electronics

Review

Flexible Fluidic-Type Strain Sensors for Wearable and Robotic Applications Fabricated with Novel Conductive Liquids: A Review

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Abstract: Flexible strain sensors with high sensitivity, wide sensing range, and excellent long-term stability are highly anticipated due to their promising potential in user-friendly electronic skins, interactive wearable systems, and robotics. Fortunately, there have been more flexible sensing materials developed during the past few decades, and some important milestones have been reached. Among the various strain sensing approaches, liquid-type (fluidic type) sensing has attracted great attention due to its appealing qualities, including its high flexibility, broad electrochemical window, variety in design, minimal saturated vapor pressure, and outstanding solubility. This review provides the comprehensive and systematic development of fluidic-type flexible strain sensors, especially in the past 10 years, with a focus on various types of liquids used, fabrication methods, channel structures, and their wide-range applications in wearable devices and robotics. Furthermore, it is believed that this work will be of great help to young researchers looking for a detailed study on fluidic strain sensors.

Keywords: fluidic-type sensors; conductive liquids; wearable; flexible; robotics

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1. Introduction

Flexible electronics is embarking on its journey by rapidly evolving in the field of electronics. The innovative methods of fabrication enable this field to be environmentally friendly, cost-effective, faster, and robust [1–4]. They can be reformed to tolerate mechanical deformations. They can bend [5], stretch [6], compress [7], twist [8], and warp [9] because the flex circuit or flex electronics are mounted on a flexible soft substrate [10]. Flexible electronics are becoming more popular since they are adaptable. They are inexpensive, customizable, and portable [11–15]. They have a whole new world of applications to set a benchmark, from collecting energy from temperature differences caused by our bodies and the environment, to folding phones, to wearable bioelectronics devices with sensors to evaluate and diagnose health issues [16–22]. They have huge potential for adoption in medicine, bioelectronics, or wearable devices [23].

Flexible devices draw great attention because of their efficiency, light weight, flexibility, and stretchability [24–28]. These devices are skin-friendly and made of soft materials attached to human skin, ensuring users' comfort as much as possible while wearing them [29–35]. They are used in bioelectronics to calculate wrist pulses [36], glucose [25], body motion [37–41], temperature [40,42], and other physiological signals [43]. Among these devices, sensors [44–46] are popular because they have a wide variety of applications in bioelectronics as well as healthcare. They play an important role in these wearable devices because of their having of the capability of guaranteeing the accuracy of signal capture. Highly elastic sensors have been encouraged by wearable sensors for human activity detection, whereas strain sensors are super elastic and highly stretchable for wearable devices [47]. Among these strain sensors, fluidic sensors have been recently used in wearable devices [33,39,48–52] and a few robotic applications [44,45].

Recently, fluidic strain sensors have been in high demand because of their ability to monitor and sense physiological signals and are vital because they are cost-effective, highly compliant, weigh little, and can sense complex environments [26,49,53–55]. Because of their high sensitivity, mechanical flexibility, and stretchability, these strain sensors normally function by utilizing the resistive effect of conductive liquid [39,40,45,52,56]. Fluidic strain sensors combine conductive liquids within a flexible substrate's narrow channel and fabricate specific patterns to improve stretchability [40,41,57]. Microfluidic strategies have been introduced lately because they are easy to fabricate with plastic and soft elastomers, and they are lightweight and consume less energy, which makes them suitable for large stretchable electronics [58]. Microfluidics is the main element in fluidic soft sensors. The conductive microfluidic fillers used by strain sensors can be ionic, metallic, or other chemically synthesized liquid solutions. Their detecting technique is based on the fact that when a particular amount of strain is given to the fluid, the fluid deviates from its original shape, allowing the sensor to perceive [59,60]. Flexible devices in challenging settings can use fluidic strain sensors in a broad range of ways. These sensors can be used in wearable electronics, surgical equipment, robot feedback sensing, and health monitoring systems [61–63].

Numerous studies and research projects have been conducted to develop highly stretchable fluidic soft sensors using a variety of fluidic materials, including ionic liquids (graphene [64], potassium iodide [65], sodium chloride [66]), metallic liquids (eutectic gallium-indium [67], gold [68], copper [69]), and other liquid solutions. Ions in liquid form have been proven to be conductive because they are free and in constant motion, which makes them a crucial component to use in strain sensors. When a proton travels from an acid to a base, ionic liquids are created [70]. On the other hand, metal atoms have delocalized electrons with a high energy level that can cause them to engage in conduction [71]. These liquids are fabricated on a soft substrate in a certain pattern or structure that directs the field flow and transition of the kinetics of different microstructures of these liquids used in the fluidic sensors. These patterns are created using different techniques such as lithography, 3D printing/screen printing, and direct inking. These patterns are of different shapes, such as sinusoidal [44,45,60], square [72–74], rectangle [75,76], wavy [39,44,77], and other patterns. Despite very few recent studies on liquid-type strain sensing devices, it is evident that the pace of research in this particular field is quite high. Furthermore, it is pertinent to consolidate all recent works and provide a comprehensive review to the research community.

This review presents the comprehensive progress of fluidic strain sensors with an in-depth analysis of various conductive liquids used, in addition to the channel structures. All liquid categories, such as ionic, liquid metal, and other conductive liquid solutions have been well explored, including their chemical, physical, and mechanical properties. Furthermore, different structures (recently reported) have been discussed in detail with a focus on their advantages and disadvantages in the sensor's performance. Figure 1 represents the overall sections covered in this study. In addition, detailed tables of comparison with a wide number of attributes, such as stretching, memory effect, gauge factor, operable frequency, simulations, targeted applications, and other relevant parameters have been provided. To the best of our knowledge, this review will be the first dedicated effort to cover almost all major topics related to fluidic type strain sensors, including wearable and robotics applications (the numbers of researches selected in this study is graphically presented in Supplementary Figure S1).

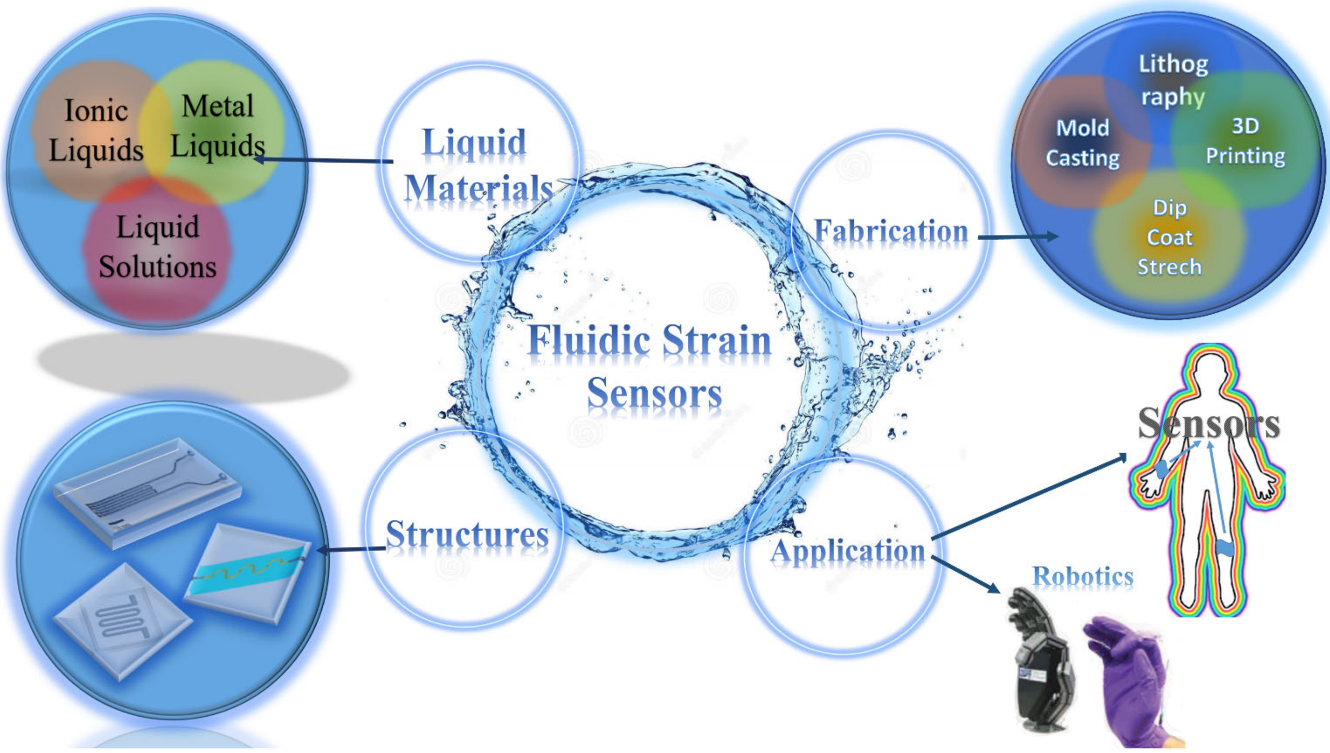

Figure 1. Classification of fluidic type strain sensors fabricated by exploiting either of channel structures, liquid materials, manufacturing approach, and targeted applications.

2. Conductive Liquids for Strain Sensing

The fluids in liquid strain sensors are used to help with the strain stretchability. When a certain amount of strain is applied to liquid-containing devices, its resistance varies and converts the applied stimulus into electrical resistance that as a result gives us certain stress or strain. These fluids are conductive and are embedded inside a soft elastomeric material.

2.1. Ionic Liquids

Ionic liquids (ILs) were first discovered in the year 1914 by Paul Walden, who discovered ethyl ammonium nitrate, but they did not gain much recognition at that time. In the past two decades, ILs have attracted a large amount of interest due to their unique features [78]. They are salts that are composed of ions in the form of liquid and have the properties of non-flammability, high ion conductivity, and high thermal stability, and are mostly biocompatible. Moreover, they are known for their low vapor pressure, high electro-elasticity, and liquid crystalline structures. These liquids have melting points below room temperature or below 100 °C [79]. Ionic liquids are composed of organic cations and inorganic anions. To maintain the liquid state, the cations should be unsymmetrical [80]. These ionic liquids are further divided into categories, such as room temperature, ionic liquids (RTILs) [81–84], supported ionic liquid membranes (SILMs) [85–87], task-specific ionic liquids (TSILs) [88,89], and polyionic liquids (PILs) [90]. They have lower symmetry and have been widely used to design sensors, especially fluidic strain sensors. Table 1 shows the comparison of strain sensors fabricated by using different ionic liquids

An Ionic-based fluidic strain sensor for wearable devices has been reported [40] as shown in Figure 2a, which uses potassium iodide and glycerol solution (KI-Gly solution) as an ionic liquid on a soft silicon substrate and has durability and flexibility for up to 1000 cycles. The flexibility of the sensor is shown in Figure 2a(i) where the designed sensor is in its original state, whereas Figure 2a(ii,iii) represent the stretching and bending of the sensor, respectively. This sensor was developed under a multilayer structure and used microcylinder fillers in the channel along with the stiffed substrate to help with sensitivity and linearity. Similarly, Zhou et al. in [41] used glycerol and graphite suspensions in polydimethylsiloxane (PDMS) tubes, which have the capability to increase the conductivity by simply pinching and stretching the tubes. These tubes were then knotted, responding to local as well as global stimuli. The orientation of these packed fillers was shown to be controlled by the flow field direction and the packing structure of the graphite fillers, which showed memory effects on the shear history. Further, in a recent study [51], reduced graphene oxide and deionized water (rGO/DI) have been introduced within a soft Ecoflex substrate, enabling it to retain its stretchability for more than 10,000 cycles. The reduced graphene oxide form has a reversible micro-contact condition, helping them calculate the resistance of the strain. The sensing behavior of this liquid is analyzed in Figure 2b where the pressure was applied to the rGO/DI liquid. Figure 2b(i) shows the original state of the liquid, whereas Figure 2b(ii,iii) show the behavior of the liquid under 5 kPa and 10 kPa, respectively. Similarly, Figure 2b(iv) shows the original state of the liquid after being refreshed, and then the mechanism of the liquid was analyzed under 5% strain and 10% strain, as shown in Figure 2b(v,vi), respectively. The designed sensor has great sensitivity and is suitable for stretching and bending applications such as human motion detection, including drinking, speaking, and clenching.

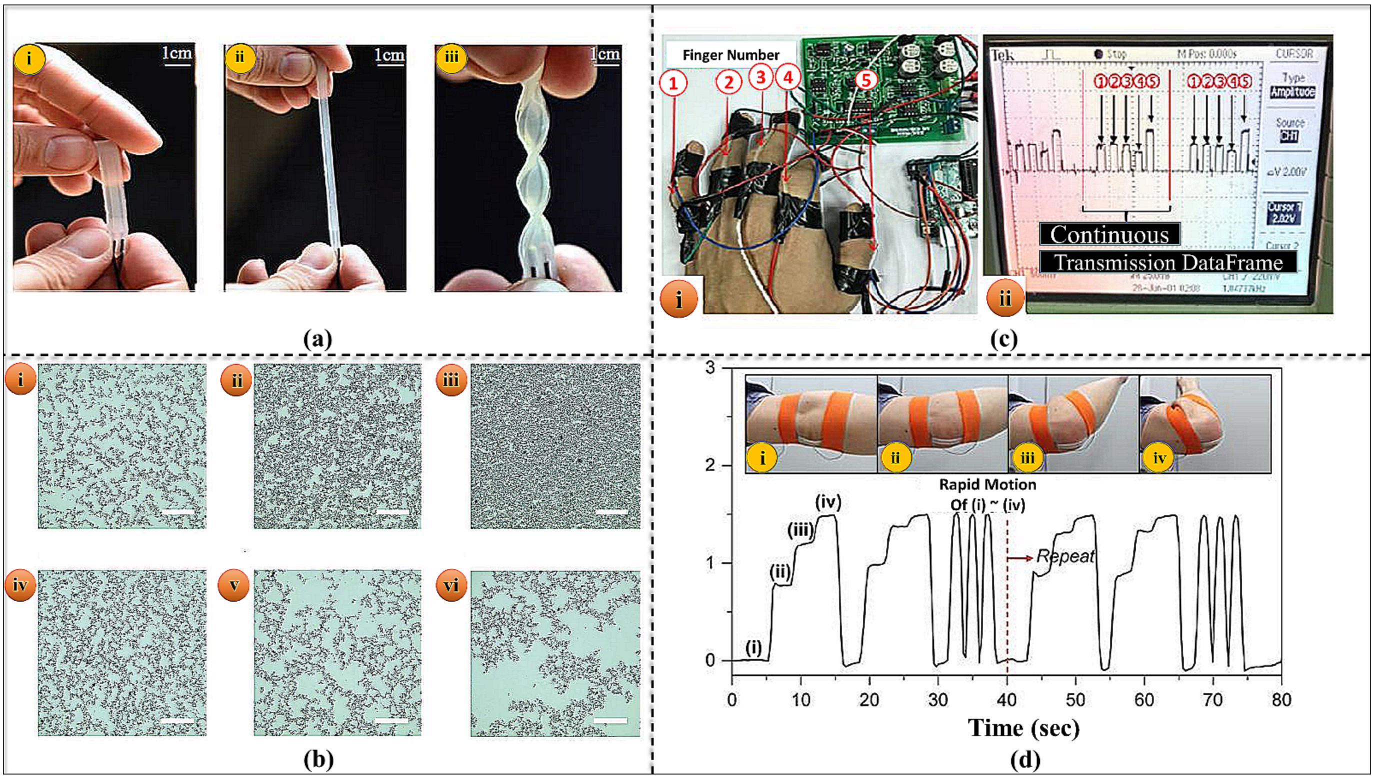

Figure 2. Conductive ionic liquid-based strain sensors: (**a**) a highly stretchable strain sensor's bending and twisting deformation [40]. (**i**) originl state (**ii**) stretching (**iii**) bending (**b**) rGO/DI ionic liquid behavior under applied strain [41]: (**i**) original state, (**ii**) under 5 Kpa, (**iii**) under 10 KPa, (**iv**) refreshed to obtain the original liquid state, (**v**) liquid under 5%, and (**vi**) under 10% strain. (**c**) The result of the 5 sensors attached to the fingers were analyzed through oscilloscope [91]. (**i**) evaluating the motion of the finger (**ii**) analyzing dataframes in oscilloscope (**d**) Analysis of the bending of the strain sensor [39]. (**i**) original state (**ii**) slightly bending the elbow (**iii**) normal bending (**iv**) complete bending.

On the other hand, a low-cost, highly flexible sensor with aqueous sodium chloride and glycerin-sealed, gold-coated electrode mixture filled inside the silicon tube was presented in [91]. The sensor has a negative temperature coefficient that reduces the gauge factor from 2.1 to 1.6 with the rise in temperature. This factor should be improved to make it applicable for wearable applications. Each finger and the thumb are attached to the sensors to evaluate the motion of the fingers, for which the analogue-switching IC was attached in the circuit designed for providing AC source to the sensors, as is shown in Figure 2c(i); the oscilloscope then shows the data frames that were sent from the controller to the server. The finger motion affects the amplitude of the sensor, as is shown in Figure 2c(ii).

However, Choi et al. in their work [39] presented a strain sensor using ethylene glycol/sodium chloride ionic solution within a soft substrate of Ecoflex-0030 for a highly stretchable sensor for up to 300% strain over 3000 cycles. Ethylene glycol was preferred in the study because of its electrochemical stability and low vapor pressure, which is ideal for this sensor because its operating voltage is 4 V and its low vapor pressure is suitable for long-term stability. This sensor has high durability and low hysteresis. The sensor is attached to the elbow joint through the adhesive tape to analyze the motion as shown in Figure 2d(i) where the sensors is attached to the elbow. Similarly Figure 2d(ii,iii) shows that the sensor is bended slightly and normally respectively. Whereas Figure 2d(iv) shows the full bending of the elbow. The results of these motions are analyzed in real-time. The resistance is increased with the bending of the elbow joint and remains the same when the sensor is flexed. The maximum strain is recorded with the bending of elbow joint is 70%. A similar study [31] showed the strain sensor using the graphene/glycerin solution sandwiched in an ecoflex rubber, and is highly stretchable as shown in Figure 3a(i), having a gauge factor of 45.13. The sensor is bendable and twistable as shown in Figure 3a(ii,iii) respectively. The IL solution has a self-lubricating property that makes it super stretchable for up to 1000% over 10,000 cycles. The resistance of this strain sensor is calculated with the change in graphene flaxes. The resistance decreases with the increment in conductive graphene flaxes and increases with the decrement in graphene flakes.

Moreover, the sensor discussed in [92] is unique and different in terms of manufacturing/fabrication and design methodology. The sensor uses ILs of different types, namely, IL1: 1-butyl-3-methylimidazolium trifluoromethanesulfonate (([BMIM][Otf]), IL2: 1-butyl-3-methylimidazolium dicyanamide ([BMIM][N(CN)2]), and IL3: 1-ethyl-3-methylimidazolium dicyanamide ([EMIM][N(CN)2]), for the fabrication of the sensor but they were removed later on, leaving only the IL on the edge and replacing them with air, causing an ultra-high cross-sectional area. Furthermore, conductive polymer nanocomposites (CPNC) with carbon nanofiber (CN) and 1-butyl-3-methylimidazolium hydrogen sulfate [BMIM][HSO4] ionic liquid (IL) as fillers were introduced in [93] to design a strain sensor; the schematic diagram of the PVDF(matrix)/CNP(conductive fillers) membrane filled with IL is shown in Figure 3b. The IL, along with CN and CPNC, has helped in the durability of the strain sensor with a high gauge factor of 4.08.

The advancement in ionic-liquid-based strain sensors has been proven to be ideal in the world of strain sensors. A microfluidic strain sensor [94] with 1-butyl-3-methylimidazolium bis-(trifluoromethanesulfonyl)imide ([BMIM][Ntf2], Sigma-Aldrich) and 1-butyl-3-methyli midazolium acetate ([BMIM][Ac], Sigma-Aldrich) ionic liquid mixtures embedded inside the polydimethylsiloxane (PDMS) matrix aimed to achieve high stretchability and low hysteresis. When external force is exerted on the sensor, it produces distinct changes in the electrical signal caused by different motions such as bending, stretching, and torsion. Similarly, the mixture of conductive ionic liquid of sodium chloride with glycerin within the elastomeric material to increase the stretchability of up to 40% of the strain sensor is presented in [57]. The strain sensors' sensing mechanism relies on electrochemical impedance spectroscopy (EIS) at different applied frequencies and strains. Conversely, conductive sodium chloride (NaCl) liquid inside the soft elastomer substrate along with the gold-sputtered electrodes to enhance the biocompatibility is presented in [49]. The sensor proposed a strain of 40%, 21.34% hysteresis, and is completely soft, making it desirable for highly stretchable medical applications. The piecewise constant curvature technique is used to construct the sensor in a STIFF FLOP surgical manipulator for application purposes. Furthermore, the detail analysis of studies published is provided in Supplementary Data.

1-Decyl 3-methyl imidazolium chloride (DMIC) (Sigma-Aldrich, Germany), along with conductive carbon black (CB)-filled conductive rubber composites (CRCs), were introduced in [95]. The IL here was used to increase the sensor's consistency as well as the flexibility of the composites. Similar work was conducted in [96] using the same ionic liquids and carbon black (CB), but instead of CRCs, styrene-butadiene rubber was used to achieve the stretchability of the ionic strain sensor. The schematic illustration of bound rubber with ILs is represented in Figure 3c, where the red line represents the pathways the electrons can move to work as a conductive material.

Another highly stretchable (for up to 100% strain over 8000 cycles) strain sensor composed of glycerol and potassium chloride (Gly-KCl) ionic liquid in an Ecoflex 00-30 elastomeric substrate has been presented in a recent work [45]. The testing was conducted using a custom-made tensile testing machine under relative humidity, making it suitable for underwater robotic feedback as well as wearable applications. Furthermore, 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonylmide) ([EMIM][TFSI]) ionic liquid with an Ecoflex polymer in a PDMS mold was fabricated in [48]. The sensor has a wide range of strain from 0.1% to 400% with a gauge factor of 7.9. The sensor accurately identifies factors such as breath, swallowing, and others such as finger and wrist movement capturing. The sensor is attached to the back of the wrist and elbow joint detecting the bending and movement of it by representing change in resistance, as is shown in Figure 3d. Similarly, a novel 1-butyl-1-methylpyrrolidinium bis(trifluoromethylsulfonyl)imide ionic liquid-based sensor in a silicon tubular microchannel has been introduced [50], where the ionic liquid was inserted into the silicon tube where then the copper electrodes were placed at both ends of the tube, sealed by medical-grade epoxy (Epotek 302M) to achieve the strain sensor.

A 1-butyl-3-methylimidazolium tetrafluoroborate ([BMIM][BF4], Sigma-Aldrich) and EG ethylene glycol (Sigma-Aldrich)-based ionic liquid-based strain sensor is presented in [97]. The sensor used a mixture of IL and EG instead of using pure IL, which makes it highly durable with a gauge factor of 2.3 under 200% strain. The microfluidic is injected inside the soft PDMS and Ecoflex materials, showing great compatibility with ethylene glycol.

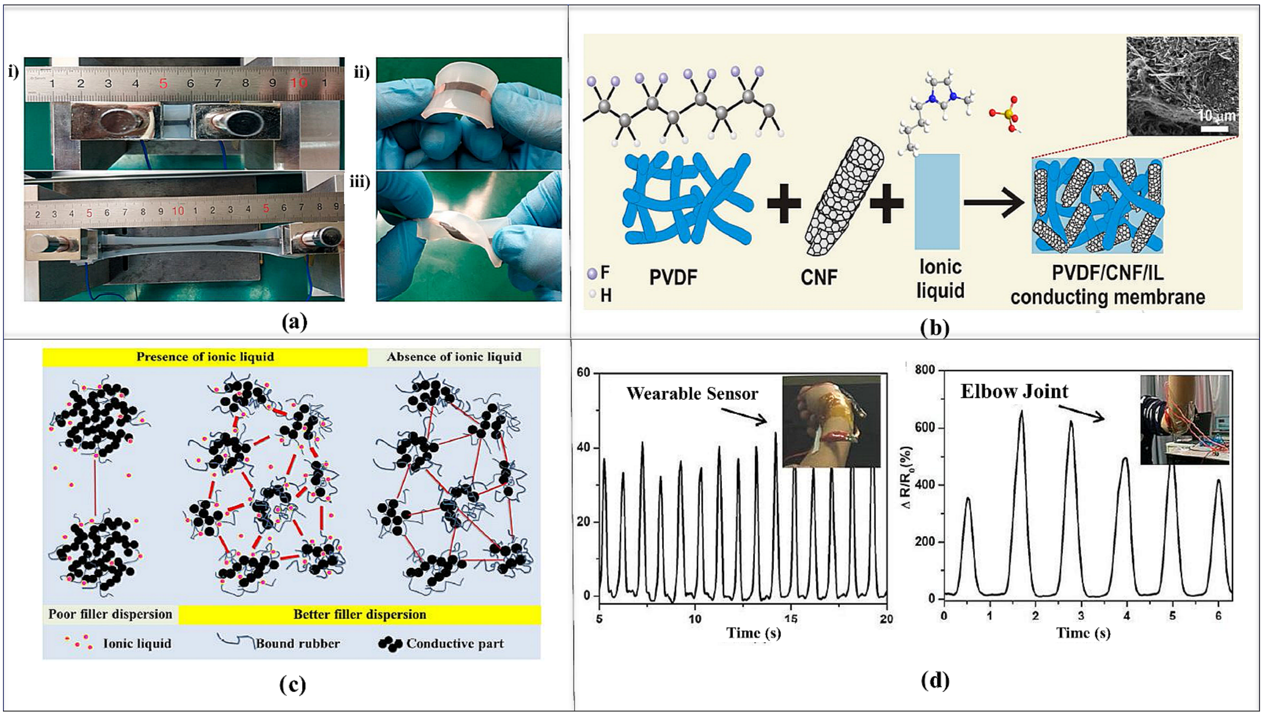

Figure 3. Conductive ionic based strain sensors: (**a**) representation of the designed strain under (**i**) stretching, (**ii**) bending, and (**iii**) twisting [31]; (**b**) the conductive material made when IL was added to the PVDF and CNF membrane [93]; (**c**) the schematic diagram representing the effect of IL on the bound rubber [96]; (**d**) the resistive change by the movement of the strain sensor [48].

Table 1. Comparison of strain sensors based on different ionic liquids.

Sensing Liquid	Stretchable Substrate	Strain	Strain Speed/ Frequency	Hysteresis	Gauge Factor	No. of Cycles	Optimization through Simulation	Ref.
Graphene/glycerin	Ecoflex	1000%			45.13	10,000	No	[31]
Ethylene glycol/NaCl	Ecoflex	250%	–	6.52%	<4	3000	yes	[39]
Potassium iodide and glycerol solution (KI-Gly)	Silicone rubber EcoFlex 0030			5.3%	2.2	1 Hz	No	[40]
Graphite/glycerol	Elastomer PDMS	100%					electro-rheological testing module	[41]
Gly-KCl (glycerol and potassium chloride)	Ecoflex	100%	5 Hz	4.23%	2.7	8000	Yes	[45]
1-Ethyl-3-methylimidazolium bis(trifluoromethylsulfonylmide) ([EMIM][TFSI]) ILs	Ecoflex	400%			7.9	1500	No	[48]
Sodium chloride (NaCl) solution	Gold-sputtered electrodes	64%		21.34% of resistance			No	[49]
(1-Butyl-1-methylpyrrolidinium bis(trifluoromethylsulfonyl)imide	Silicone tube (DOW Corning Q7-4750)	10% and higher			2 and 2.5			[50]
rGO (reduced graphene oxide)/DI (deionized water)	Ecoflex	400%		-	31.6	<10,000 for stretching, >15,000 cycles for pressuring	No	[51]
Glycerin with aqueous sodium chloride	Elastomer	40%					No	[57]
Aqueous sodium chloride and glycerin	Silicone tube	50%			2.3			[91]
IL1: 1-butyl-3-methylimidazolium trifluoromethanesulfonate (red), IL2: 1-butyl-3-methylimidazolium dicyanamide (blue), and IL3: 1-ethyl-3-methylimidazolium dicyanamide (black)	PDMS	(0–15%)		<1.5%	3000	720	No	[92]

Table 1. *Cont.*

Sensing Liquid	Stretchable Substrate	Strain	Strain Speed/ Frequency	Hysteresis	Gauge Factor	No. of Cycles	Optimization through Simulation	Ref.
1-Butyl-3-methylimidazolium bis-(trifluoromethanesulfonyl)imide ([BMIM][Ntf2], Sigma-Aldrich) and 1-butyl-3-methylimidazolium acetate ([BMIM][Ac], Sigma-Aldrich)	PDMS elastomer	(Min < 50%) (max = 200%)	Average 3.9 mm/s	Negligible, average DH 2.41%	Min at 2, max at 40		No	[94]
1-Decyl-3-methyl imidazolium chloride (DMIC)	Styrene-butadiene rubber (SBR)	5%	10 Hz	-	30	-	No	[95]
Ethylene glycol (EG) and ionic liquid (IL)	PDMS	200	16.667 mm/s (highest)	0	2.3		No	[97]
1-Decyl-3-methyl imidazolium chloride (DMIC)	Styrene-butadiene rubber (SBR)	7.5%				100	no	[96]

2.2. Metal Liquids

Metal liquids are fluids made up of alloys that form a eutectic at low temperatures. They may be easily identified by their liquid formation and electrical, thermal, and mechanical conductivity. They are necessary for flexible sensing because of their interfaces. Liquid metals Ga (gallium) along with its alloys have good conductive properties and have utmost flexibility, which is why they have now been widely used in flexible sensors. Different experiments and research have been conducted where metal liquids have been utilized in strain sensors. The comparison of metallic liquid-based strain sensors is given in Table 2.

Table 2. Comparison of strain sensors based on different metal liquids.

Sensing Liquid	Stretchable Substrate	Strain	Strain Speed/ Frequency	Hysteresis	Gauge Factor	No. of Cycles	Optimization through Simulation	Ref.
Galinstan (Ga67, 3In19, 2Sn13.5)	PDMS	105%	58 ms	0.07	2.33	8000	no	[72]
Eutectic gallium–indium	PDMS	160%			3.2		no	[73]
Liquid metal eutectic gallium indium (EGaIn)	Ecoflex 00-30	320%	116 ms	1.02	4.91	500	no	[77]
Liquid metal-like Ag NP ink	PDMS	800%	0.5 Hz		6.5 at 100% strain, 9.3 800% strain	5000	yes	[98]
Ni-doped liquid metal (Ni-GaI	Ecoflex 0030 Ecoflex 0030-ZnS	10, 50, 100%				200	no	[99]

Table 2. *Cont.*

Sensing Liquid	Stretchable Substrate	Strain	Strain Speed/ Frequency	Hysteresis	Gauge Factor	No. of Cycles	Optimization through Simulation	Ref.
Eutectic gallium-indium (EGaln)	Ecoflex	550%			4.95		Yes	[100]
EGaln ferromagnetic Ag−Ni microparticles.	Polydimethylsiloxane (PDMS)	60%			0.077		No	[101]
Two layers of liquid-metal-alloy-filled microfluidic channels	Silicone elastomer	15%	1.5 GHz	0			no	[102]
A gallium-based eutectic alloy	Ecoflex 00-30, Smooth-On	350%				50	no	[103]
Eutectic alloy of gallium, indium, and tin (62.5% Ga, 21.5% In, 16% Sn) sonicated at 0.4 kJ/g with 2 wt % nickel nanoparticles	Smooth-On Ecoflex 30	200		0		375	no	[104]
Gallium, indium, and tin	PDMS	13–25% and 25–40%				3500	no	[105]
Gallium–indium–tin eutectic	PDMS	0.3%	300 mm/s	0.11	2.2	3500	no	[106]
—-	PDMS				0.8		no	[107]
EGaIn	Ecoflex 00-30	178%	120 ms	1.14%	3.04	100	no	[108]

The super elastic sensor introducing low hysteresis using conductive liquid metal eutectic gallium–indium (EGaIn) with the Ecoflex 00-30 was introduced in the study of [77], retaining the durability of 320% with the gauge factor of 4.91 over 500 cycles. The sensor is wearable and was tested by it being worn on an index finger and by analyzing the resistance change of the sensor by grasping different things of different sizes, as shown in Figure 4a(i–iii). The greater resistance was detected when the smallest object was grasped, causing maximum bending. Huang et al. [98] introduced the liquid metal-like Ag nanoparticle ink-based strain sensor with PDMS material using 3D printing technology to attain a high stretchability of 800% over 5000 cycles. The sensor was tested by designing the stretchable led circuit to test the strain at 0, 200, 400, 600, and 800%, as shown in Figure 4b. Furthermore, liquid metal gallium–indium (GaIn) doped in Ni incorporated between Ecoflex 00-30 and Ecoflex 00-30 ZnS was introduced in [99] using a three-axial printing method to gain the strain of 160% with the gauge factor of 3.2. This wearable sensor had been worn on each finger as well as the thumb of the hand to analyze the real-time behavior of the sensor, as shown in Figure 4c.

A metallic liquid eutectic gallium–indium (EGaln)-based strain sensor with high durability and skin accountability, having a gauge factor of 4.95 along with a strain of 550%, was introduced in [100]. The study chose lithography techniques to achieve the microfluidic channel to obtain desirable size and flatness with metallic liquid and Ecoflex soft substrate. Another similar study with the liquid metal eutectic gallium–indium (EGaln) incorporated in a polydimethylsiloxane (PDMS) film with a strain of 50% under electronics properties is presented in [101]. The study proposed the *z*-axis conductors along with liquid metal because of their transparency and bonding properties, which eliminated the manual wire insertion process. This is because the manual wire insertion procedure causes disasters such as LM leakage, wire slip out, and labor intensiveness, as discussed in the paper. Conversely, Cheng et al. presented a whole new approach to a wireless strain sensor using multi-layer microfluidic stretchable radiofrequency electronics (µFSRFEs) along with PDMS material with an elongation of 15% reported in a recently published study [102]. The sensor has a patch antenna with two LM channels that are deformable as well as reversibly stretchable and applicable for larger areas (around 100 cm^2).

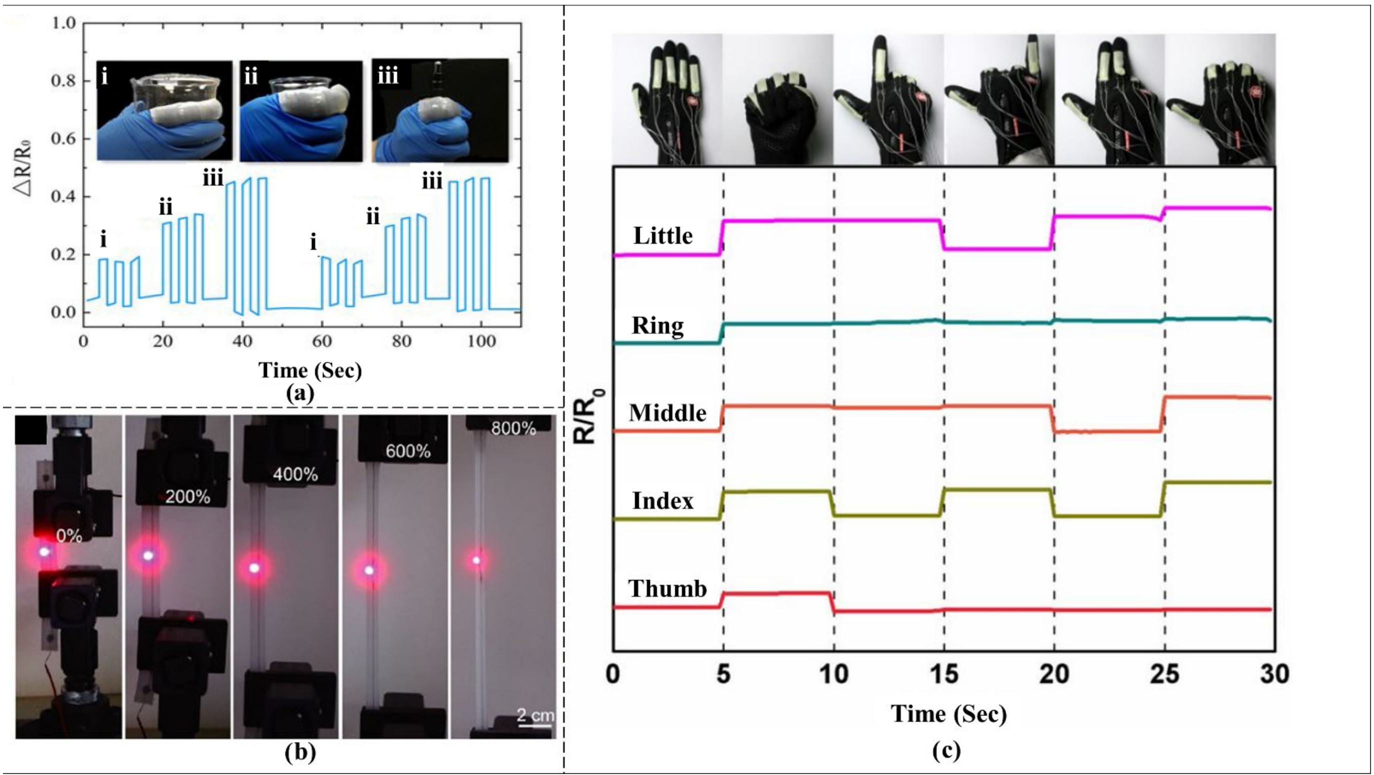

Figure 4. Conductive metal liquid-based strain sensors: (**a**) analyzing the resistance change of the sensor at different sizes [77]; (**i**) analyzing resistance change through bending an index finger by grabbing a large object; (**ii**) medium object; (**iii**) and small object (**b**) testing the stretchability at different strains [98]; (**c**) real-time analysis of the change in resistance by movements of the fingers [99].

However, Wu et al. in [72] presented a strain sensor that uses conductive Galinstan metal liquid with a PDMS substrate for a highly stretchable sensor with a strain of 105% over 8000 cycles designed for a variety of applications in health, monitoring, and gaming. Similarly, gallium-based eutectic alloy metallic liquid with a soft substrate (Ecoflex 00-30 and Smooth on) was introduced in [103] using the shrink stretch patterning (SSP) method to achieve high stretchability (350%) for about 50 cycles. The designed sensor with liquid alloy is shown in Figure 5a(i), along with the performance measurement of the sensor in 20-time cycles, as is shown in Figure 5a(ii). In Figure 5a(iii), the sensor is demonstrated in a real-time scenario by connecting the sensor at the left wrist in the direction of the palm to analyze the motion of the sensor.

A eutectic alloy of gallium, indium, and tin as a liquid metal used in a 3D printed approach to design a strain sensor with Ecoflex soft material retaining stretchability (200%) for over 375 cycles was introduced in [104]. The sensor was attached to the elbow joint of the hand and was bent at a certain angle to analyze the behavior and stretchability of the sensor through a 4 wire ohmmeter (HP 34401A), as shown in Figure 5b. The sensor was pre-strained at 50% in order to keep it in tension; Figure 5b(i) shows the bending of elbow several times at different angles (45°, 70°, and 120°), whereas Figure 5b(iii) shows the repeated flexion of elbow at 120°. Similar work has been conducted by Hu et al. in [105] using gallium, indium, and tin (GaInSn) liquid metals incorporated between the PDMS material and magnetorheological elastomers (MREs) for the detection of comprehensive force as well as the magnetic field. The sensor has stretching and bending capabilities. When an external force is applied, the sensor becomes impacted, making it a magneto-resistive sensor as well. Wu et al. in [106] introduced a high-performance strain sensor, realizing the young moduli's match between the soft substrate (PDMS) and inorganic conductor (GaInSn) liquid metal fiber. The sensor retains its gauge factor of 2.2 over 3500 cycles. The sensor is practical and is wearable on the skin to monitor the bending motion, such as with the sensor being attached to the wrist, index finger, elbow joint, and knee joint to demonstrate and analyze the position of the sensor, as is shown in Figure 5c. The resistive change was analyzed by bending of the finger in real time, as shown in Figure 5c(i), whereas the senor was also attached to the wrist and the relaxative motion was detected from a certain angle (0 to 90°), as shown in Figure 5c(ii), as well as the motion being detected for a wiggle elbow, where the result is demonstrated in Figure 5c(iii). The sensor was then attached to the knee joint to detect the change in resistance during continuous marching (Figure 5c(iv)) and squatting (Figure 5c(v)). The 13, 9, and 6 s chinnings in frequency were identified during frequency detection (see Figure 5c(vi)).

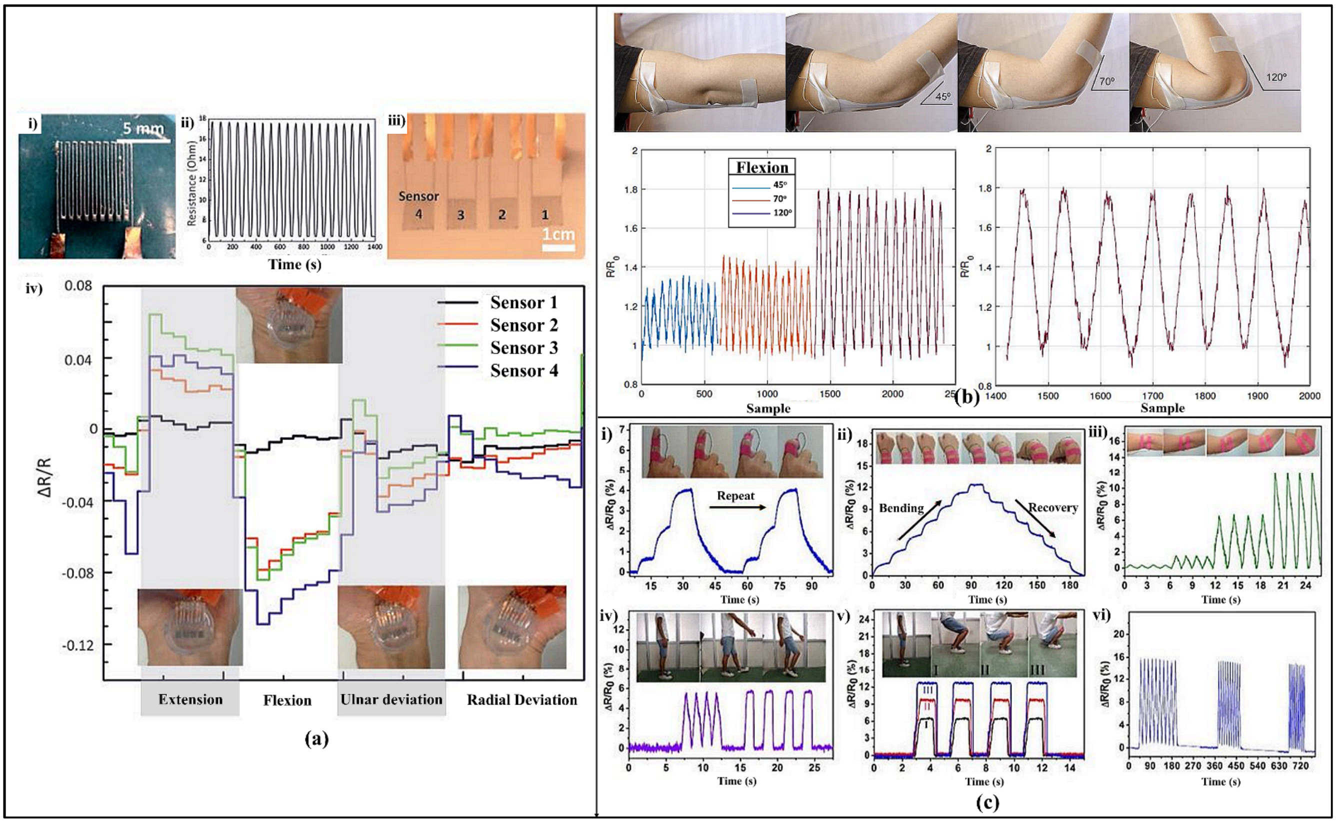

Figure 5. Conductive metallic liquid-based strain sensors: (**a**) Fabrication and demonstration of strain sensor: (**i**) designed strain sensor with liquid alloy; (**ii**) performance measured; (**iii**) fabricated strain sensor array; (**iv**) demonstration of the real-time response of 4 wearable strain sensor [103]. (**b**) Testing the bending and analyzing the result of strain sensor [104]. (**c**) Real-time monitoring of finger bending, wrist motion, elbow wiggle, and knee joint [106]. (**i**) analyzing the resistive change; (**ii motion detection of wrist**); (**iii**) motion detection of wiggle elbow; (**iv**) motion detection of knee joint (marching); (**v**) motion detection of knee joint (squating); (**vi**) frequency detection.

Another work was conducted by Yan et al. in [73] that was based on eutectic gallium–indium conductive metal liquid for stretchable strain sensors along with PDMS material to attain stretchability (160%) with a gauge factor of 3.2.

A micro finger was reported in [107] consisting of a pneumatic balloon actuator (PBA) and a strain sensor using liquid metal. The sensor detects the bending motion of a PBA and is highly stretchable, having a gauge factor of 0.8.

Yan et al. [73] introduced the stretchable cable behaving as a strain sensor for motion detection, designed by using EGaIn liquid metal with PDMS material to achieve stretchability of more than 350%. Similar work has been conducted by Liu et al. [108] where EGaIn liquid metal was used to design a strain sensor along with an Ecoflex 00-30 soft substrate used to measure the strain up to 170%.

2.3. Chemically Synthesized Liquid Solutions

Apart from ionic and metal liquids, other liquids have been introduced into the world of flexible strain sensors, such as multi-walled carbon nanotubes (MWCNTs), which have been gaining more popularity in fluidic strain sensors. MWCNTs are made when single-walled carbon nanotubes are combined, enhancing their electrochemical properties along with their thermal properties. This liquid solution has been proven to be highly conductive and hence desirable in the fabrication process of many fluidic sensors. Table 3 shows the comparison of strain sensors based on different liquid solutions.

Table 3. Comparison of strain sensors based on different liquid solutions.

Sensing Liquid	Stretchable Substrate	Strain	Strain Speed/ Frequency	Hysteresis	Gauge Factor	No. of Cycles	Optimization through Simulation	Ref.
Liquid polymer PEDOT:PSS	Polydimethylsiloxane (PDMS)	30%	0.1, 0.25, and 0.75 mm/s	<9%	12,000		Yes (Labview controlled strain generation setup)	[37]
Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate multiwall carbon nanotube (PEDOT:PSS/MWCNT)	Ecoflex	150%	10	1.56%	89.4	1000	No	[44]
DI EG30 EG45 EG55	PDMS	1%				200	No	[74]
Blood mimicking fluid (BMF)	CB-PDMS (carbon black—polydimethylsiloxane)	50%			5	35	No	[76]
MWCNTs and KH570 with ethanol	PDMS	100%			1.55	4000	Yes	[109]
Single-walled carbon nanotube (SWCNT) ink	Polyester woven elastic band (PEB)	1.5–5%	0.1–1 Hz	Pre-cracked (20)	up to 3550	5000	no	[110]
Carbon nanotubes (MWCNT)	PDMS	200%				1000	no	[111]

A poly(3,4-ethylene dioxythiophene) polystyrene sulfonate multiwall carbon nanotube (PEDOT: PSS/MWCNT) liquid-based strain sensor was introduced by Jabbar et al. [44], where a soft substrate (Smooth-On) was used along with the liquid solution using 3D printing fabrication techniques to retain sensor's conductivity and stretchability with 30% strain up to 1000 cycles along with gauge factor of 89.4. The sensor is highly stretchable and was tested by a custom-made system to test the stretchability of the sensor, as shown in Figure 6a(i). Conversely, Figure 6a(ii) shows the optical images of the sensor at 0, 50, 100, and 150% strain. The designed sensor worked as a feedback sensor with the robotic leg, making it applicable in wearable electronics. On the other hand, Bhattacharjee et al. [37]

presented a strain sensor based on poly(3,4-ethylenedioxythiophene) polystyrene sulfonate polymer liquid incorporated inside the PDMS material to achieve a strain of 30% and an extremely high gauge factor of 12,000. The sensor bears the deformability at certain angles, as shown in Figure 6b(i). Alternately, Figure 6b(ii) shows the temporal response of the sensor at bending and Figure 6b(iii) represents the behavior of the sensor at different bending angles. Finally, the real-time analysis of the sensor was conducted at different bending (B) and relaxation (R) cycles, as shown in Figure 6b(iv).

Similarly, Ryu et al. [74] have reported multi-walled carbon nanotube (MWCNT) solutions spray coated on a PDMS soft substrate. The strain sensor was used for the detection of the strain as well as fluid flow. The MWCNT junctions in the sensors were attached and detached with the deformability of the PDMS tube caused by certain fluid flow. Another study was conducted by Yang et al. in [109] using MWCNT and PDMS materials to design a fluidic strain sensor, retaining stretchability and a gage factor of 100% and 1.55 over 4000 cycles, respectively. Furthermore, a pre-cracked approach using the dip-coat-stretch method with the Ag particle/singled wall carbon nanotube (SWCNT) inks along with polyester woven elastic band was introduced in [110]. The sensor was made when the polyester woven band was dipped in the ink with the pre-cracked method to retain higher stretchability from 1.5 to 5%, with a gauge factor up to 3550. In another study, MWCNTs along with fluorinated PDMS substrate were reported [111] in order to retain the mechanical robustness of the sensor by enhancing liquid impalement resistance through a multi-fluorinated approach. The designed sensor proposed a high stretchability of 200% strain. The designed sensor showed excellent mechanical robustness and was tested by knife scratch as well as hand rub, as is shown in Figure 6c(i,ii), respectively.

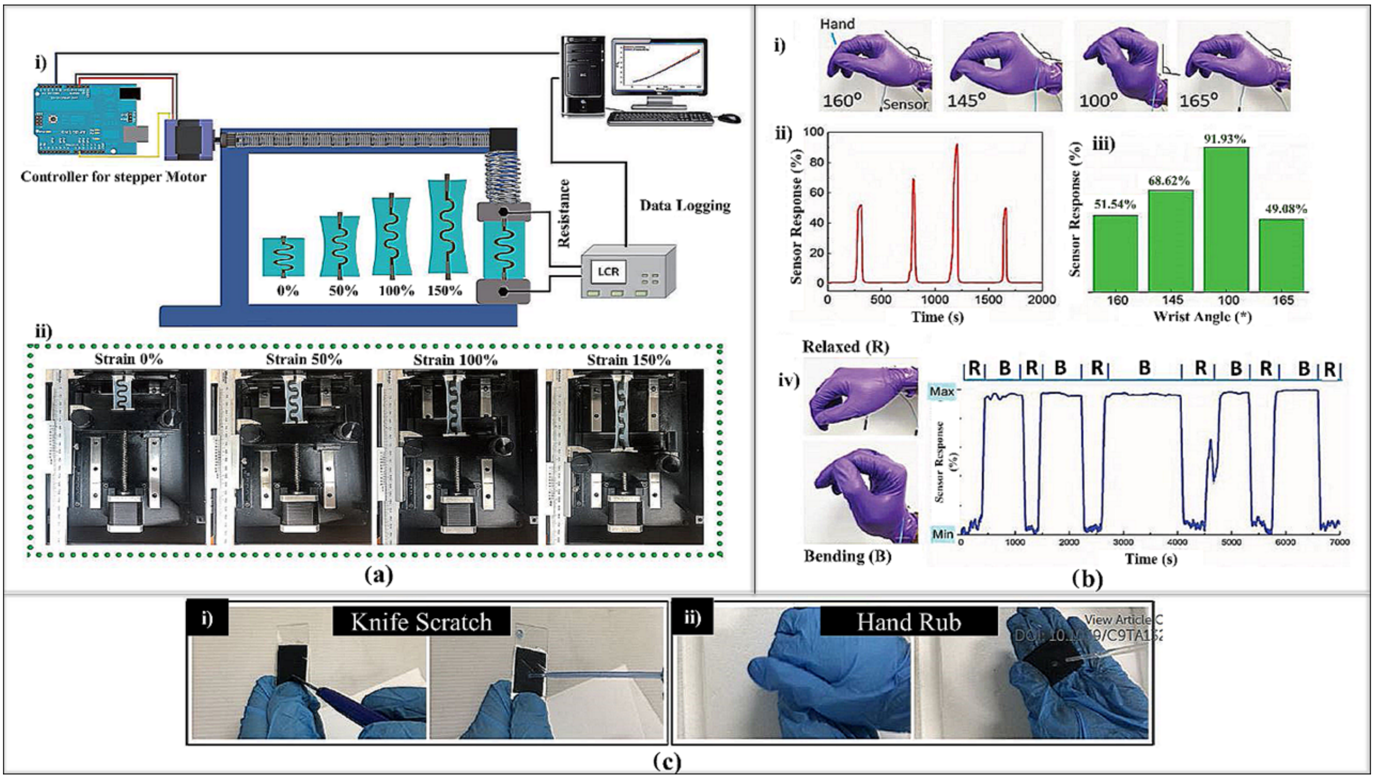

Figure 6. Conductive liquid solution strain sensors: (**a**) Demonstration of design strain sensor: (**i**) variable strain applied to the designed strain to test the stretchability; (**ii**) optical images of the sensor under different strains applied (0, 50, 100, and 150%) [44]. (**b**) Analysis of the sensor by wearing it on the hand: (**i**) bending the sensor at certain angles; (**ii**) analyzing the temporal response; (**iii**) sensors' response at different bending angles; (**iv**) demonstration of bending (B) and relaxation (R) of the sensor [37]. (**c**) Testing the mechanical robustness of the sensor by (**i**) knife scratch and (**ii**) hand-rub [111].

2.4. Disadvantages and Advantages of Different Conductive Liquids

Ionic liquids are claimed to be crucial in the design of strain sensors due to their usefulness as electrolytes in electrochemical sensors, as well as their linearity, sensitivity, low viscosity, and low melting point. However, their toxicity and preparation costs present certain drawbacks. On the other hand, metallic liquids are flexible, accurate, and reliable, having excellent conductivity, but because of their low gauge factor they have a limited range of force detection and they are expensive to design. We have also covered various chemically manufactured liquid solutions, such as liquid polymers and MWCNT, that assist in obtaining high strain and reliability in addition to ionic and metallic liquids. The disadvantage of CNTs is their low stability and reduced efficiency.

In terms of flexibility, accuracy, and stability, metallic liquids outperform all other conductive liquids discussed in this study. Despite being expensive, they are desired for a number of wearable applications, including sports, motion detection, and health monitoring where high strain is required.

3. Channel Structures

In fluidic strain sensors, it is important that the sensor can retain ideal stretchability when it faces deformation, stretching, and reversible stretchability, but because of direct filling, it can cause failures when deformation and stretching occur. The liquid materials used to fabricate strain sensors are printed/filled on or are within the elastomeric material with different structures in order to enhance their stretchability and promote low energy dissipation. Sinusoidal, flat, wavy, and square are the few examples of these structures adopted by the researchers discussed in this paper.

One of the most common structures used to design fluidic strain sensors is the wavy structure as shown in Figure 7a,d. This is because these types of sensors need to withstand high strains, which cannot be achieved by simple structures because either the inorganic materials have low elasticity, leading to destruction, or the active materials may lose their electric contact due to continuous deformations. Furthermore, strain-gauge-shaped channels were adopted in [71,99,100] to help in deformation and motion monitoring applications as shown in Figure 7b.

Sandwiched and flat structural methods are also used to create strain sensors; these structures are said to be sandwiched and flat because the liquid metals are injected between soft substrates (PDMS, Ecoflex, Smooth-On, etc.) through direct liquid pouring through syringes into soft molds and through a microchannel (made for these liquids) as shown in Figure 7c,h. The strain sensors in [41,77] were designed using sandwiched patterning to achieve a strain of 400% and 320%, respectively. Additionally, Choi et al. in [39] developed a sensor with both flat and wavy structures to demonstrate that the wavy structured sensor has a higher strain, lower hysteresis, and exceptional durability as compared to the flat structure strain sensor. In order to make the fluidic sensors more flexible, many patterns have been created utilizing various fabrication techniques [40,56,73,75,91,98,101,105,107,108] some of them are shown in Figure 7e,f.

Sinusoidal structure patterning has been used in recently reported studies [44,45] for stability, high strain, high sensitivity, and to reduce the memory effect. Apart from this, liquid metals are injected into microchannels or tubes made of the soft silicon substrate, as shown in Figure 7g [37,48–50,73,91,94–97,105,107]. The liquid metal circuit with a wearable touchpad with a z-film seal that enables direct electrical contact with the skin was patterned by Lu et al. [101]. Similarly, a new structure was developed by Votzke et al. [104] that mimics a dog bone shape and helps to achieve low hysteresis as well as high durability as shown in Figure 7i. Furthermore, strain-gauge-shaped channels were adopted in [72,99,103] to help in deformation and motion monitoring applications.

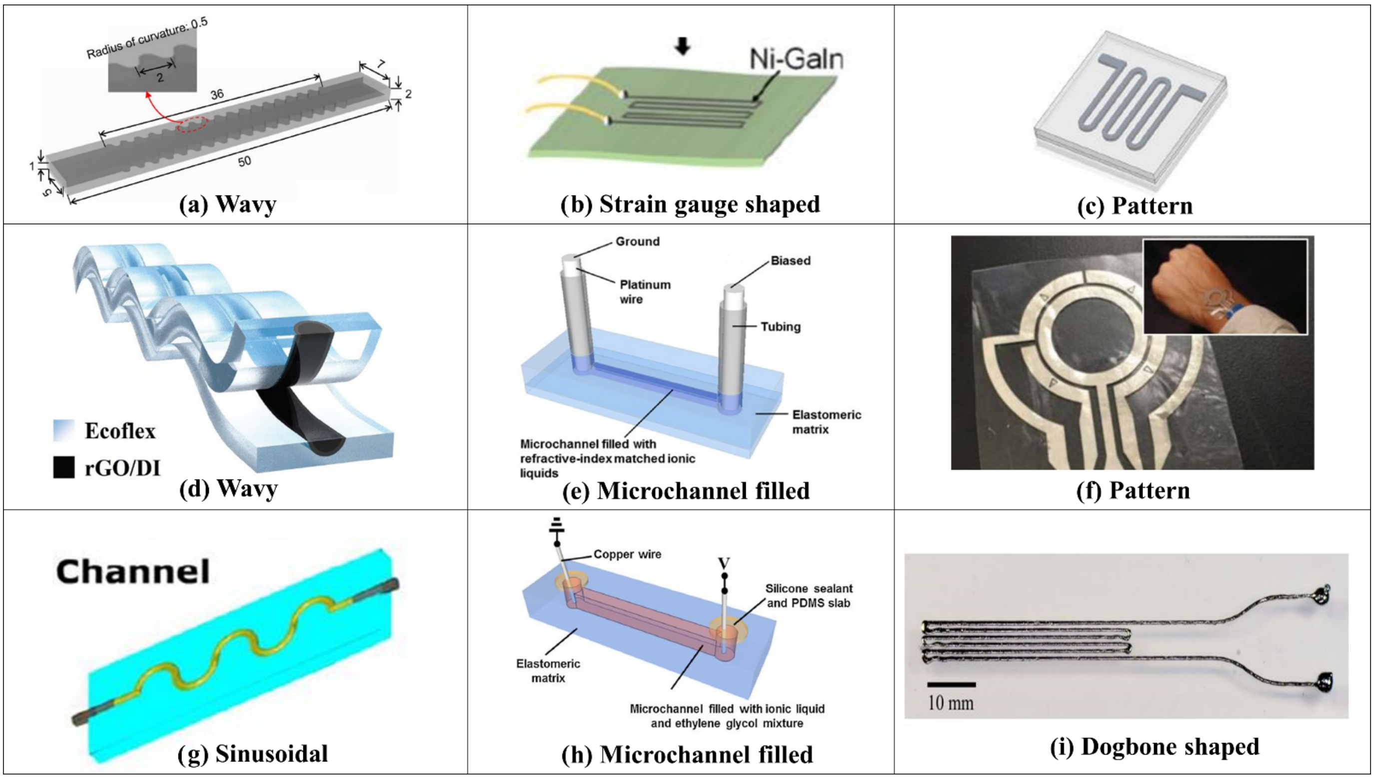

Figure 7. Different structures adopted by sensors to design a conductive fluidic strain sensor: (**a**) wavy [39]; (**b**) strain gauge shaped [99]; (**c**) pattern [100]; (**d**) wavy [41]; (**e**) microchannel filled [94]; (**f**) pattern structure [101]; (**g**) sinusoidal structure [45]. (**h**) Microchannel [97] and (**i**) dog bone shaped [104].

4. Fabrication Techniques

Different fabrication methodologies have been introduced to design the fluidic strain sensors. Some of the methods widely used and adopted by the studies discussed in this paper are as follows: 3D printing [73,98,99,108], lithography [77], mold casting [105,108], dip-coat-stretch [110], and shrink-stretch patterning (SSP) [103]. The three-dimensional (3D) printing method or additive manufacturing is an advanced micro or nano fabrication technology, one that is highly applicable in optics, energy, biomedicine, and lightweight engineering. Charles Hull's stereolithography process, which allows for the manufacturing of complex 3D structures with design freedom, considerable material savings, and quick fabrication periods, built the foundation of this 3D printing technology in the year 1983 [112]. It is basically a method of printing three-dimensional objects layer by layer whose designs are created by a computer software. Thermoplastic, metals, resins, and ceramic material can be used in a 3D printer to print objects. This method is widely appreciated in soft robotics and is mostly used in fabrication procedures because of its functionality to customize the fluidic channels in the strain sensors. This provides multiple advantages in terms of time, material usage, accuracy, and precision. The 3D printing method was used in [74] to design a stretchable strain sensor. Similarly, Huang et al. in [98] designed a sensor where Ag NPs were directly inked on a substrate using 3D printing technology. Apart from all the advantages of the 3D printing technique it possesses, some disadvantages include its limited build size and material. It might have some lower tolerances that may cause difference in the designed and final product.

Another method that has been utilized in the fabrication process of soft robotics/sensors is lithography techniques where the ink is applied to the grease treatment or a flat and blank image surface, which then repels the ink because of the wet surface. Lithography techniques possess high resolution and have the ability to pattern a variety of substrates and surfaces using lithography; the metal liquids (ink) are deposited on a soft substrate and achieve the desired pattern or structure for the strain sensor to make it super stretchable, as shown in Figure 8a. Lithography techniques have some limitations (such as only being suitable for flat surfaces and having a limited wavelength), which is not always ideal in the design of strain sensors.

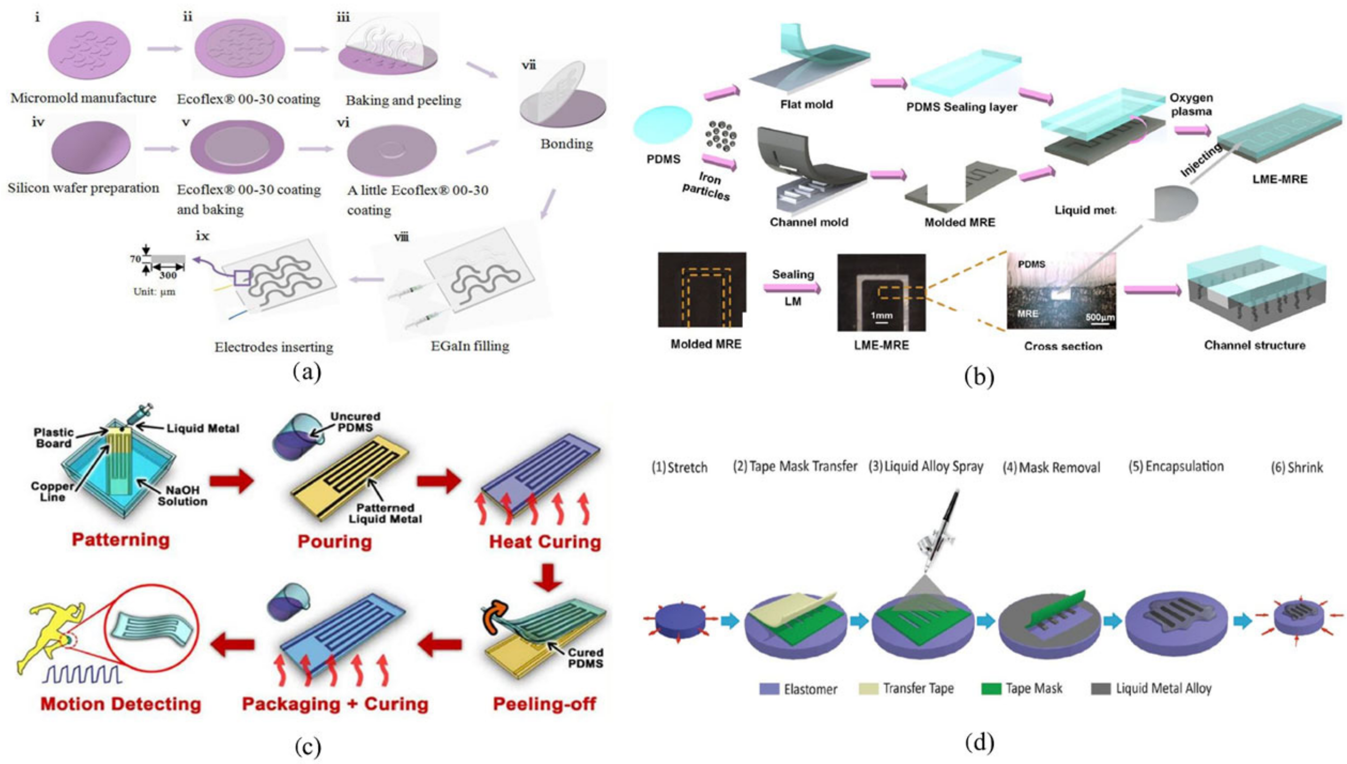

Figure 8. Fabrication methods to design a fluidic strain sensors: (**a**) a sensor designed using the soft lithographic technique [77]; (**b**) a sensor designed through the mold-casting method [105]; (**c**) a sensor fabricated using the wetting and pouring method [72]; and (**d**) the shrink-stretch pattern (SSP) method was used along with tape transfer and the spraying technique to design the sensor [103].

The mold casting method is highly used among all the fabrication methods [25,31,37,39,40,45,49,105]. The mold casting method is beneficial because of the molds being reusable, having dimensional accuracy and surface finish. This method includes a process where a liquid material is poured inside the molds and tightens them; then, they are set aside until the materials become hard and have the required shape. These molds are designed using either 3D printing or other techniques. Using this process, casting is performed by pouring/injecting the substrate or liquid metals into the molds to design a durable strain sensor, as is shown in Figure 8b. This method is expensive because it might involve the 3D printing techniques for casting, which also makes this method quite time consuming.

Another method was introduced by Wu et al. [72], where the strain-gauge-shaped foil was partially wetted in a NaCl solution and then the LM liquid was injected onto this copper foil, as shown in Figure 8c; this method is called the direct pouring method [72]. Alongside these, a new method named dip-coat-stretch was introduced by Ko et al. in [110]—the name of the method is self-descriptive. Woven elastic material was used in the study to obtain the desired durability. This elastic material was then dipped and coated in the conductive liquid material in order to obtain a highly stretchable and efficient strain sensor. However, the shrink-stretch-pattern (SSP) method was introduced by Sahlberg et al. in [103], as shown in Figure 8d, where the tape transfers patterning along with spray coating to design a fluidic strain sensor with special patterning to produce a stretchable strain sensor

5. Applications of Fluidic Type Strain Sensors

Fluidic strain sensors have been used in a wide range of applications, not only limited to wearable applications such as health monitoring, sports, and gaming, but also in robotics. In this section, different applications are discussed in detail.

5.1. Wearable Devices

Fluidic strain sensors are widely applicable in motion detection applications by wearing them on different parts of the body, such as the knee, elbow, or finger. Sensors are attached to the skin, and adhesive tape is used to make them easily accessible. strain sensor designed to monitor movements [73] are shown in Figure 9a whereas In [40], the strain sensor was designed to detect the motion of the finger. Here, the sensor was attached to the index finger, detecting whether the fist is closed or the finger is extended as shown in Figure 9b. Similarly, finger movement, rotation of the wrist, and water drinking were detected in [31]. The sensor was attached to the skin to distinguish the static as well as dynamic motion of the body. Similarly, Choi et al. [39] showed a sensor applicable for health monitoring, smart clothing, and virtual reality systems by detecting the responses of the electrical resistance caused by deformations. Furthermore, low-cost and highly stretchable sensors were designed in [19,49,91] for medical, flexible, and wearable applications. Similarly, wearable sensor to detect elbow flexation [104] has been designed and shown in Figure 9c. Gao et al. in [100] present a sensor with outstanding mechanical deformability that can be attached to joints, fingers, wrists, etc., For the detection of skin movements. sensor worn to detect bicep muscle tuning were reported in [109] as shown in Figure 9d. For chronic monitoring applications, interfacing low-power wearable electronics with low sensor resistance but good strain sensors was presented in [76]. Moreover, wearable sensor to detect the motion of the knee was introduced in [91] and can be shown in Figure 9e. Another sensor has been designed in [110] for the firefighter's glove for the motion detection which can be seen in Figure 9f.

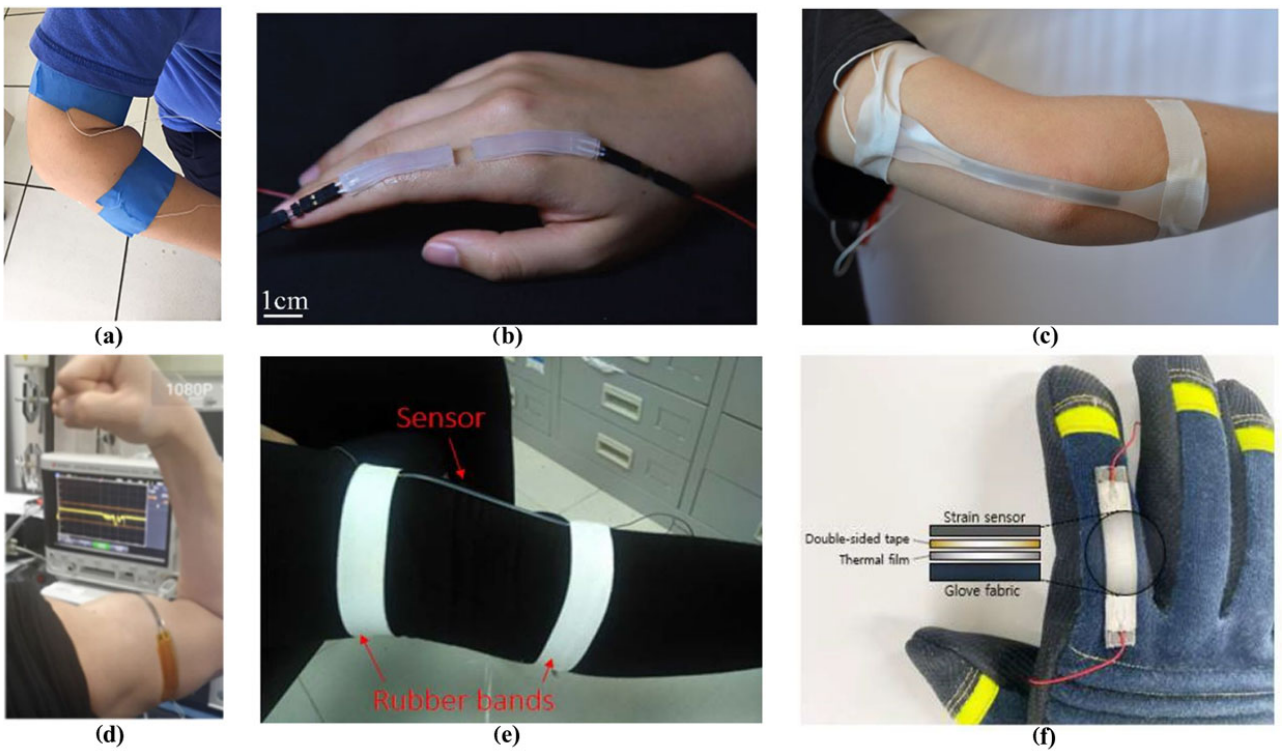

Figure 9. Applications of wearable strain sensors: (**a**) strain sensor designed to monitor movements [73]; (**b**) wearable strain sensor to detect finger movement [40]; (**c**) wearable sensor to detect elbow flexation [103]; (**d**) sensor worn to detect bicep muscle tuning [109]; (**e**) wearable sensor to detect the motion of the knee [91]; (**f**) attaching a sensor to a firefighter's glove to detect motion [110].

A robust strain sensor using a simple fabrication methodology was designed in [44] for high-end feedback applications such as monitoring the fingers, arm, joints (elbow and knee), and neck of the human.

5.2. High-End Feedback for Soft Robotics Systems

Fluidic strain sensor applications are not limited to health monitoring and other medical applications only but have broad applications in the field of robotics too. Soft sensors are necessary for wearable robots or other functional robots to allow for soft human–robot contact and feedback control of the robotic actions. These robots might be therapeutic wearable robots, transporting robots, or soft robotic grippers. These fluidic sensors are applied in conventional as well as soft robotics. Wu et al. in [72] tried to remotely control the position of the robotic hand by providing gestures with a glove-mounted sensor, as shown in Figure 10a where different motions of the fingers were analyzed by making a hard fist as shown in Figure 10a(I) and analyzing the motion by closing and opening number of fingers as shown in Figure 10a(II–V). Furthermore, for soft robotics, the stretchable strain sensor was designed in [77,94], showing the potential to implement the strain sensors in soft robotics as shown in Figure 10b where the study in [77] presented a robot which is designed with the help of strain sensors to analyze the motion of the robot joint.

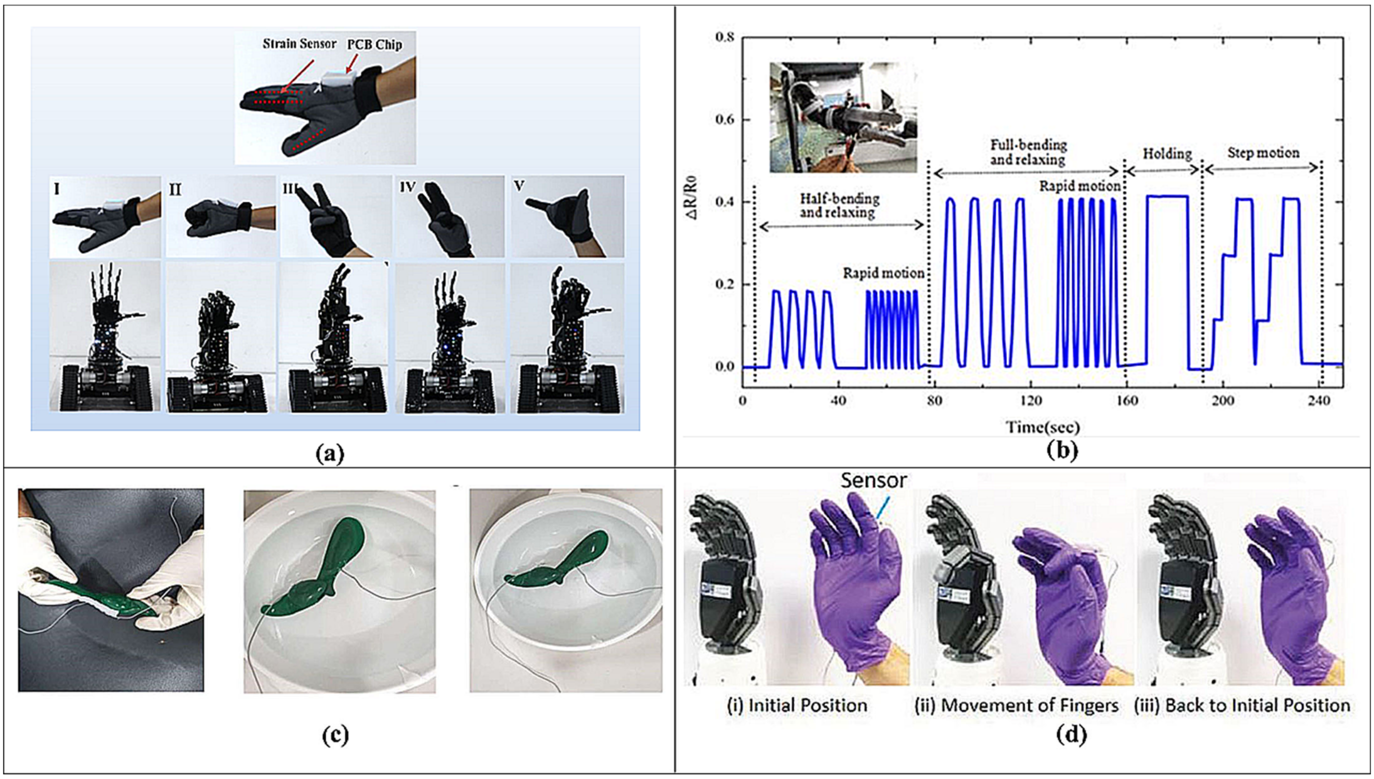

Figure 10. Flexible strain sensor application in robotics: (**a**) controlling a robotic hand from the remote position [72]; (**I**) original state (**II**) hard fist (**III**) bending 3 fingers (**IV**) bending 2 fingers and (**V**) and bending 4 fingers (**b**) the sensor is attached to the robot joint to analyze the movement [77]; (**c**) the sensor attached to the legs under water [45]; (**d**) to move the robotic finger as feedback, the sensor is attached in the human finger [37].

Similarly, Soomro et al. in [45] presented a sensor that is applicable in motion detection as well as robotics applications. The designed sensor was attached to the adhesive bandages for detection purposes, whereas the sensor was used to mimic a robotic leg, which was designed by using a commercial 3D printer that was tested and analyzed underwater, as is shown in Figure 10c. To determine the displacement of the robot's grippers and pneumatic as well as hydraulic actuators, a fluidic strain sensor was designed by Keulemans et al.

in [50]. However, the study in [37] have designed a robotic hand where the sensor is attached to the human finger to get the feedback from the robotic finger as shown in Figure 10d. Similarly, The studies in [73,103,106] showed that the relative change responses in the deformation of strain sensors represent a high potential for small-scale robotics systems. In one study, a fluidic strain sensor [102] with high elasticity and deformation (to some extent) offers applications in smart textiles, healthcare/fitness, and remote sensing of a robot's motion, or expansion and contraction of building and bridges. There are other varieties of applications that involve flexible strain sensors based on conductive liquids such as in artificial skin [45,113,114], where the conductive liquid-based strain sensors are embedded or attached to the skin, where strain sensors work with a textile called e-textile [92,115] for a wide range of purposes, as well as in physical training [97,116] to detect the bending and motion.

6. Challenges and Future Trends

Many attempts have been made to create innovative conductive liquid materials and unique channel designs for the manufacturing and characterization of stretchable strain sensors in light of current advancements in material science and composite structuring. These strain sensors have been applied to sports, healthcare, and human motion detection. The optimization of the composite structural interfaces, design and manufacturing repeatability, modification of the percolation threshold, and incapability to execute long-term operations as wearable devices, however, prevent them from achieving specific performance capabilities [44]. Furthermore, the hysteresis is still the main problem, in addition to the attainment of a higher gauge factor. There is also a bottleneck in increasing the sensitivity by introducing less viscous liquid; however, this comes with the compromise of noise. Moreover, attainment of high GF over a wide range (ideally full range) is also a challenge for the researchers. For this, a specific operating range is selected where the GF is almost constant [45]. It is common practice to disregard the sensor's resistance to numerous ambient conditions including humidity, temperature, light, and other disturbances. Researchers should be careful to test their devices in such a real-world context because the devices are often created and manufactured in a controlled environment [46,60]. This will further enable the device to be robust and will provide a more accurate and reliable output. In addition, due to injecting the liquid, there are often leakage problems that limit the long-term operation of the sensor. There is a need for developing a better, simpler, and reproducible fabrication technique that mitigates this issue. Most importantly, the readout circuits limit the flexibility and conformity of the device due to their rigid nature, temperature variations at long periods of operation, and increasing disturbance for the user when using it as a wearable device.

Furthermore, a complicated system in a single device is what the future holds. This may involve combining flexible sensors with integrated chips and other pertinent readout circuitry. This raises questions about the potential restrictions for fluidic type strain sensors, which can leak at high strains because of the integration of chips. The development of flexible chips and other circuits that can be combined with the sensor to create a single package ready to be utilized for diverse applications will be a new trend in the future. Making this feasible will provide crucial support for the mainstream adoption of the internet of things (IOT). Similar to this, it will be necessary to use materials that can survive chip forms with arbitrary mechanical properties or sharp edges. To overcome these challenges, the novel composition of conductive liquids and channel structures should be introduced with a focus on the optimization of design using rigorous simulation work and mathematical modeling. The viscosity of the liquids used can be optimized for attaining better sensitivity and less hysteresis. Digital fabrication techniques can be explored to innovate conformal, durable, and reliable devices with flexible read-out circuits. Furthermore, adhesive bio-liquids can be used for fixing the sensor on the human body, rather than using any disturbing fixture. In addition, the bioliquids should also be explored for their conductive and strain sensing abilities, which will enable the risk-free use of such wearable devices.

7. Conclusions

The development of fluidic-type flexible strain sensors is discussed in this paper, considering a variety of liquid types, including liquid metals, ionic liquids, and chemically produced liquids. Additionally, various channel structures, manufacturing methods, and applications of these sensors in wearable as well as soft robotics have been covered in detail and explored with an emphasis on their performance comparison. Fluidic strain sensing has only lately gained attention, and therefore it has several difficulties such as poor and variable GF, sensitivity, high cyclic response, biocompatibility in liquid materials in particular, liquid leakage, and conformal device fixing to the human body. This analysis also outlines potential trends for the future and ways to approach the problems. Additionally, the goal of this work is to provide readers with thorough yet accessible comprehension.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/electronics11182903/s1, Figure S1: Information regarding various reported works, (i) using various fabrication techniques, (ii) liquid materials, and (iii) channel structures.

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