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Smart Textile Pressure Sensor Matrices—Investigation of Sensor Characteristics for Use in the Surgical Environment [†]

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Abstract: This paper presents research on flat textile pressure sensor characteristics that are advantageous for use in the surgical environment. Eight, 4 by 4 textile pressure matrices were subjected to sensor error testing to evaluate the sensor output differences on foam vs. no foam. The pressure matrices were tested using a compression tester while monitoring the voltage output. The errors analysed included the span, sensitivity, and nonlinearity. The findings show that for use in the surgical environment, prototypes two and three demonstrate better performances in the tests on foam, and both prototypes exhibit properties that are more suited for the surgical environment and warrant further prototype development.

Keywords: sensor characteristics; smart textiles; mechanical testing; foam surfaces; piezoresistive; surgical environment

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1. Introduction

Pressure sensors are used extensively in surgical procedures, help to provide real-time feedback on the forces applied to the characteristics of tissues, and help to reduce accidents and the number of surgical instruments used [1]. Piezoresistive sensors have been shown to be extremely valuable in the medical field, with sensors being used for pressure monitoring and mapping, feedback systems, and force sensing and analysis. Pressure mapping is used to monitor body positioning, including monitoring pressure injury (PI) development. In the literature, it is heavily documented that pressure sensors have been integrated or retrofitted into exiting mattresses to allow for monitoring, such as Mater et al. [2], who designed a bed sheet containing textile pressure sensors that demonstrated a promising use in posture identification. The use of these types of sensors to monitor PIs in surgery has not been documented; however, the prevalence of PIs in surgical patients undergoing spinal surgery in the prone position was 23% [3]. This is due to morphological changes, the patient's immobility, and the lack of opportunity to reposition the patient. This supports the need to develop sensors that can be used in the surgical environment, specifically on soft foam surfaces that are used to support the patient's positioning during surgery.

2. Materials and Methods

2.1. Design of Sensor Matrices

The developed sensor design follows a sandwich-type structure where, in the most basic description, there are three layers: a top electrode, a piezoresistive middle layer, and a bottom electrode layer (Figure 1).

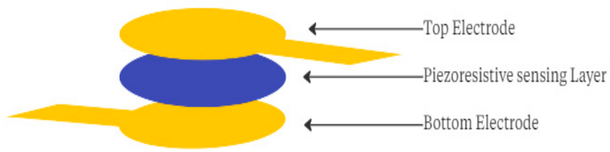


Figure 1. Sensor structure sandwich type.

Inter-spitzen AG (FRTI) in St. Gallen, Switzerland manufactured and produced eight flat 4 by 4, flexible textile sensor matrices using a consistent manufacturing process and varied materials for comparison. The matrices, sized 230 mm L × 160 mm W in a rhombus layout, were integrated into Baxter Healthcare Corporation's spinal table. The sensor matrices have a total of 16 sensor intersection points (Figure 2). Each sensor intersection point's sensing area is 10 mm^2. The maximum force applied was 200N over the entire matrix (and bolster during testing). Tests were based on an average body weight of 65 Kg, assigning 20 Kg per bolster, aligning with a maximum of 200N during testing.

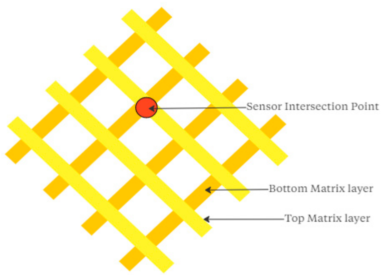
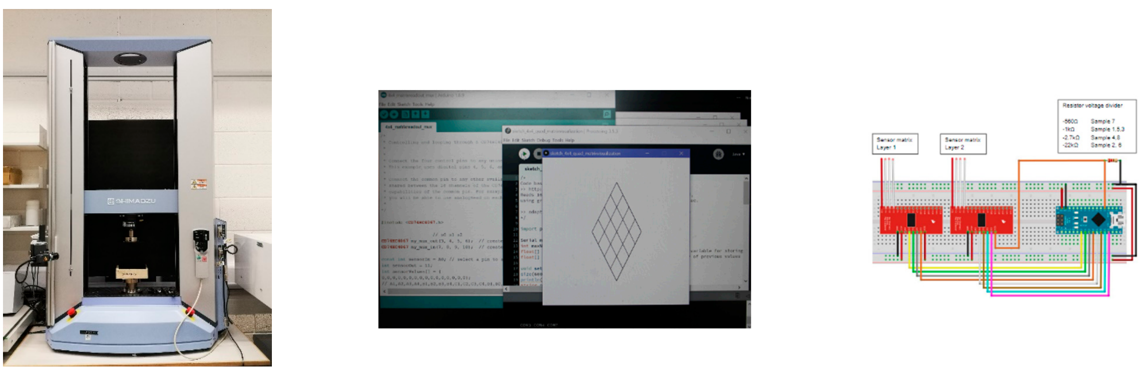


Figure 2. The 4 × 4 matrix structure with sixteen sensor intersection points.

2.2. Test Methodology

Eight prototypes were tested using a Shimadzu Mechanical Tester AG-X Plus (Shimadzu Corporation, Kyoto, Japan) with a 1KN load cell. Each prototype was secured onto a custom load cell rig to prevent movement, ensuring consistent testing methods. The setup remained identical for both foam and no-foam tests. A microcontroller (Arduino) was integrated with Processing IDE, facilitating data collection from all 16 sensor intersection points, recording analogue signal readings every 1000 milliseconds (Figure 3).



(**a**) (**b**) (**c**)

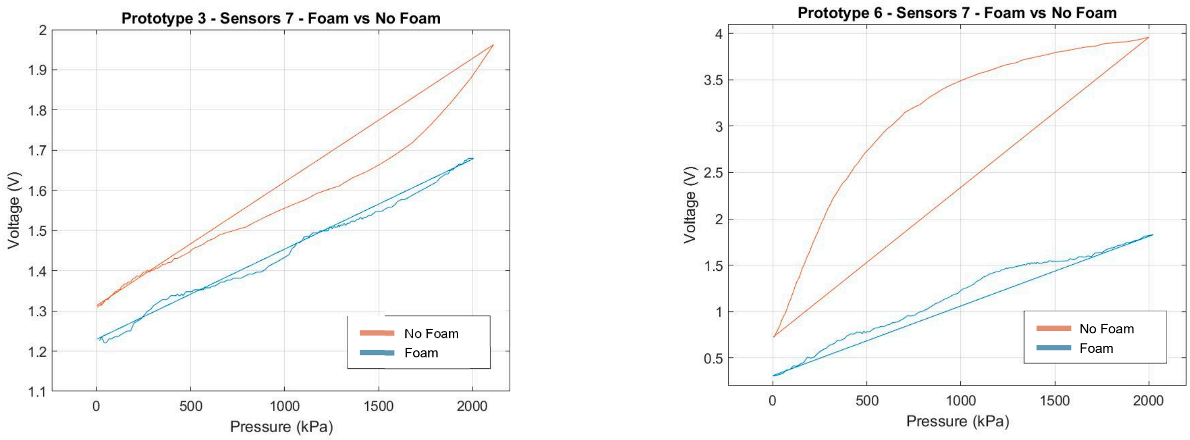
Figure 3. Compression setup. (**a**) Compression apparatus. (**b**) Software visualisation of the textile sensor matrix. (**c**) Hardware electronic schematic setup.

2.3. Sensor Characterisation

In order to investigate the effect that a foam surface has on sensor outputs, the prototypes were subjected to compressive loads with data captured to compare the sensitivity, span, and nonlinearity. These three main sensor errors are comparable, whether the prototypes are on foam or on solid surfaces. Hysteresis was another important characterisation. However, these data were impossible to produce on foam, due to the foam recovery when compression was unloaded. Similarly, the intended use of the sensor does not require frequent on- and offloading of forces; therefore, hysteresis was excluded from the analysis.

3. Results

Data from all 16 sensors were collected; however, sensor intersection 7 (highlighted in red in Figure 2) was analysed in more detail due its central position in the matrix, minimising the potential signal deviation found at the foam pad's edge. Analysing the voltage output (Figure 4a,b) compared between hard surfaces and foam showed notable differences. Overall, a non-linearity error decrease was observed across all prototypes when evaluated on foam, except for prototype 4 (Table 1).



(**a**) (**b**)

Figure 4. (**a**) Prototype 3 results for foam vs. no foam. (**b**) Prototype 6 results for foam vs. no foam.

Table 1. Nonlinearity error of prototypes—no foam vs. foam.

Prototype	NL No Foam %	NL Foam %
1	42.66	37.01
2	9.17	5.21
3	−14.69	−3.14
4	11.89	26.28
5	45.83	41.01
6	35.60	11.47
7	43.40	23.81
8	41.78	36.62

Table 1 highlights all the results for nonlinearity for all prototypes. These finding show that due to a load being applied to a foam structure, the foam will yield elastically and absorb the force being applied. The rate of compression for the foam tests were 20 mm/min, which was considerably faster than with no foam compression (0.5 mm/min). This could account for the instability in the signal, as the foam does not have enough time to recover.

Table 2 shows the sensitivity and span of the sensor outputs with and without the foam surface. The results from this are varied, with the sensitivity increasing and decreasing over multiple different prototypes. However, for prototype 4, the sensitivity is very similar for both the foam and no-foam results; similarly, the span is stable for both results.

Table 2. Sensitivity and span results for the prototypes. No foam versus foam.

Prototype Number	Sensitivity No Foam mV/Pa	Span of Millivolts from 0N–200N No Foam	Sensitivity Foam mV/Pa	Span of Millivolts from 0N–200N No Foam
1	0.0391	835	0.0861	1733
2	0.1099	2304.3	0.0474	942.3
3	0.0355	748	0.0231	459
4	0.0942	1977	0.0944	1884.7
5	0.0297	596	0.0857	1709
6	0.1623	3235.6	0.0753	1523.4
7	0.0596	1196	0.0648	1285
8	0.0832	1685	0.105	2100

However, the nonlinearity results of prototype 4 contradicted all the other results, which indicate that nonlinearity improves the foam structure. If we look at the prototype 2 and 3 results, we can see that they have the least nonlinearity error, and the span decreases and the sensitivity increases (the smaller value, the greater the sensitivity) when tested on foam. If we compare this to other sensor results, such as prototype 1, 7, and 8, where the sensitivity worsens on foam and the span increases, we can see that these sensors suffer from a high nonlinearity error. Therefore, in this investigation, we can assume that the discrepancies in the span and sensitivity are due to nonlinearity.

4. Discussion and Conclusions

In this investigation, the sensor characteristics of eight 4 by 4 textile pressure sensors were explored. The effect of foam on these custom sensors had varying effects due to the specific sensor error tests conducted in this investigation. From the results, two possible prototypes (prototype 2 and 3) were identified to continue to be developed for use on foam surfaces due to their characteristic of having a better nonlinearity error on foam. The implications of this research will help to further the development of custom textile pressure sensors to monitor PU development and monitoring during surgery.

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Conflicts of Interest: Authors Julia Fleischer and Pascal Stark were employed by the company Inter-Spitzen AG. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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