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Hit the Ground Running—Wearable Sensors to Measure Foot Plantar Pressure †

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Abstract: Flexible pressure sensors can be used to predict possible injuries and inform the wearer about their foot posture and landing positions during both walking and running. This work focuses on designing and producing capacitive pressure sensors and integrating them into a smart insole. The suitability of sensors was assessed using a mechanical test rig to measure the change of capacitance under different loads. The effects of introducing micropores into the dielectric layer using two fabrication methods were analysed. The results obtained imply that the use of micropores has the potential to increase the sensitivity and improve the response time of the sensors.

Keywords: capacitive pressure sensor; wearable electronics; foot plantar pressure; smart insole

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1. Introduction

Foot plantar pressure is an essential parameter for sports and healthcare applications. Pressure sensors, integrated into force plates and shoe insoles, are amongst the main tools used to measure foot plantar pressure which can analyse various movements performed by the user. Insole pressure sensors have a broad spectrum of multiple applications, for instance, in gait and motion analysis, rehabilitation, sports training, step counting, and detection of loss of balance [1]. These applications need to measure pressure in different parts of the sole in order to identify foot posture related to the wearer's movement activities.

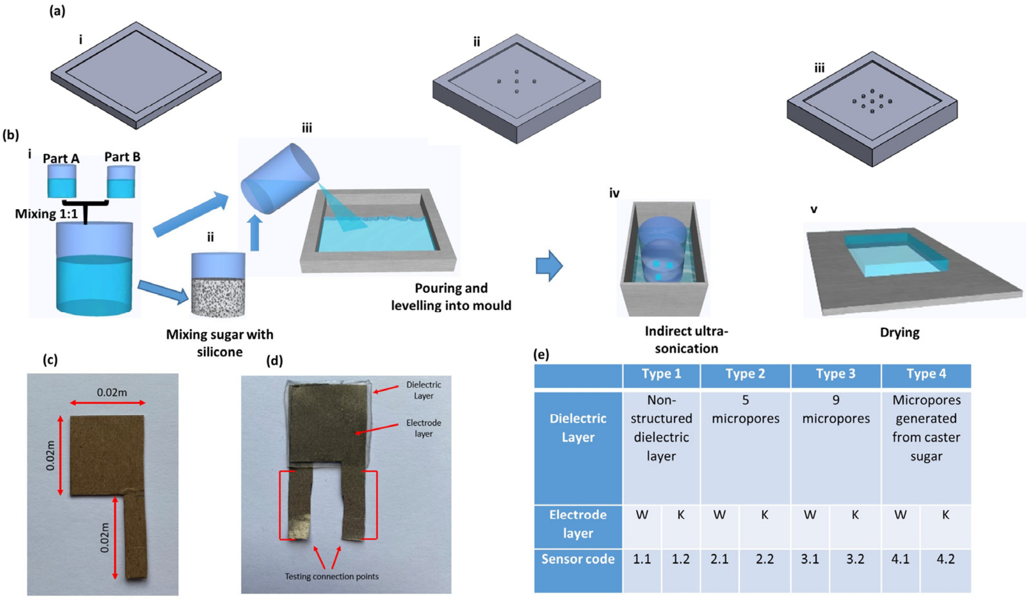
This creates a need for robust pressure sensors that can be integrated using textile manufacturing techniques and ensure that the device has suitable properties to be worn inside the shoe. As with developing any wearable sensor, there are some properties to consider. Stretchability is one of the essential characteristics of a wearable sensor due to the naturally irregular surface of the skin, and changes can be presented as a consequence of the normal movement [2].

This work demonstrates an initial development of a low-cost pressure sensor that can be embedded into an insole to continuously measure foot plantar pressure over time, giving the user a more natural movement and therefore obtaining better readings. This, in turn, will lead to better measures for injury prevention. The developed sensor employs a conductive fabrics and silicone elastomer to fulfil the stretchability property.

2. Materials and Method

In this study, parallel plate capacitive pressure sensors were created using a layered structure of conductive fabrics with a middle dielectric elastomer layer. Two types of conductive fabrics were used as conductive layers, a woven (70% polyester, 16% copper and 14% nickel $-0.2\ \Omega$ per 20 cm) layer and a knitted fabric (83% nylon and 17% silver $-1.4\ \Omega$ per 20 cm) layer. Ecoflex 00-30 was used as the middle dielectric layer. In addition, Chitosan (medium molecular weight) and Acetic acid (99.7%) were purchased from Sigma-Aldrich to prepare the insulation layer.

Three aluminium moulds were created to fabricate the dielectric layer of the sensors, with dimensions of 0.041 m × 0.041 m × 800 µm. Two moulds were made with vertical columns (diameter 600 µm each, with 5 and 9 columns) to insert vertical pores into the dielectric layer (Figure 1a), while the remaining one was without columns.



	Type 1		Type 2		Type 3		Type 4	
Dielectric Layer	Non-structured dielectric layer		5 micropores		9 micropores		Micropores generated from caster sugar	
Electrode layer	W	K	W	K	W	K	W	K
Sensor code	1.1	1.2	2.1	2.2	3.1	3.2	4.1	4.2

Figure 1. Fabrication process and surface examination of sensors. (**a**) Moulds prepared for dielectric layer fabrication, showing moulds (i) without vertical columns, (ii) with 6 vertical columns and (iii) with 9 vertical columns; (**b**) dielectric layer fabrication, showing (i) mixing Ecoflex part A and Part B 1:1, (ii) mixing with sugar granules, (iii) pouring into the prepared mould, (iv) indirect ultra-sonication and (v) final dielectric layer; (**c**) electrode dimensions, template for fabrication; (**d**) fabricated capacitive pressure sensor with conductive fabric electrode layers and a middle dielectric elastomer layer; (**e**) fabricated sample categorization.

Ecoflex 00-30 silicone solutions A and B were mixed in a 1:1 ratio. The mixture was poured into moulds and kept inside the oven at 70 °C for two hours to cure the silicone (Figure 1b). Cured silicone was extracted carefully for the secondary process. A second approach to integrating porosity within the dielectric was taken, using microcrystals that could be dissolved after curing. The process was repeated to fabricate the dielectric layer by adding caster sugar in the initial mixing phase. A 20 g volume of the Ecoflex 00-30 solution was mixed with 5 g of caster sugar. Once the solution was homogenous, it was poured into the mould with no holes and kept in a 70 °C oven for 2 h. Indirect ultra-sonication dissolved the sugar granules and created a microporous structure. Developed dielectric layers were cut into 21 mm × 21 mm dimensions. Eight samples were developed using knitted and woven fabrics separately, along with four dielectric layers (Table 1, Figure 1e). After that, 1.5 g of chitosan was mixed with 2% Wt % Acetic solution 50 mL and stirred using magnetic stirring for 4 h at 40 °C. The solution was poured into a casting mould and kept for 6 h to dry at 40 °C. An insulation layer made with chitosan was made as a pouch, and the fabricated sensor was put into the pouch before characterizing.

Table 1. Slope and R^2 values calculated for all sensors.

Sensor Type	Slope	R^2 Value
Type 1.1	4.21	0.95
Type 1.2	3.39	0.95
Type 2.1	3.44	0.82
Type 2.2	4.92	0.98
Type 3.1	3.17	0.97
Type 3.2	3.88	0.98
Type 4.1	3.05	0.98
Type 4.2	2.05	0.96

3. Results

SEM imaging was carried out with Jeol JSM-IT 100 InTouchScope SEM at the top surface and tilting angle of 70°. From the SEM image, the thickness of the dielectric layer was measured as 780.729 µm. Additionally, the average size of the sugar granule was 616.519 × 203.338 µm (Figure 2a,b). SEM images confirmed that the ultrasonic process caused all the sugar granules in the dielectric layers to be dissolved, creating a pore with 521.265 × 255.178 µm. A Keysight U1701B handheld capacitance meter and Univert CellScale Machine were used to test the fabricated capacitive pressure sensors (Supplementary note S1). Using the CellScale machine, the force was applied by changing the displacement in true strain function with stretch, recovery and holding for 10 s, respectively. Stretch magnitude was changed between 2%, 3% and 4% displacement. Each test comprises five cycles (supplementary note S2). Graphs were plotted between constant displacement and average capacitance for all sensors (Figure 2c). Line of best fit and regression analysis was carried out to find the relationship between the displacement and capacitance. The recorded slope and coefficient of determination (R^2 value) values for each sensor are given in Table 1.

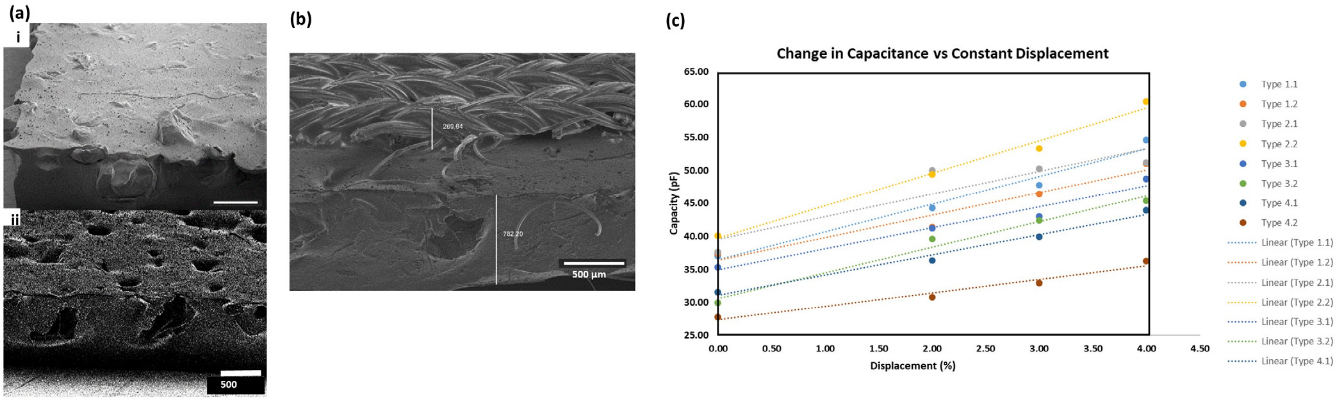


Figure 2. (**a**) SEM images of sugar granular mixed dielectric sample (i) before and (ii) after washing, (**b**) SEM of fabricated sensor (**c**) Comparison of 8 sensors capacity change with respect to displacement.

4. Discussion

The slope of the graph indicates the sensitivity of each sensor, while the R^2 value indicates the linear relationship between the displacement and the capacity. Sensor type 1 is the non-structured dielectric layer. This sensor acted as the control throughout the project to compare the different dielectric layers.

Sensor type 2 and type 3 are made with vertical pore structures. The experimental results indicate that the sensor type 2 woven electrode has a low sensitivity and linearity, and that the knit electrode has a high standard deviation for all three constant displacements individually. On the other hand, sensor type 3 with the woven electrode had an average performance, while the knit electrode demonstrated a high sensitivity and linearity along with a high standard deviation (supplementary note S3). Further investigations are required to prove the effect of adding more vertical pore structures over the surface.

Sensor type 4 has a microporous dielectric layer created from sugar granules. This sensor has a low standard deviation and a moderate slope. This shows that the sensor is moderately sensitive to a change in capacitance when the constant displacement percentage increases.

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \tag{1}$$

The formula (Equation (1)) for a parallel plate capacitor's capacitance (C) can be broken into four variables (ε_r, d, A: relative permittivity, thickness and area of the dielectric material, respectively and ε_0: permittivity of the vacuum). Air has an ε_r of 1.0005 while Ecoflex 00-30 has ε_r of 2.8 [3]. This indicates that an increase in air gaps can reduce ε_0 ε_r, thus reducing the capacitance. The reduction of the capacitance of sensor type 4 gives evidence of this behaviour. This could indicate that a further increase in micropores in a smaller dielectric area could reduce the capacitance. However, when pressure is applied to the sensor, the air gap between the two layers is reduced. This causes a more significant deformation, resulting in a higher sensitivity in the sensor [4]. Based on the limitations of the measurement techniques observed in this study, the further development of the testing conditions and use of the more sensitive LCR meter and high frequency, high force linear actuation system would be needed to allow for accurate comparisons to be between the different approaches to fabricated capacitive pressure sensors.

5. Conclusions

This work presents the development of a capacitance-based flexible pressure sensor using textile-based materials. Two methods of adapting the properties of the dielectric layer were tested by increasing the porosity of this layer. The porosity of the layer was confirmed using SEM imaging. The results obtained imply that sensitivity and response time can be improved by implementing microporous structures in the dielectric layer. The study used Chitosan as an insulation layer around the pressure sensor to shield from external interference with the sensor. The use of chitosan enhances the wearable requirements of a sensor placed in contact with the body in terms of biocompatibility and antibacterial properties. The developed sensor has the potential to be integrated into a smart insole which would contribute towards better indicators for injury prevention, rehabilitation progress, fitness assessment and sports performance.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/engproc2023030006/s1, (Supplementary note S1–S3).

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Conflicts of Interest: The authors declare no conflict of interest.

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