Conformable Packaging of a Soft Pressure Sensor for Tactile Perception

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Abstract

Humans can perceive surface properties of an unfamiliar object without relying solely on vision. One way to achieve it is by physically touching the object. This human-inspired tactile perception is a complementary skill for robotic tactile perception. Robot perception depends on the informational quality of the tactile sensor; thus, packaging sensors and integrating them with robots plays a crucial role. In this work, we investigate the influence of conformable packaging designs on soft polydimethylsiloxane (PDMS)-based flexible pressure sensors that work in a variety of surface conditions and load levels. Four different 3D printed packaging designs capable of maintaining sensor trends have been developed. The low detection limits of 0.7 kPa and 0.1 kPa in the piezoresistive and piezocapacitive sensors, respectively, remain unaffected, and a performance variation as low as 30% is observed. Coefficient of variation and sensitivity studies have also been performed. Limit tests show that the designs can handle large forces ranging from 500 N to more than a 1000 N. Lastly, a qualitative study was performed, which covered prospective use-case scenarios as well as the advantages and downsides of each sensor casing design. Overall, the findings indicate that each sensor casing is distinct and best suited for tactile perception when interacting with objects, depending on surface properties.

Keywords: Conformable packaging, flexible sensors, printable sensors, robotics, soft sensors, surface identification, tactile perception, tactile sensing, terrain identification

1. Introduction

Humans can learn more about an object and acquire data about the features of their surroundings by using their tactile senses in addition to using eyesight. Through our sense of touch, we can discover an object's texture, pressure, and even shape [1]. We also use tactile information to perform a variety of activities, including object holding, manipulation, making tiny and precise movements, and maintaining balance and stability [2]. Additionally, it helps us to identify dangers and avoid barriers. In the past, researchers have attempted to utilize tactile sensing for robots to 'perceive' the world [3, 4]. With better tactile sensors, we expect the robots to achieve better perception. In this regard, polymer-based tactile sensors are in great demand as they are reaching closest to having a tactile feel and reaction that is comparable to skin [5, 6].

Pressure sensors that use synthetic polymers largely as their sensing element are known as polymer-based pressure sensors. In comparison to conventional off-the-shelf sensors, the newly fabricated sensors offer a number of advantages, such as design flexibility, affordability, and simplicity of

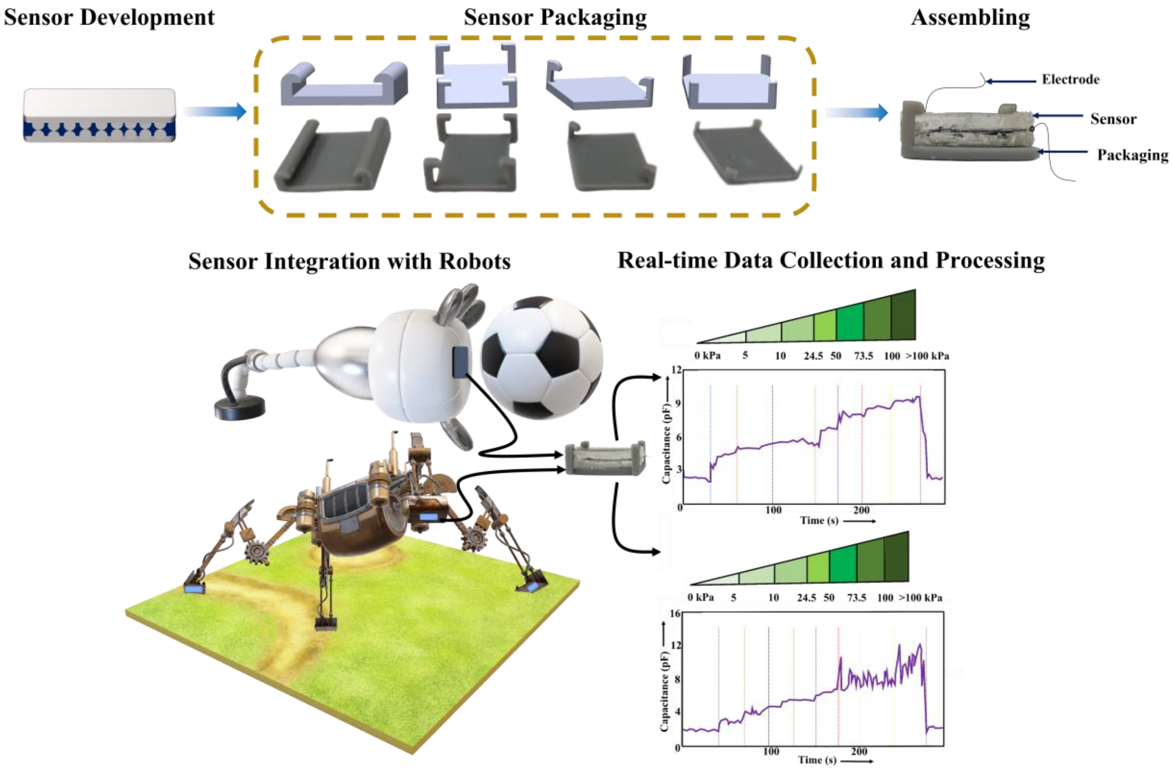

Fig. 1. Schematic illustration of the sensor and packaging capabilities.

fabrication [7]. Since they are made using a variety of materials and production techniques, they are extremely customizable and suitable to numerous uses. Polymer-based pressure sensors monitor changes in electrical capacitance or resistance to detect pressure changes. These sensors provide a broad range of pressure detection capabilities, from very low to extremely high [8-10], and make it suitable for tactile perception of robots.

Prior to packing, it is common to measure and characterize a sensor's reaction in a controlled setting. This characterization [11] includes measurements of the sensor's sensitivity, accuracy, linearity, and other significant features. The packaging used to contain and protect the sensor, however, may have an influence on the sensor's reaction, which might alter how well it functions. Packaging serves the purposes of mechanically protecting the sensor, protecting it from environmental factors including temperature and humidity, and establishing electrical connections between the sensor and external electronics. Different types of packaging could alter the electric field around the sensor, which could have an impact on electrical properties like capacitance or impedance. Additionally, the temperature gradients near the sensor may be impacted by the thermal properties of the packaging material, which could affect its performance [12, 13]. The packing technique may also affect how the sensor responds [14]. During packing, the sensor can experience mechanical stress or strain, which might alter its electrical properties or cause it to deform, lowering its sensitivity and accuracy.

Additionally, contaminants or impurities introduced during the packing process may alter the sensor's physical characteristics or affect its performance [15, 16]. Finally, packaging may influence how a sensor reacts by altering how it communicates with its environment. A tightly sealed sensor, for example, would not be able to detect changes in the humidity or gas concentration in the environment, which restricts its usefulness in particular circumstances. It is essential to carefully choose and characterize the packing materials and procedure in order to ensure that the sensor performs optimally in the application for which it is designed.

The packaging of a sensor may have a considerable influence on its performance. Numerous studies have noted the observation that sensors behave differently when they are packaged compared to when they are tested in a controlled laboratory setting. The study by [17] highlights how the alignment of numerous optical, optoelectronic, and mechanical components is the main problem with a fiber-optic sensor's package design and how the packaging could affect the sensor's sensitivity, reproducibility, and response time. While the research by [18] discusses how the packaging may affect the calibration and performance of a surface acoustic wave resonator strain sensor. A Fibre Bragg Grating (FBG) sensor's sensitivity, reaction time, long-term, and signal stability monitoring were all affected by the packaging in [19];

a MEMS sensor's reliability and detection performance were also affected in [20]; and many similar events have been reported. Numerous methodologies are used to study the effects of packaging. The finite element technique (FEM) was employed, for instance, to analyze the packing stress in a multisensor chip brought on by the mismatch of the thermal expansion coefficients (TCE) in the various materials utilized [21]. [22] looks at how the presence or absence of biocompatible silicone paste as a packaging material affects the output waveform shape and reaction time of the catheter sensor. The transient heat conduction mathematical model is built, and the time constant is computed analytically, in order to study the impact of different encasing materials on the time constant of sensors under dynamic settings [23]. This is accomplished in line with the thermal equilibrium theory and the lumped heat capacity (LHC) system. However, packing sensors has a lot of benefits in addition to drawbacks. As shown in the work of [24], fiber optics and evacuated packing may enable flexible positioning, low-power operation, and the placement of the heated sensor within a few millimeters from live tissue. [25] investigate the potential methods for enhancing tire pressure monitoring system reliability and come to the conclusion that pressure sensor die packing is an important consideration while [19] presents the creation of a simple and low-cost packaging technique that enhances the capabilities of FBG sensors. Although there are many works on various sensing modalities in the literature, there are very few works on sensor packaging for soft pressure sensors.

In this article, we investigated the conformable packaging designs of a soft pressure sensor for tactile perception. Four sensor enclosure designs were put on trial for use in applications involving tactile perception. For evaluating the behavior of each sensor case design, two kinds of soft pressure sensors, namely piezoresistive and piezocapacitive type sensors, were made and utilized. In order to assess the performance of the sensor casing, tests for sensitivity, sensor response, coefficient of variation, and limit of detection, were performed on both piezoresistive and piezocapacitive type sensors covered by each casing design. Three distinct kinds of surfaces were used for the tests, and varied loads were applied to the sensor casing. The maximum force that each sensor package design can bear before breaking was experimentally investigated for each casing design containing pressure sensors. Further, a qualitative analysis based on the experimental test's quantitative results was carried out, and highlighted the benefits and drawbacks of each sensor casing design with possible application scenarios. A schematic illustration of the work and its possible use case scenario is depicted in Fig.1.

2. Methodology

2.1 Stereolithography 3D Printing of Sensor Casings

In this study, the casings of the soft pressure sensors were manufactured for conformable packaging using an advanced

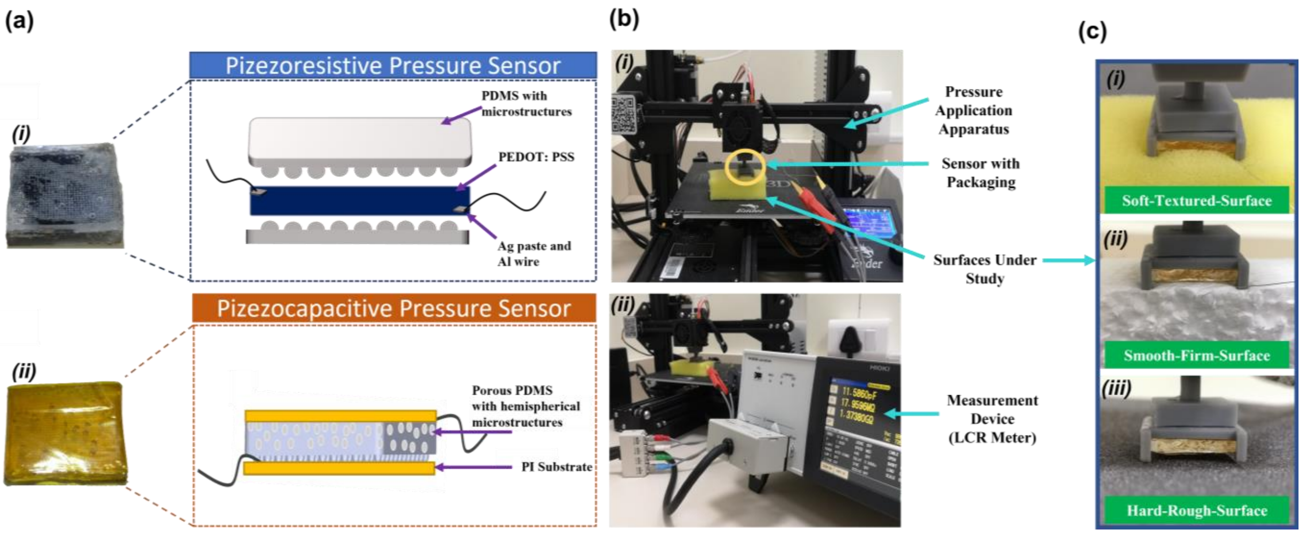

Fig. 2. (a)(i) A double-layer piezoresistive pressure sensor with PEDOT:PSS as the sensing layer and hemispherical microstructures on PDMS. The aluminum (Al) wires were joined using silver (Ag) paste to the corners of the two PDMS slabs, and (a)(ii) A single layer piezocapacitive pressure sensor with porous PDMS having hemispherical microstructures and polyimide (PI) as the substrate. (b)(i) Experimental setup to apply pressure using the sensors fabricated on different surfaces. (b)(ii) Measurement device to observing changes in electrical parameters with application of pressure. (c) Different surfaces on which experiments were performed which are (i) STS, (ii) SFS and (iii) HRS.

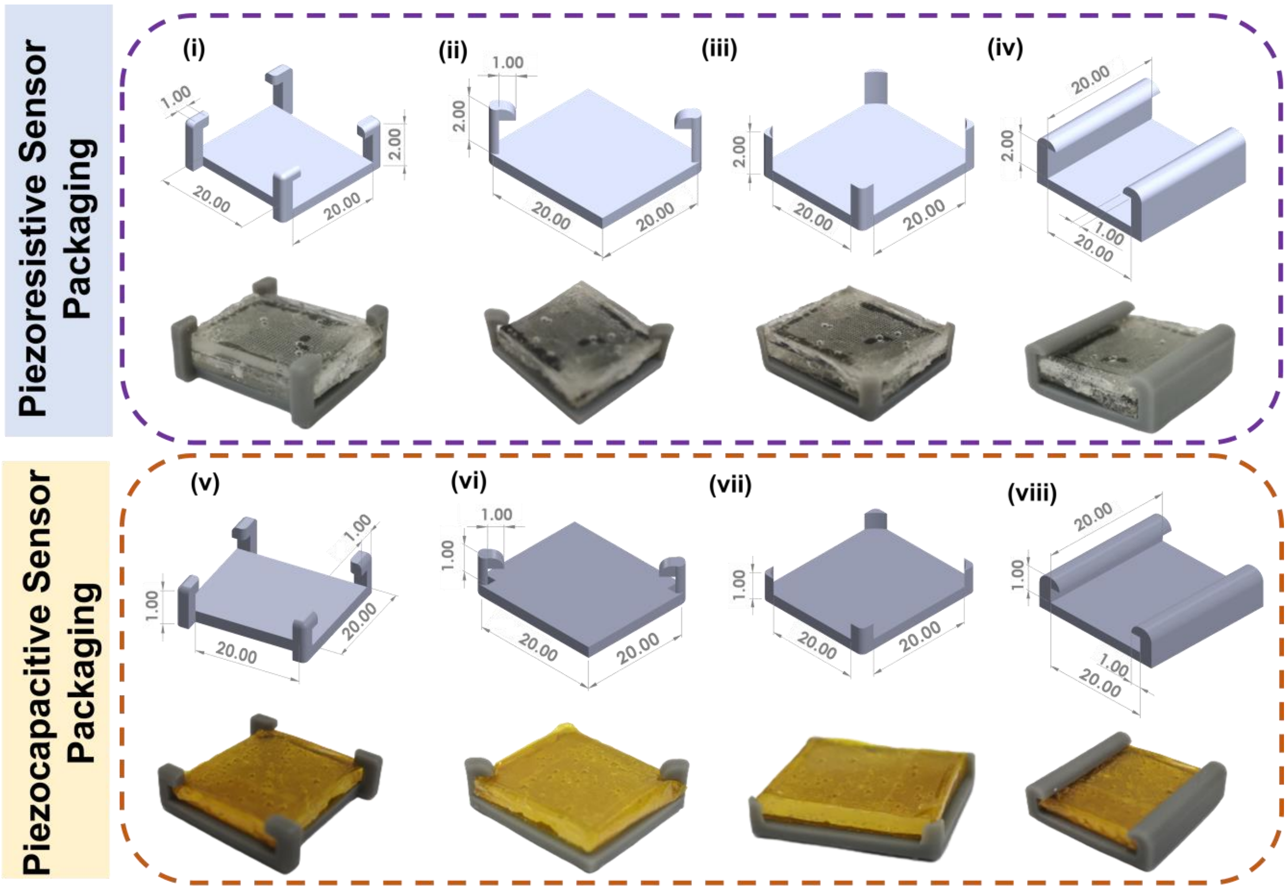

Fig. 3. Different packaging designs of piezoresistive and piezocapacitive pressure sensors. (i, v) Design I - four corner claw type design. (ii, vi) Design II – two-corner support structure. (iii, vii) Design III – four-side support with no protrusion. (iv, viii) Design IV - two side support for maximum structural integrity. Their corresponding real-life 3D printed variants with sensors fitted are shown.

desktop 3D printer (FORM 3B+, Formlabs), which utilizes stereolithography (SLA) technology that employs a laser to transform liquid resin into plastic, which is then solidified by UV radiation. Through the SLA printing process, the casings were upside-down 3D printed. To create a cross-section of the 3D model (physical casing) and selectively harden the resin, the UV laser is directed through a clear glass galvanometer at the bottom of the resin tank. Each layer that is put on the print is less than 100 µm thick. For prototyping pressure sensor casing designs, we utilized the gray resin from Formlabs, which is ideal for the proposed application in this study, given its print resolution of 25 µm. As per the manufacturer [26], the gray resin used in this work possesses a tensile modulus of 2.6 GPa, a flexural modulus of 2.2 GPa, an ultimate tensile strength of 65 MPa, and an elongation of 6%. After the casing molds have been cleaned with isopropyl alcohol, a process known as post-curing is carried out in this study to enable the fabricated casings to achieve their maximum strength and stability. This technique was used to create four different types of casings for double-layer piezoresistive pressure sensors and single-layer piezocapacitive pressure sensors.

2.2 Fabrication of Soft Pressure Sensors

We fabricated piezoresistive type pressure sensors [27, 28] (Fig.2 (a)) and piezocapacitive type pressure sensors [29] (Fig. 2 (b)) for the conformable packaging analysis carried out in this study. Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) from Sigma-Aldrich is used as the sensing material for the piezoresistive pressure sensor. It is based on the principle that as pressure increases, more conducting points form, reducing contact resistance. The production of this sensor involves using replica moulding, and the mould for the substrate was created using the 3D printer from Formlabs. The polydimethylsiloxane (PDMS) gel used in this study is SYLGARD® 184 from Dow Inc. and is the substrate for the sensor, formed by mixing PDMS elastomer and curing agent in a 10:1 (w/w %) ratio. After being put into the 3D-printed mold, the mixture was cured for 180 minutes at 70°C. Once well-cured PDMS layers were carefully removed, PEDOT:PSS was drop-cast onto the microstructured face [30]. The complete structure was then dried in an oven for 20 minutes at 50°C. The aluminum wires were joined by applying flexible conductive silver (Ag) paste (Sigma-Aldrich) to the corners of the two PDMS slabs, and then sandwiching and joining the two slabs using ESSR bond epoxy.

The piezocapacitive pressure sensor is a type of parallel plate capacitor in which the area and dielectric constant are established during fabrication and the applied pressure modifies the electrode distance and, consequently, the capacitance. The fabrication method for this sensor also used replica molding but additionally included sugar templating, which is adding sugar granules in a 1:4 (w/w %) ratio to a PDMS-curing agent of 10:1 (w/w %) ratio mixture. This was then poured into the mold and made to undergo a 300-minute curing process at 70°C and was subsequently placed in deionized water for 5 hours to dissolve the sugar and introduce micropores into the structure. Ag paste is applied to opposite faces to attach aluminium wires and held in place by Kapton tape from Essence Tape International Pvt. Ltd., a polyimide (PI) base that serves as our substrate. The electrodes are fixed using ESSR bond epoxy and found to be stable during the applications.

The readings from piezocapacitive pressure sensors were obtained using an LCR meter (Model IM3536, Hioki), and resistance values from piezoresistive type pressure sensors were collected with a digital multimeter (DMM6500, Keithley). The pressure stress tests were carried out by applying loads on the pressure sensors using calibrated standard weights and a custom-made pressure application apparatus.

2.3 Sensor Casing Designs for Conformable Packaging

The piezoresistive [31] and piezocapacitive [32] based pressure sensors have high sensitivity for low-pressure applications. This makes it an intriguing tool for use in a variety of robotics applications, including robotic hand for human-machine interface [33], gait analysis [34], estimating deformed surface displacement from contact pressure distribution [35], and dead reckoning in a dynamic quadruped robot [36]. Unfortunately, the sensor's nature makes it susceptible to damage if directly exposed, therefore, it cannot be utilized in demanding situations or for a long duration. Hence, the key to solving this challenge is appropriate sensor packaging. The casing should be designed so that (a) to minimize the interference with the sensor performance [37, 38], (b) to tightly packed not allowing disintegration, and (c) to maximize the surface contact [39], which can vary depending on situations. In this research, four package designs were developed that took into account each viable way the sensor could be held. The dimensions of polymer-based pressure sensors are quite small, with the double-layer piezoresistive sensor (Fig.2 (a)) being 20 mm (length) × 20 mm (breadth) × 4 mm (height) and the single-layer piezocapacitive sensor (Fig.2 (b)) comprising 20 mm (length) × 20 mm (breadth) × 2 mm (height).

Design I, shown in Fig.3 (i, v), is of a claw-type structure to hold the sensor in place at all four corners with a minimum amount of contact (an intrusion of 1 mm), which is not obstructing the sensor's sensing abilities and allows layers to be densely packed but encounters a problem when the sensing face comes into contact with a surface. With Design II (Fig.3 (ii, vi)), the contact points are further optimized so that the sensor face is better exposed. By holding the device just at the two diagonally opposite corners, a larger contact area is created at the expense of a slight reduction in stability and strength. Design III (Fig. 3(iii, vii)) completely removes the need for claws from the surface by holding the sensor along the edges, allowing it to operate without any deviation but at the expense of less dense packaging structure. Finally, Design IV (Fig.3 (iv, viii)) closely packs the sensor along any two edges, significantly increasing safety and tight packing of the sensor and having the highest strength but greatly lacking sensor-to-surface contact. With these four designs, one can choose a specific packaging structure compromising less important attributes in a given application as seen in Fig.3 (i-viii). It is observed that the packings have provided the sensor with protection from external influences and higher mechanical stability during application. However, response of the sensor remains mostly unaffected.

3. Experimentation and Results

3.1 Analysis of Sensor Response and Sensitivity Before Packaging

The fabricated sensors possess high sensitivity compared to similar fabricated sensors [40-43] and is capable of picking up even the smallest changes in applied pressure. The sensitivity (S) of the sensors were calculated by taking the change in output signal (δS), relative to the initial signal (S_0) divided by the change in applied pressure (δP), which in the case of the piezoresistive pressure sensor is:

$$S_{(resistive)} = \frac{\frac{\delta R}{R_0}}{\delta P} \tag{1}$$

where δR is the relative change in resistance and R_0 is the original base resistance. While that of the capacitive sensor is:

$$S_{(capacitive)} = \frac{\frac{\delta C}{C_0}}{\delta P} \tag{2}$$

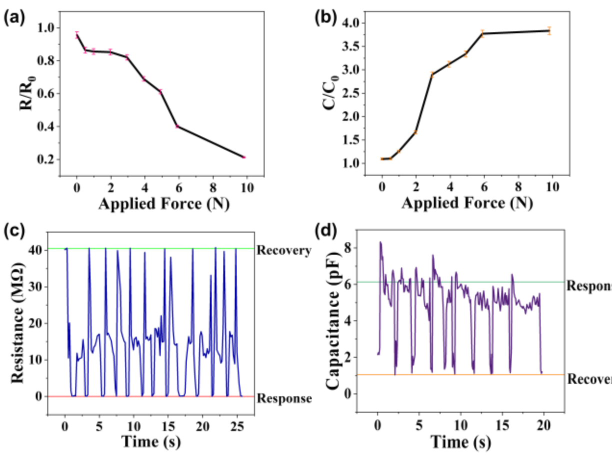

Fig. 4. Sensor performance without packaging. (a) and (b) shows the response of piezoresistive and piezocapacitive sensor, respectively. (c) and (d) shows the real-time response of piezoresistive and piezocapacitive sensor, respectively, for a tapping experiment.

where δC is the relative change in capacitance and C_0 is the original base capacitance.

As described in this study [44], the limit of detection (LOD) was determined by applying pressure at or near the expected LOD to each sensor before calculating the average and sample standard deviation (σ). Next, increasing pressures were given to each sensor to create the calibration curve. This information was used to determine the calibration curve's slope, or m. The LOD is then calculated with the following formula:

$$LOD = \frac{3\sigma}{m} \tag{3}$$

For the piezoresistive pressure sensor, the LOD was estimated to be 0.7 kPa and it had a sensitivity of 8.21 kPa^{-1} before packaging (Fig.4 (a)). In comparison, the piezocapacitive pressure sensor had an estimated LOD of 0.1 kPa and a sensitivity of 6.68 kPa^{-1} before packaging (Fig.4 (b)). Lastly, response and recovery time of sensors was obtained through tapping experiments for both the sensors as shown in Fig.4 (c), (d). The response and recovery time for the piezoresistive sensor was 0.68s and 0.2s, respectively, while that of the piezocapacitive sensor was 0.16s and 0.37s.

3.2 Analysis of Sensor Response and Sensitivity After Packaging

Three types of terrain: (a) a hard, rough surface (HRS); (b) a smooth, firm surface (SFS); and (c) a soft, textured surface (STS)—were utilised to evaluate the performance of the fabricated sensors integrated with casing designs. Loads of calibrated weight were applied to the sensors to see whether there was any response for all types of terrain.

The sensitivity of developed sensors was calculated before and after packaging in different casing designs. We also checked the coefficient of variation (CoV), which is a statistical indicator of how evenly distributed the data points are with respect to the mean. It is calculated with the following formula:

$$CoV = \frac{\sigma}{\mu} \tag{4}$$

where σ is the standard deviation and μ is the mean. In this case, it gives us an idea about surface texture wherein a larger deviation implies a rougher surface and a smoother one has lesser deviation, as seen in Fig.5 (g) and Fig.6 (g).

Design I (four corners) showed increasing response with the increased load when tested on a soft surface as the material deforms and comes into contact with the sensing face, irrespective of the modifications. However, in the case of a firm surface, the sensor showed a response only after crossing the 10 N force mark (weight of 1 kg), which is when the casing started to bend, and so did the surface, allowing contact between the two, but for the hard surface, no response was seen (Fig.5 (a) and Fig.6 (a)). This trend was also observed for Design II and Design IV (Fig.5 (b),(d) and Fig.6 (b),(d)). Design II, however, showed a more significant response than Design I for the same tests, which could be attributed to two factors, namely increased contact to the surface since modifications were only on two corners and instability of the system, the tendency to bend to the non-supported corners which further increased the pressure applied as opposed to the first case. Meanwhile, Design IV showed a lower response due to greater modification on the surface of the sensor which reduces the total amount of pressure applied to the area of

TABLE 1: Sensitivity Comparison of Fabricated Sensors With and Without Packaging.

Sensor Design	**Piezoresistive Before Packaging (kPa^{-1})**	**Piezoresistive After Packaging (kPa^{-1})**	**Piezocapacitive Before Packaging (kPa^{-1})**	**Piezocapacitive After Packaging (kPa^{-1})**
Design I		1.82		1.47
Design II		2.24		1.81
Design III		4.67		3.79
Design IV	8.21	1.33	6.68	1.07

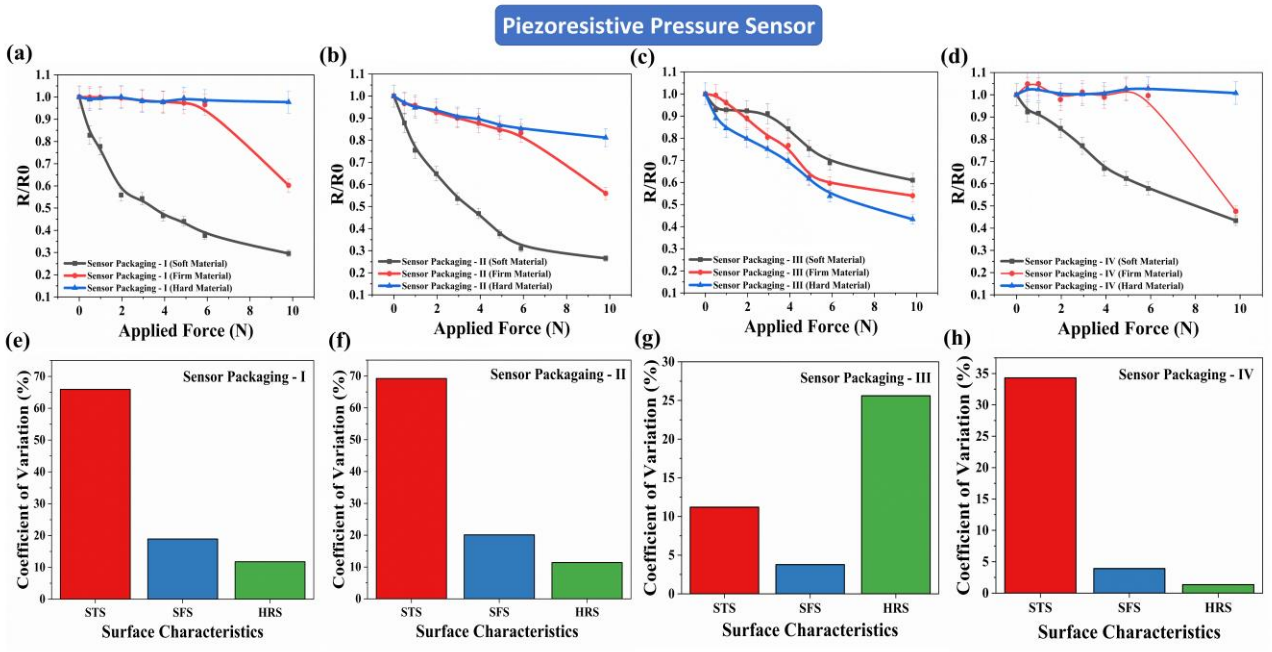

Fig. 5. (a-d) shows the sensor response of piezoresistive pressure sensor in different packaging designs. (e-h) gives the corresponding variation of readings from the mean in the three distinct surface types.

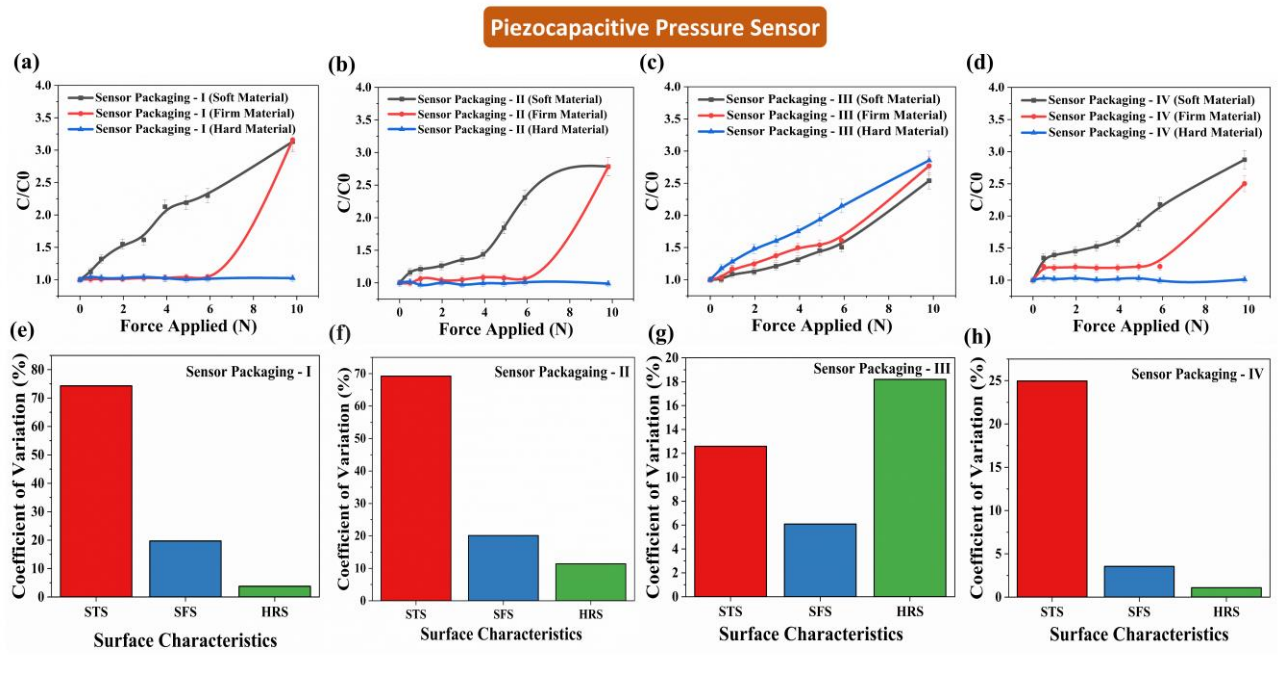

Fig. 6. (a-d) shows the sensor response of a piezocapacitive pressure sensor in different packaging designs. (e-h) gives the corresponding variation of readings from the mean in the three distinct surface types.

contact. Among these, Design III stood out as it was the closest one capable of showing the trends observed in both sensors without any casing (Fig.5 (c) and Fig.6 (c)), which is a greater response for a harder surface and reduced response as the stiffness of surface decreases. In all the cases, the response showed a deviation which is summarized in Table 1 and is within the expected range. This goes to show that the system designed is consistent for both types of sensors and, once calibrated to a specific application, can function without any loss of properties.

TABLE 2: Sensor Packaging: Qualitative Analysis and Comparisons.circumstances.

Sensor Design	Advantages	Disadvantages	Use Case Scenarios
Design I	• Greater strength and good stability • Good response to soft materials • Moderate response to stiff materials	• No response for hard materials	• Applications using large force and soft material substrates
Design II	• Better response for soft materials • Good response for stiff materials	• No response for hard materials • Unstable design and low strength	• Applications using low force and moderate-to soft substrates
Design III	• Shows trends in all sur-faces • Easy to fit in and remove the sensor	• Reduced ability to hold the sensor Low strength •	• Material-specific applications such as characterization or identification
Design IV	• Ability to tolerate immense pressure • Good response to soft materials	• No response for stiff and rigid materials	• Applications using large force and soft material substrates

3.3 Limit Tests on Sensor Casing Designs

The four sensor casing designs underwent a limit test to determine the maximum force they could withstand before cracking. A continually increasing weight was applied to them, and the breaking point (within 5% error) was determined. The maximum force sustained by each sensor casing design can be observed in Fig. 7. While the pillar constructions are limited in their ability to endure pressure, Design I can withstand up to 900 N of force since it balances relatively steadily and distributes the stress evenly to all corners. The lowest breaking point was found in Design II, which broke at around 500 N of applied force. Due to the design's high pressure on the corner supports, it is unstable under high loads and begins to bend in the center. Design III failed at around 600 N. The Design III structure, which includes filleting the pillars, lowers its structural integrity, leading it to shatter even if it can disperse the force slightly better. Design IV provides the highest structural stability and strength, with the potential to endure more than 1000 N of force before cracking. The thick supports provide enough strength, making it a choice for situations requiring heavy equipment and high contact forces.

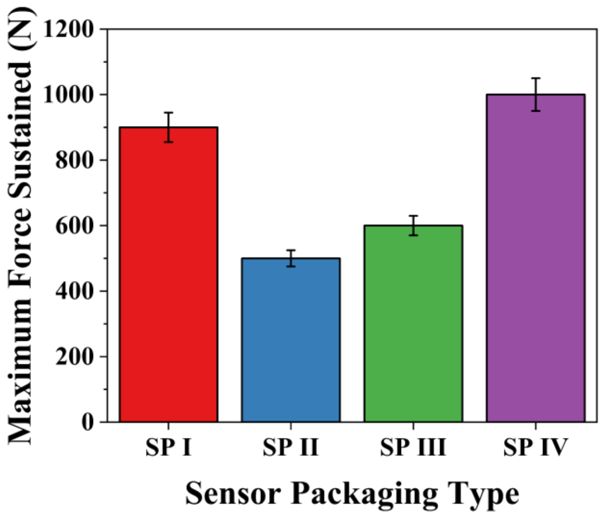

Fig. 7. The plot presents the maximum force that each sensor package design can sustain. Sensor packaging I (SP I) is the sensor placed in Design I, sensor packaging II (SP II) is the sensor placed in Design II, sensor packaging III (SP III) is the sensor placed in Design III, and sensor packaging IV (SP IV) is the sensor placed in Design IV.

3.4 Usage of Sensor Packaging: A Qualitative Analysis

Based on the quantitative sensor response analysis, sensitivity analysis, and limit tests conducted, the packaging designed for the soft pressure sensors eliminates the difficulties they had as standalone sensors, but it has certain disadvantages, including a decreased sensor response, lower sensitivity, and inability to exhibit the full trend anticipated for the sensor. Nonetheless, each design has a distinctive quality that enables it to be employed in an appropriate set of Table 2 presents the advantages and disadvantages of each sensor casing design with use case scenarios. The entire system operates as a simple plug-and-play mechanism, enabling multi-functionality and user-friendliness. The conformable packed soft pressure sensor for tactile perception has a variety of real-world applications. For example, the usage of Design III can be applicable to legged robotics [41, 42] for terrain mapping and decision making for tactile intelligence; and Design I, II, and IV can be used in Assistive Robotics for human-robot interaction [43], under actuated grasping and dexterous manipulation [44].

4. Conclusion

In this article, we have presented and analyzed four conformable packaging designs of a soft pressure sensor for tactile perception. Piezoresistive and piezocapacitive type pressure sensors were utilized in this study. After each sensor casing was manufactured, it was fitted with a pressure sensor to study its behavior. The experimental findings show that the piezoresistive and piezocapacitive sensors have outstanding sensitivity of 8.21 kPa^{-1} and 6.68 kPa^{-1}, respectively, limits of detection of 0.7 kPa and 0.1 kPa, and response/recovery times. The performance of the four distinct design structures were examined after packing. In the case of designs with protrusions above the sensor face (Designs I, II, and IV), no reaction was detected for hard surfaces, while adequate pressure was required for softer surfaces. Design III provided the greatest response results; however, it lacked packing capabilities since the contact points were only in the corner and could not tightly hold the sensor. The maximal force that each sensor enclosure could endure was determined in laboratory experiments. The testing findings demonstrate that each sensor casing fractured at various force levels, with the lowest force withstood being about 500 N and just one casing design reaching the maximum value of 900 N. A qualitative investigation was carried out by identifying the benefits and limitations of each sensor casing design and suggesting the most appropriate use case scenarios for each design.

In our future research, we intend to use an appropriate sensor case design for robotic applications such as integrating with quadrupedal legs for terrain detection in both indoor and outdoor environments and integrating with the fingers of the robotic arm to recognize commonly available objects in the home environment without the aid of cameras.

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