# FUNCTIONAL FABRICS FOR MULTILAYERED TEXTILE PRESSURE SENSORS: COMPARISON OF STRUCTURES AND SENSITIVITY CHARACTERISTICS

**Aleksandrs Okss, Aleksandrs Valisevskis, Ugis Briedis, Ilze Baltina**
Riga Technical University, Latvia
aleksandrs.okss@rtu.lv, aleksandrs.valisevskis@rtu.lv, ugis.briedis@rtu.lv, ilze.baltina@rtu.lv

**Abstract.** In the field of protective smart clothing, such topics as monitoring of wearer's vital signs and spatial position are thoroughly studied in the literature. On the other hand, solutions for monitoring of hazardous events, such as high-energy impacts with foreign objects are studied to less extent. Such protective clothing is intended both for operators, working in environments with a risk of injury due to impact with moving parts or falling objects, e.g. operators of heavy agricultural machinery, first responders etc. Such a sensor would enable to detect the location of the impact, its force and would allow to develop a system that sends appropriate emergency signals. The proposed paper focuses on the development of such a sensor, giving a special attention to its structure and usable materials. The proposed matrix array sensor consists of three layers: upper and lower layers with electrically conductive traces and the intermediate piezoresistive layer. Due to the intended application, a textile piezoresistive layer is chosen and after studying the commercially available materials, EeonTex LTT-SLPA 60 kOhm conductive polymer-coated knitted fabric and Sefar Carbotex 03-120CF, 03-160CF and 03-205CF carbon/polyester woven fabrics were selected as the most suitable candidates for further testing. The testing was accomplished using Zwick/Roell Z2.5 compression/strain testing column and Agilent A34970A ohmmeter. The testing focused on changes in fabrics' conductivity under cyclic stress, sensitivity, measurement hysteresis and repeatability. Different technologies for connecting the piezoresistive and the outside layers were tested as well: direct connection and connection using conductive adhesive textile tapes. Based on the results obtained during testing, recommendations are given for the usage of the studied materials, based on their performance under various levels of stress. During the experiments the best metrological results were demonstrated by piezoresistive fabrics with conductive polymer coating. Besides that, it was concluded that while hot-melt adhesive conductive tapes substantially degrade the sensors' properties, the use of self-adhesive conductive tapes ensure constant and stable contact between the sandwich layers and thus improve the measuring stability.

**Keywords:** smart textiles, sensors, protective garment.

## 1. Introduction

First responders frequently operate in dangerous scenarios, where they cannot be directly monitored. Wearable technology can help monitor vital signals of first responder, protect from sudden threats and hazards, detect potential injuries. A set of solutions has been proposed to provide protective garment for first responders with various types of sensing elements [1; 2]. Most attention has been paid to environmental hazards detection, monitoring temperature, heart rate and respiration [3], stress level detection [4]. Unfortunately, one of the very serious threats, such as risk of mechanical injuries from falling, flying or crumbling objects or parts of structures, is underestimated in terms of identifying such injuries and assessing their severity.

The present research is the first step to overcome this gap and to develop a system, which provides a possibility to detect placement and intensity of outside mechanical load to first responder's body. We propose to solve the above-mentioned problem by using an array of piezoresistive pressure sensors in the form of an additional specific pressure sensing layer integrated in protective garment. Evidently, that from the ergonomic point of view this layer must be lightweight and soft, easily deformed, not to decrease comfort of the original garment. Besides that, it should be reliable to stretching, bending and friction tear, be simple from the manufacturing point of view, taking into consideration the complex 3D body shape, and be low cost to be available for wide application. Such demands in general can be fulfilled by using a fully textile sensing layer with construction based on commercially available materials.

There are two main approaches to designing pressure sensor arrays: single sensor arrays and matrix arrays. As a rule, arrays of single sensors are used with a relatively small number of sensors [5; 6], since each sensor must have at least one separate contact, and an array of $n$ sensors has at least $n + 1$ conductive traces. At present, such matrices with a large number of single sensors can be manufactured mainly using printing technologies that do not have sufficient wear resistance when printing on fabrics subjected to bending and tensile deformation, which is typical for the use of protective clothing. A more

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durable solution – printed sensor arrays on plastic films, are not suitable for our case due to insufficient flexibility and reliability of printed films to bending, tension and friction loads.

The use of the matrix sensor arrays makes it possible to create large sensory surfaces with a significantly smaller number of conductive pathways (an array of $n \cdot m$ sensors has $n + m$ conductive traces) compared to the case of single sensors [7]. Most sensor arrays are a sandwich of three layers: a middle piezoresistive pressure-sensitive layer is sandwiched between two outer layers with embedded parallel conductive tracks (hereinafter the outer layers are referred to as conductive layers). Such completely textile-based arrays have been developed and successively tested in a number of applications: a sitting posture control device [8], a sports mat [9], a smart bed [10] and others.

But the use of the developed textile matrix arrays in clothing can lead to a number of problems, since most of the existing solutions are designed for a flat, horizontal, stable installation, and the conductive paths have weak contact with the piezoresistive layer [11]. In particular, integrating existing array designs into clothing can cause resetting of sensitive points as well as relative displacement of the conductive layers when the clothing is stretched or folded and affects the measurement stability. Also, the weak point of the existing solutions is the high level of crosstalk currents due to the low resistivity range of the pressure-sensitive layer under load (it becomes comparable to the resistivity of conductive traces). Such crosstalk can be a source of erroneous data generation [11]. To avoid these problems, it is necessary to use additional complex technical solutions [12] or data processing algorithms [13].

Human body has many surfaces to be monitored from mechanical overloading. So, despite of the abovementioned challenges, it was decided to develop a pressure sensing layer of protective garment using the matrix approach and to improve existing solutions by decreasing of crosstalk and adjusting the technology of connection between piezoresistive and conductive array layers. It was also decided to use low cost commercially available textile materials for matrix array construction.

This article presents the results of the first stage of the development of a matrix array of pressure sensors: the selection and testing of pressure-sensitive and conductive textile materials for the development of a sensor array, as well as the technology for connecting the piezoresistive and conductive layers.

## 2. Materials and methods

### 2.1. Materials

An analysis of commercially available pressure-sensitive piezoresistive textile materials, as well as existing solutions [9; 10; 14] showed that polyester knitted fabrics with a piezoresistive polymer coating and carbon-polyester fabrics [15] are most suitable for our needs.

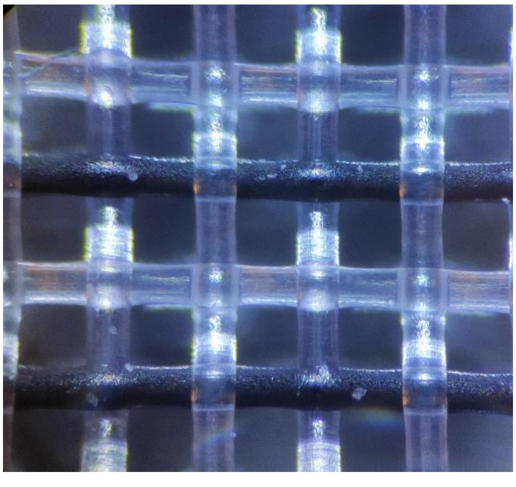


Fig. 1. **Structure of Sefar Carbotex 03-205CF, 100x magnification**

According to datasheets and availability on the market EeonTex LTT-SLPA 60 kOhm polymer coated knitted fabric and carbon/polyester Sefar Carbotex 03-120CF, 03-160CF, 03-205CF woven fabrics were selected as the most suitable candidates for further testing. In following these fabrics will be referred to as respectively *samples* 1 *to* 4:

- *sample* 1: EeonTex LTT-SLPA 60 kOhm;
- *sample* 2: Sefar Carbotex 03-120CF;
- *sample* 3: Sefar Carbotex 03-160CF;
- *sample* 4: Sefar Carbotex 03-205CF.

Sefar Carbotex fabrics have carbon-impregnated composite threads interwoven in warp direction with alternating polyester threads. Warp threads are exclusively made of polyester. The structure of Sefar Carbotex 03-205CF is shown in Fig. 1. Other materials of Carbotex line have carbon threads with different sizes and configuration.

For conductive layers and traces, hot melt adhesive and self-adhesive electrically conductive textile fabrics/tapes with conductive adhesives (Holland Shielding Systems B.V.) were used.

### 2.2. Methods

To test the pressure sensitivity of the selected piezoresistive fabrics, 200x200 mm samples were cut. These samples were tested using the Zwick/Roell Z2.5 compression/strain testing column by pressing the fabrics between copper plates measuring 20x20 mm, connected directly to the Zwick clamps, with an initial preload of 0.5 N for three ranges of the pressing force: 0.5-6.0 N, 0.5-50.0 N, and 0.5-100.0 N, which corresponds to the pressure levels up to 15 kPa, 125 kPa, and 250 kPa.

The Agilent A34970A ohmmeter was used to measure resistance during the experiments. According to the manufacturer's accuracy specifications, this device has a high claimed accuracy of 0,008% of reading plus 0.001% of range. This has a minimal effect on the experiments due to the nature of materials subjected to testing, due to the drift and hysteresis observed during experiments.

To test the possibility of using textile adhesive conductive tapes as conductive layers/traces with stable contact between conductive and piezoresistive sensing layers, the copper plates were replaced with pieces of a conductive fabric of the same size 20x20 mm to form outer layers of a three-layer pressure sensor. The outer layers were connected with a piece of a textile self-adhesive tape 10x50 mm with Zwick clamps (Fig. 2). Depending on the type of conductive fabrics, they were glued to the piezoresistive fabric with a hot iron (hot melt adhesive tape) or by pressing (self-adhesive tape). For the same loading options as above, the dependences $R(P)$ were again recorded and processed.

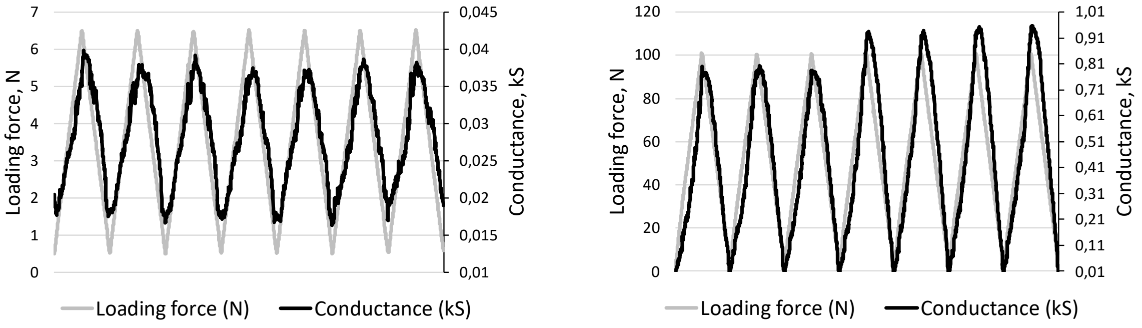
Fig. 2. **Connection to Zwick using self-adhesive strips**

## 3. Results and analysis

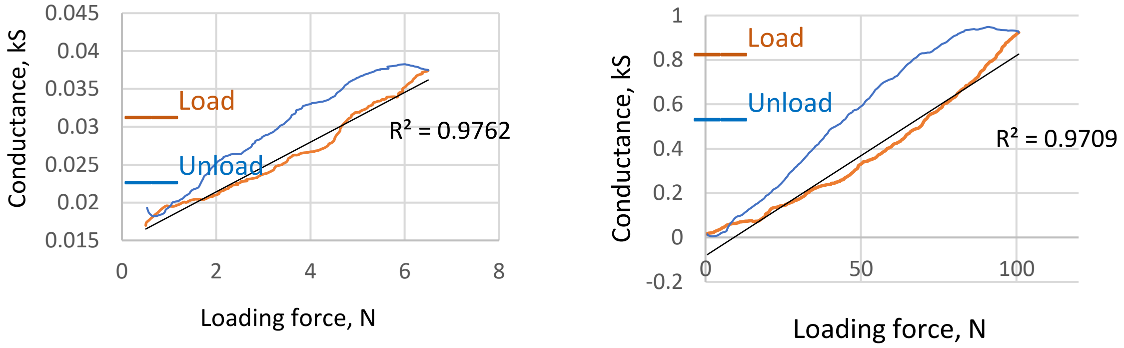
### 3.1. Tests with copper electrodes

Tests with copper conductive layers made it possible to minimize possible problems with contact between layers and the effect of conductive pathways on the resistive properties of the investigated piezoresistive fabrics. The results of these tests became the basis for evaluating the effect of using the adhesive fabric/tape as conductive layers/pathways on sensitive properties. Some examples of processed data for *samples* 1 and 4 are represented on Fig. 3 and 4. Fig. 3 shows behaviour of polymer-coated fabric (*sample* 1), but Fig. 4 – carbon-based fabric (*sample* 4).

It can be seen from the figures that both fabrics have good load cycling repeatability in both the low and high load ranges, but the carbon-based fabric has a much narrower hysteresis loop in the low load range (Fig. 3(b) vs. Fig. 4(b)), and both fabrics have good linearity with increasing load over the entire measurement range (Fig. 3(b), (d) and Fig. 4(b), (d)). Similar results were obtained for other types of fabrics studied. Data analysis also showed that the resistance of the coated fabric is an order of magnitude higher than that of carbon-based fabrics.

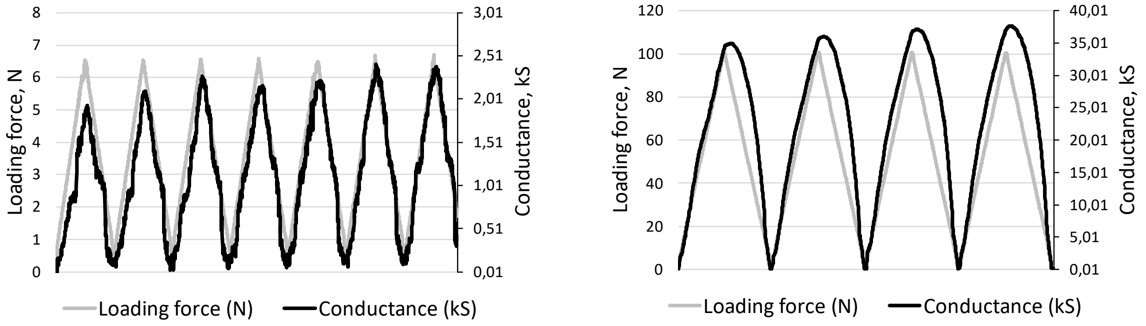


**a) conductance, 0-6N force range** **c) conductance, 0-100N force range**

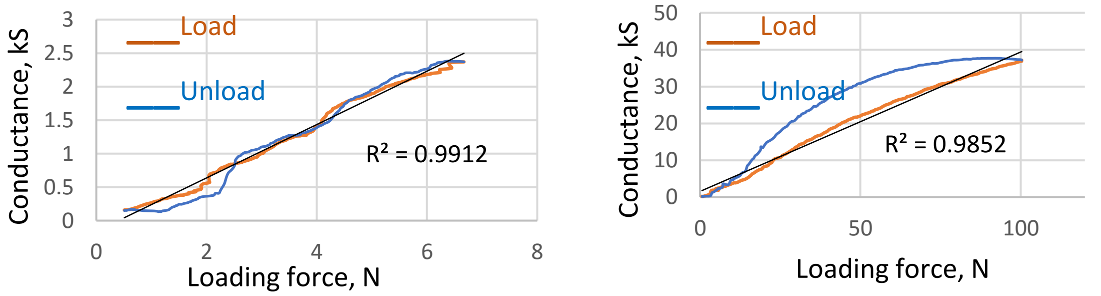


**b) hysteresis, 0-6N force range** **d) hysteresis, 0-100N force range**

Fig. 3. **Sample 1 test results**



**a) conductance, 0-6N force range** **c) conductance, 0-100N force range**



**b) hysteresis, 0-6N force range** **d) hysteresis, 0-100N force range**

Fig. 4. **Sample 4 test results**

### 3.2. Tests with adhesive electroconductive fabrics/tapes

Two types of adhesive fabrics/tapes were used in our study: hot melt adhesive and self-adhesive. The first was attached to the piezoresistive layer by hot pressing conductive fabric. The self-adhesive fabric/tape was attached by pressing without heating. The resulting sandwich structures were tested for various types of loading: compression, tension, bending, twisting and showed reliable adhesion between the layers. Thus, the use of adhesive fabrics/tapes as conductive layers, instead of the traditional approach of non-adhesive fabrics with embedded electrically conductive strips, ensures constant stable contact between the layers.

#### *Conductive layers with hot-melt adhesive*

The study of samples with layers of the conductive fabric with hot-melt adhesive showed that the attachment of this type of layers leads to complete degradation of the piezoresistive properties of all samples. This is clearly seen in Fig. 5, which shows the data for *sample* 1 with conductive layers with hot melt adhesive.

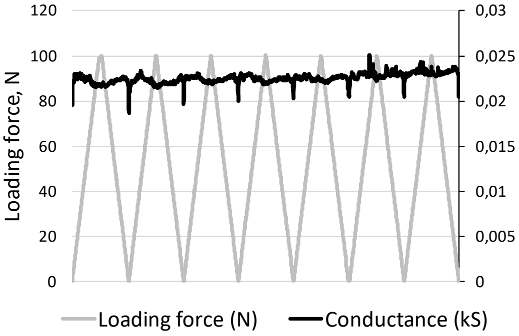
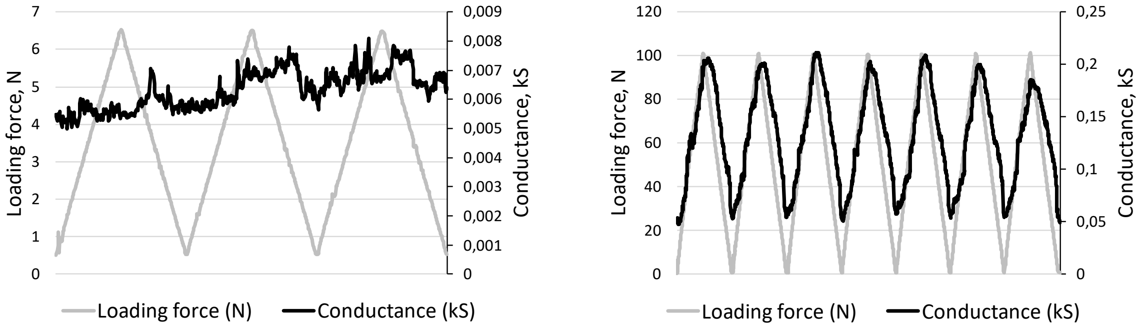


Fig. 5. **Sample 1 with hot-melt adhesive conductive layers**

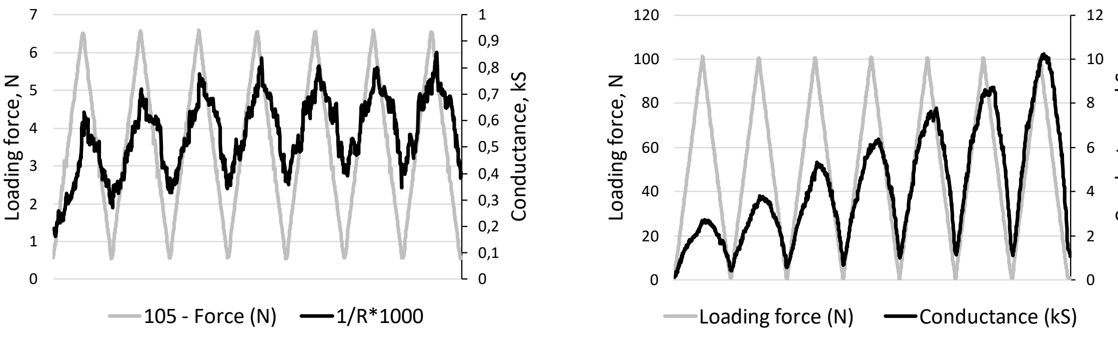
#### *Self-adhesive conductive layers*

Figs. 6 and 7 show examples of measurements for *samples* 1 and 4 with attached self-adhesive conductive layers. It can be seen that using the self-adhesive conductive fabric as a conductive layer affects metrological data of the sandwich pressure sensor when compared to copper plates. For example, *sample* 1 became completely insensitive to low pressure loadings (see Fig. 6(a)). Also, the self-adhesive tape of conductive layers causes gradual increase in the conductivity of carbon fabrics (Fig. 7(a), (c)) from cycle to cycle within 5-10% with a tendency to saturation. This affects the repeatability of measurements under cyclic loading. Despite this, in each cycle, the dependences S(F) (corresponding to the period of load increase) are very close to a linear function.



**a) conductance, 0-6N force range** **b) conductance, 0-100N force range**

Fig. 6. **Sample 1. Connection through self-adhesive textile strip**



**a) conductance, 0-6N force range** **b) conductance, 0-100N force range**

Fig. 7. **Sample 4. Connection through self-adhesive textile strip**

## 4. Discussion

The conducted studies have shown that all the studied samples of piezoresistive fabrics can be used as a sensitive layer in pressure sandwich sensors. In the case of copper conductive layers, they all have a sufficiently high sensitivity to pressure fluctuations over the entire measurement range. *Sample* 1 is a fabric with a polymer coating, which has a significantly greater resistance both in a loaded and unloaded state compared to carbon-based fabrics. This is advantageous in terms of reducing crosstalk currents in matrix structures. Among carbon fabrics, *sample* 2 has the highest resistance – a fabric with the thinnest carbon fibres and the highest structure density.

Measurements obtained with conductive layers of adhesive fabrics have shown that the use of fabrics with hot melt adhesive tapes leads to a complete degradation of the pressure-sensitive properties of the sandwich structure. Perhaps this is due to the fact that the high temperature required in this case for the process of gluing the sandwich layers leads to the destruction of the surface of the layer of the piezoresistive polymer coating of the fabric in *sample* 1, and also ensures the impregnation of the fabric with conductive glue, especially fabrics with a mesh structure like *samples* 2, 3 and 4.

On the contrary, the use of self-adhesive conductive layers causes an increase in the resistance of the sandwich structure, which can be beneficial for suppressing possible crosstalk effects in matrix structures. At the same time, the use of such a fabric as conductive layers can reduce the sensitivity, especially of sandwich sensors with polymer-coated piezoresistive fabric in the low-load region. It also leads to poor repeatability of results under cyclic loading of carbon fabrics. The latter phenomenon can be explained by the gradual penetration of conductive glue into the mesh structure of carbon fabrics. However, in the case of non-cyclic loading such as impacts or shocks, etc., a carbon-based pressure-sensitive fabric sandwich can provide an effective measurement.

The sensitivity of the resistive pressure sensor (S) is defined by equation:

$$S = \frac{\Delta R / R_0}{P}, \qquad (1)$$

where $\Delta R$ – change of resistance and
$R_0$ – initial resistance without applied pressure.

In Table 1 the sensitivity values for the sensors tested calculated according to (1) can be found. With the increase of pressure resistance decreases, thus the values are negative.

But in general, in the medium and high loading range, the multilayer pressure sensor with a sensitive layer of coated piezoresistive fabric (*sample* 1) has the best metrological characteristics.

Thus, the present study showed that, despite some of the drawbacks noted above, the use of self-adhesive conductive fabrics as conductive layers in pressure sandwich sensors allows us to solve an urgent problem: to ensure constant and stable contact between the sandwich layers in any position and deformation of the sandwich. This solution may in the future help develop sensitive layers for protective clothing based on the matrix array of pressure sensors.

Table 1

**Sensitivity of the tested piezoresistive materials**

| **Material** | **Applied pressure range, *kPa*** | **Sensitivity, kPa$^{-1}$** |
|---|---|---|
| EeonTex LTT-SLPA 60 kOhm (*sample* 1) | 0-15 kPa | -0.021 |
| | 0-250 kPa | -0.013 |
| Sefar Carbotex 03-120CF (*sample* 2) | 0-15 kPa | -0.045 |
| | 0-250 kPa | -0.014 |
| Sefar Carbotex 03-160CF (*sample* 3) | 0-15 kPa | -0.098 |
| | 0-250 kPa | -0.022 |
| Sefar Carbotex 03-205CF (*sample* 4) | 0-15 kPa | -0.07 |
| | 0-250 kPa | -0.019 |

## Conclusions

1. The tests with the commercially available piezoresistive fabrics showed that the best metrological characteristics of sandwich-type pressure sensors among the tested samples has the fabric with polymer coating.
2. The use of fabrics with hot melt adhesive as conductive pathways leads to a complete degradation of the pressure-sensitive properties of the sandwich structure.
3. The use of self-adhesive fabrics as conductive pathways causes an increase in the resistance of the sandwich structure, which can be beneficial for suppressing possible crosstalk effects in matrix structures but can reduce sensitivity in the low-load region.
4. The use of self-adhesive conductive fabrics as conductive layers in pressure sandwich sensors allows to ensure constant and stable contact between the sandwich layers in any position and deformation of the sandwich.

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## Author contributions:

Conceptualization, methodology, experimentation, data acquisition, data analysis and visualization: A.O. and A.V.; modelling embroidered layer, preparation of textile sensor: U.B.; testing properties of materials: I.B.; writing – original draft preparation, A.O.; writing – review and editing, A.V. All authors have read and agreed to the published version of the manuscript.

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