structures, which can increase the printing complexity. Currently, for different foot sizes, there is no customizable solution to overcome this problem. Some wearable systems, such as socks and insoles, on the other hand, offer flexibility and portability and are suitable for both indoor and outdoor monitoring. However, they are primarily suited for situations that do not demand highly accurate measurements. Thus, identifying suitable soft and flexible materials for 3-D printing that exhibit both good mechanical properties and pressure-sensing capabilities can be challenging. The chosen material should have the required elasticity and sensitivity to pressure changes.
2) *Coherency:* Some research showed that even under the controlled 3-D printing environment, the sensor quality and properties still varied significantly [136]. Future work should focus on improving methods for consistently 3-D printing flexible filament, inks, or other materials, such as modifying the direct-drive extruder component of the printer so that the filament is extruded at a more constant rate.
3) *Durability:* Soft materials may be prone to wear and degradation over time, especially in applications with frequent or continuous outdoor use. Ensuring the durability and wear resistance of 3-D printed soft pressure sensors is essential for long-term reliability.
4) *Sensitivity:* It is easy to achieve high sensitivity in a limited pressure range, whereas the realization of sensitivity in a wide linearity region for high-performance piezoresistive sensors still presents a crucial challenge, especially when dealing with soft materials. The sensor's intricate structures and fine detail might be compromised, impacting the accuracy and reliability of pressure readings.
5) *Electrical Integration:* Incorporating electrical components, such as conductive fillers or sensor arrays, into the 3-D printed soft sensor without compromising its mechanical properties is a complex task. On the other hand, integrating the sensors into a circuit board using traditional or flexible connectors remains a challenge [163].
6) *Scaling Production:* Scaling up the production of 3-D printed soft pressure sensors for commercial applications may face challenges in terms of consistency, quality control, and cost-effectiveness.

To address the current challenges in footwear pressure applications, potential solutions have been proposed based on the current knowledge and state of the technology:

1) Four-dimensional printed pressure sensors present significant opportunities for integrating additional sensing functionalities, thereby paving the way for the development of intelligent load-bearing structures [164]. Through the 4-D printing process, precise control over fiber orientation is achieved, enabling tailored deformation of structures as needed [165]. Moreover, the integration of pressure sensors directly into the device during 4-D printing enhances cost efficiency and ensures robust structural integrity. With ongoing advancements in 4-D printing technology, the application scope of pressure sensors is expected to expand considerably, especially in the realm of wearable devices.
2) Advanced 3-D printing techniques have enabled the fabrication of composite lightweight structures such as pyramids, springs, and grids, surpassing the limitations of traditional layer-by-layer methods [166]. These advancements offer potential applications in hybrid construction, joining, and patch repair. Structural parameters, such as cell shape and infill density, significantly influence mechanical properties. Optimizing printing paths and topology allows for localized adjustments in fiber orientation and volume fraction, yet challenges persist in achieving continuous spatial optimization of these structures.
3) To mitigate the low durability problem, a systematic approach involving the selection or custom design of

materials with enhanced durability and wear resistance is warranted, with consideration given to factors such as friction, bending stress, and environmental exposure. Furthermore, the implementation of microstructures, supporting structures, and coatings presents a promising method to improve the sensors' resilience against wear and tear.

4) With the help of advanced design or simulation tools, such as artificial intelligence, 3-D printed pressure sensors' sensitivity can be better simulated across a wide linearity region, which can enhance the sensors' performance. Sensor array configurations can be considered to improve overall sensitivity and accuracy.
5) Collaborating with experts in electronics and sensor integration to design 3-D printable conductive materials and pathways can be a good method to solve the electrical integration problem. Efforts can be put into exploring flexible circuit technologies or integrating pre-manufactured electrical components seamlessly into 3-D printed structures. Using modular designs to simplify the integration of electronic components without compromising mechanical properties is also beneficial.
6) Automated processes can be implemented to maintain consistency in large-scale production. Advanced manufacturing techniques, such as robotic assembly or continuous 3-D printing, can be utilized to improve efficiency.

VI. Conclusion and Future Outlook

This article undertakes a comprehensive examination of 3-D printing techniques applied to plantar pressure sensing. It presents an overview of established 3-D printing methodologies, including FFF, DIW, MJ, and VP. Within this exploration, particular emphasis is placed on three fundamental pressure-sensing mechanisms—namely, piezoresistive, capacitive, and piezoelectric—highlighting their intricate interplay with various printing techniques. Moreover, this article addresses the challenges hindering the widespread adoption of 3-D printing in plantar pressure applications, along with suggestions to mitigate these obstacles.

The progressive development of 3-D printed foot pressure sensor-based monitoring techniques holds significant promise for applications in disease analysis and postsurgical rehabilitation. With the rapid evolution of flexible electronics, artificial intelligence, and advanced communication technologies, smart 3-D printed wearable pressure sensors designed for plantar pressure monitoring systems can be seamlessly integrated into daily life. Conceptualized as wearable devices, these 3-D printed pressure sensor-based footwear systems possess the capability to furnish vital foot plantar pressure data, serving as invaluable resources for health-related research and diverse applications.

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