**Paweł Kubiak,
Jacek Leśnikowski,
Krzysztof Gniotek**

Textile Sweat Sensor for Underwear Convenience Measurement

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**Institute of Architecture of Textiles,
Faculty of Material Technologies
and Textile Design,
Lodz University of Technology,**
Żeromskiego 116, 90-924 Łódź, Poland
E-mail: jacek.lesnikowski@p.lodz.pl

Abstract
The following article is aimed at researching textile-based simplified sensors to determine the human perspiration effect and sweat appearance on the body and wearing surface. Using the current flow and resistance drop effect over cotton and polyester - based textile sensors, it is possible to detect sweat appearance on their surface. The article presents how to conduct a new , low cost, textile sweat sensor designed especially for healthy persons. The sensors proposed are designed to detect the presence of sweat and not for precise measurements of sweat properties. The sensors proposed are of the resistive type, therefore the presence of perspiration causes a change in its resistance. The main novelty of the sensor proposed is that it is based only on textile materials. Additionally examples of resistance measurements of the sensors proposed are presented. The results of research on the influence of the substrate on the properties of the sensors proposed are also described.

Key words: *textronics, textile sweat sensor, perspiration sensor, wearable sensor, underwear convenience.*

Introduction

Nowadays more and more attention is focused on human convenience and well-being in textiles. A wide variety of innovative textile products are designed and created. There are many new technologies of textiles and materials with added functionality, like magnetic cellulose fibres [1], as well as specified add-ons and preparations used to create a new dimension of textiles called Smart Textiles. In the case of using the flow of electric current over the surface of textiles, this group is called textronic systems [2].

Today most of us want to wear high technology clothes made from hi-tech textiles, or wear something innovative like textiles that are able to collect, send, receive and record information about our physiological comfort. Latest technologies in textile engineering lead to the synergic combination of IT, electronics and textiles [3]. This combination opens a wide range of new capabilities and possibilities for textiles. In this article, the proposition of a textronic sensor is described, and an example measurement method will be shown to reveal its ability to determine human perspiration and moisture effects as one of the wearing comfort aspects.

There are many researches on the thermophysiological comfort and well-being of textiles [4] as well as on the different textile sensors measuring underwear convenience. They can determine the humidity and temperature [5 - 8], but not the sweat appearance. Many of them work using chemical membranes that react to specified chemical elements and particles, and therefore are useful in a wide range of sports activities, human health and healthcare [9, 10]. Some sensors may even give information about human perspiration [10], Due to their properties, like dimensions, weight, stiffness, additional electrical components etc. they could be expensive, difficult in production and hard to implement in wearable clothes. For example, the sensor described in [9] contains channel dyed fabric with a pH sensitive indicator which has a colorimetric response. LEDs positioned above the channel are used to detect colour change, using a paired LED approach, making it possible to collect

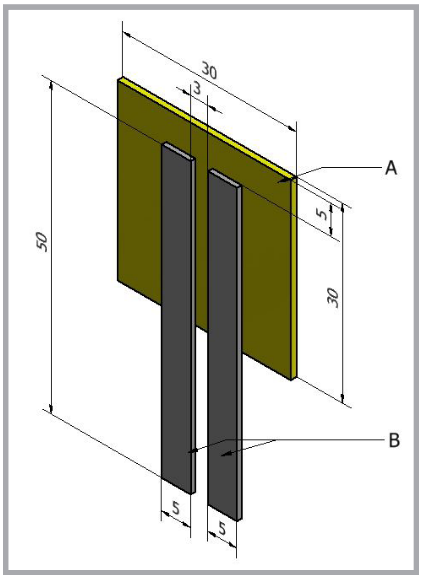


***Figure 1.** Textile sweat sensor tested: A – textile substrate, B – electroconductive paths.*

and analyse sweat. The sensor dimensions are 60 × 40 × 7 mm, which means that it is a thick sensor. Another example is that described in [10], containing two humidity sensors. The first sensor was at a distance of 0.2 cm from the skin, while the second was 1 cm from the skin. The result is that the whole sensor has a substantial thickness and can be easily felt by the user. There is, therefore, a need for a simple, fully textile, low-cost, flat and flexible sensor for measuring sweat which can be used, for example, in variable thermal insulation garments [11, 12]. A new kind of low cost and simplified sweat sensor is described in this article. The sensors proposed are designed to detect the presence of sweat and not for precise measurements of sweat properties. The main novelty of the sensor proposed is that it is based only on textile materials.

Object of research

The human sweating sensor proposed is presented in ***Figure 1***.

The sensor is fully textile and consists of a substrate layer made from specified cotton or polyester fabric and two strips made from electroconductive fabric named ‘Ponge’. The dimensions of the electroconductive strips were specially selected to be a compromise between the total dimensions of the sensor which should be as small as possible, and the ease of its manufacturing and implementation in wearable textiles, which are the main criteria for the sensor proposed. The electroconductive strips were sewed to the sensor surface in a ZigZag stitch with the following parameters: leap 4 mm, width 5 mm. Selected parameters of Ponge fabric are presented in ***Table 1***.

Ponge fabric is a fabric based on the addition of extra-conductive nickel. By using a fabric with the addition of nickel, this gave the ability to solder it to the rest of the measurement system. Moreover the sensor’s outputs can be connected to the measurement system by a mechanical clamp or be glued with specially electroconductive glue. An example of the measurement system is shown in ***Figure 2***. The resistance of the sweat sensor is converted to voltage and next to a digital signal processed by a microprocessor. Depending on the application, the microprocessor can be equipped with a radio communication module. The resistance data can be processed locally or transmitted further to a distant monitoring unit. The measurement system can be also equipped with an alarm module consisting of a light emitting diode or sound indicator engaged while human sweat appears on the sensor. The microprocessor can also be equipped with an underwear comfort control module.

The minimum amount of sweat which reacts to the system depends on the sensitivity of the measurement system operating with the sweat sensor. The minimum amount of sweat tested for the sensor described in the article is 0.5 ml. We found this amount to be easy enough for dosing and to control soaking and evaporation processes.

Different types of fabrics used as the sensor’s substrate were specially chosen to test if there is any effect of the substrate material on the sensor’s behaviour. While the sensor strips must be electroconductive, the substrate material cannot. The substrate material should be a fabric which provides constant dimensions of the sensor in different directions, and also should have the least thickness possible, which provides higher sensitivity of the sensor. The remaining parameters are not critical when choosing a substrate material.

Table 1. *Basic parameters of Ponge fabric from Soliani [13]:*

Type of raw material	Polyester fabric weft and warp
Warp density, yarns/dm	260
Weft density, yarns/dm	180
Nickel amount, g/m^2	16
Total weight, g/m^2	60 +/-15
Surface resistivity, Ohm/sq	max a verage 0.4
Temperature range, °C	from -40 to 90

One complete sensor has dimensions of 55 × 30 mm. Parameters of the cotton and polyester fabric used were measured and are presented in ***Table 2***.

The sensors should be placed in important and sensitive-to-sweat human body parts, like the chest, armpits, shoulders or loins. The sensors can be implemented in wearable textiles as integrated parts of textiles sewn into them, or as an additional attachable part. This method is more suitable when it comes to the conservation process and in the case of the necessity for detachment.

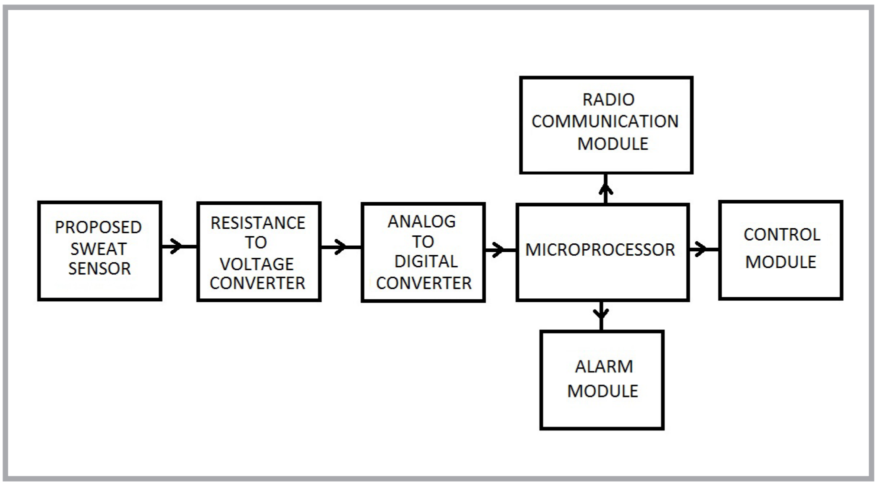
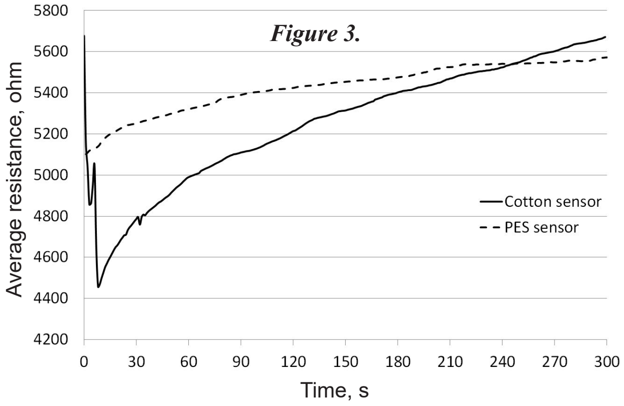
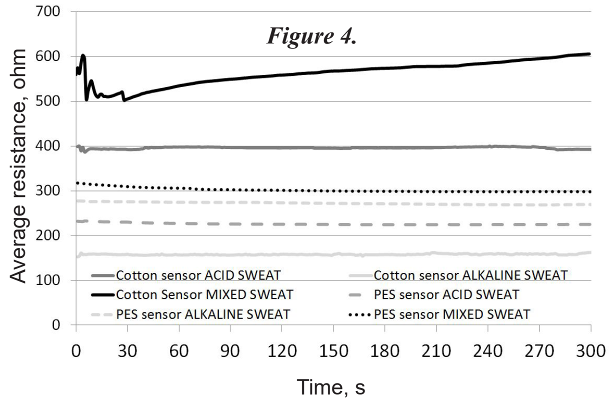


Figure 2. *Measurement system scheme.*

Table 2. *Parameters of the fabrics used as the substrate in sweat sensors*

Raw material (warp/weft)	Cotton/cotton	PES/PES
Weave, -	Plain	Panama
Warp linear mass, tex	30	26.6
Weft linear mass, tex	50	24.4
Surface mass, g/m^2	137	219
Thickness, mm	0.46	0,58
Warp density, yarns/dm	246	490
Weft density, yarns/dm	108	400
Surface resistivity, Ohm/sq	$4.8 \cdot 10^{10}$	$2.7 \cdot 10^{8}$





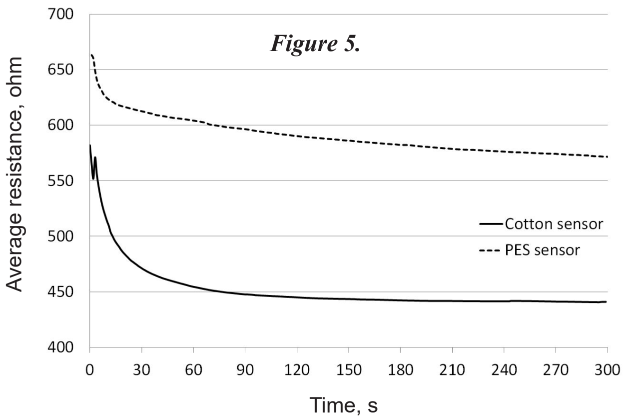


Figure 3. *Change in resistance over time after dropping water.*

Figure 4. *Change in resistance over time after dropping different sweats.*

Figure 5. *Change in resistance over time after dropping rainwater.*

Methodology of measurements

The sensor proposed is of the resistive type, therefore resistance measurements in the presence of various liquids were made. The sensor measures the appearance of the sweating effect on its substrate by way of a specified range of resistance values, under test for human sweat, tap water (Conductivity = 426 µS, pH 7.9) and rainwater (Conductivity = 208 µS, pH 7.8).

According to the ISO standard [14], human sweat varies in time from pH 5.5 to pH 8.0. As a sweat model, three different histidine hydrochlorides with pH 5.50 (acid sweat), pH 8.00 (alkaline sweat) and a mixture of them in the ratio 1:1 with pH 6.75 (mixed sweat) were used. Using a 4-wire connection method (Kelvin Method), it is possible to measure low levels of resistance, filtered from unwanted resistance decreases due to cables and connectivity self-resistance, which can cause measurement results to be more inaccurate [15]. Test leads were connected to the two electroconductive strips of the sensor tested to determine the resistance between them.

The sweating sensor was connected by the 4-wire Kelvin Method to an Agilent E4980A Precision LCD meter equipped with a notebook computer with a specified measuring procedure - LabView for data acquisition.

The measurement time was set to a 1 second interval, and the measurement current frequency was set to 1 kHz. Using accurate laboratory equipment, a 0.5 ml amount of different liquids was dropped on the sensor's surface between the conductive layers. The idea was to test the sensors for the human sweating effect on the moisture amount that is sufficient to induce an electric current flow between the two Ponge fabrics elements shorting them. Water and rainwater were dropped on the upper layer with electroconductive strips, while sweat was dropped on the bottom layer. This method reflects the influence of liquid on the sensor placed in clothes during normal operation, where the nickel conductive fabric will be placed outside the body. The sensors during the wearing process are wetted by different sweats on the other side (inner layer) from water and rainwater (outer layer).

Twenty five cotton-based sensors and twenty five polyester-based sensors were tested. They were divided into 5 equal groups, and hence there were 5 tests for each combination of sensor type (cotton and polyester) and liquid (water, rainwater and three types of sweat). The measurement data from each group were then averaged. Each sensor was used only once, and the procedure starts again with a new sensor. Immediately after the liquid was dropped, the procedure started to collect data in 5 minutes.

Results

The data collected from each of the five sensors (both for cotton and PES sensors) used with each liquid were averaged. Results of the average resistance for the different liquid values are shown in ***Figures 3-7***.

The average resistance diagrams of each liquid dropped clearly show the difference between water and all other liquids. While both types of sensors (cotton and PES) behave similarly over time for all the liquids, the resistance values collected were different. It is

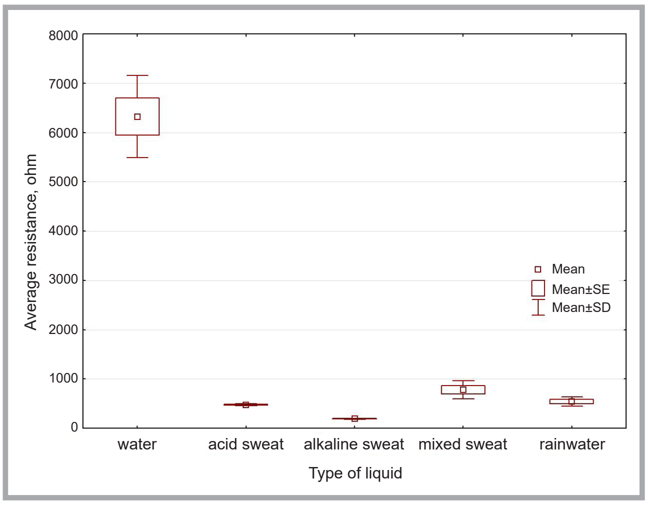


Figure 6. *Average resistance of the sensor tested with a cotton substrate wetted by different kinds of liquids.*

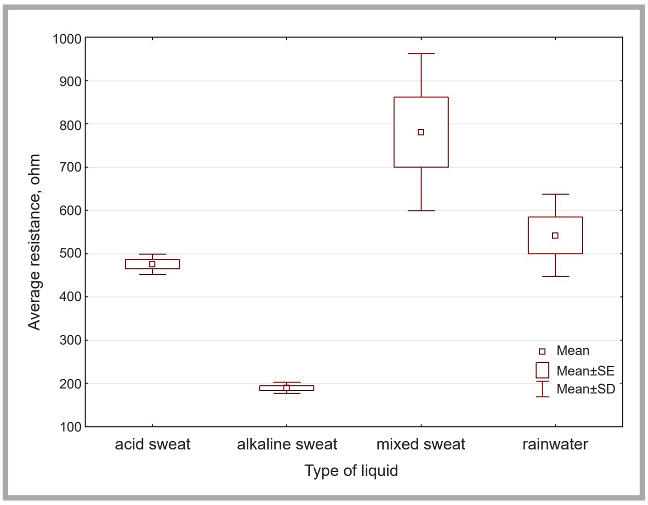


Figure 7. *Average resistance of the sensor tested with a cotton substrate wetted by different kinds of liquids, with the exception of water.*

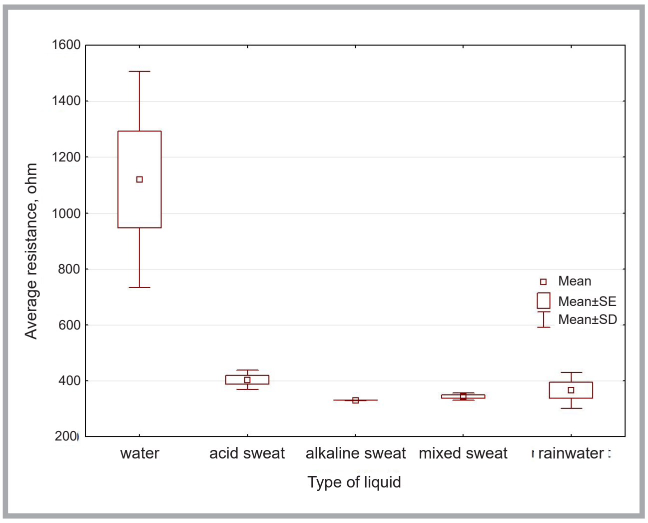


Figure 8. *Average resistance of the sensor tested with a polyester substrate wetted by different kinds of liquids.*

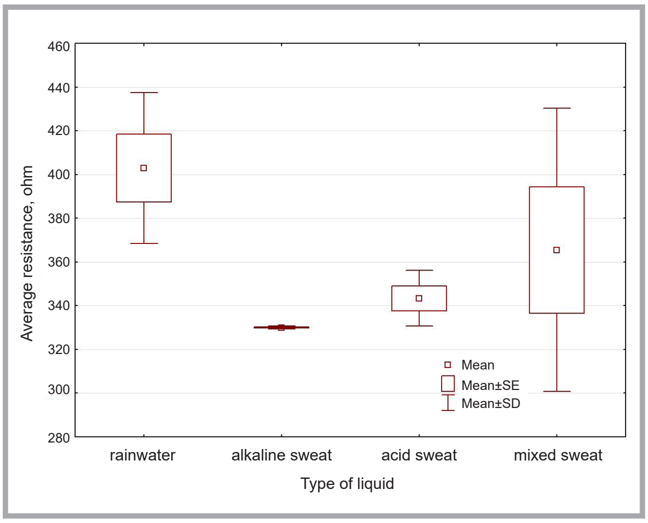


Figure 9. *Average resistance of the sensor tested with a polyester substrate wetted by different kinds of liquids, with the exception of water.*

clearly shown that the PES-based sensor collects data more steadily when it comes to water (***Figure 3***) and all three types of sweat (***Figure 4***). The cotton-based sensor has greater changes in resistance over time.

For statistical study, all values of resistance as a function of time obtained for each sensor were averaged. This resulted in obtaining 5 values for each fluid, in total 25 values for cotton and 25 for the PES type of sensor. Averaged resistance data collected were tested statistically.

Statistical analysis of the influence of different kinds of sweat and water on the resistance tested was performed using the nonparametric Kruskal-Wallis test instead of the Anova test due to inhomogeneous variances in the groups tested. Using the Kruskal-Wallis test with the significance level α = 0.05 (probability $p = 0.95$), the null hypothesis of equal average resistance measurements taken in the presence of different liquids on the sensor was tested. Two tests were conducted; the first taking into account water in the group of liquids, and the second without water in the group of liquids. As a result of the first and second test, for the cotton sensor, factors of $p = 0.0002$ and $p = 0.0012$ were obtained. This at given levels of significance and probability leads to the rejection of the null hypothesis assuming the equality of the average impedance in the groups tested, and confirms the hypothesis of a significant impact of the kind of liquid on the sensor's resistance. Examples of the mean values obtained with the standard error (SE) and standard deviation (SD) are shown in ***Figures 6*** and *7*.

As for water, the resistance measured is totally different comparing to all other liquids. This situation may depend on the lack of conductive elements and particles that affect the current flow, while human sweat contains many more conductive elements. To improve visibility, this liquid was taken out of ***Figure*** *7*.

Also for the sensor with a polyester substrate, final factors of p = 0.0019 (taking into account water in the group of liquids) and $p = 0.0379$ (without water in the group of liquids) were obtained with the significance level α = 0.05 and probability p = 0.95. This also confirms

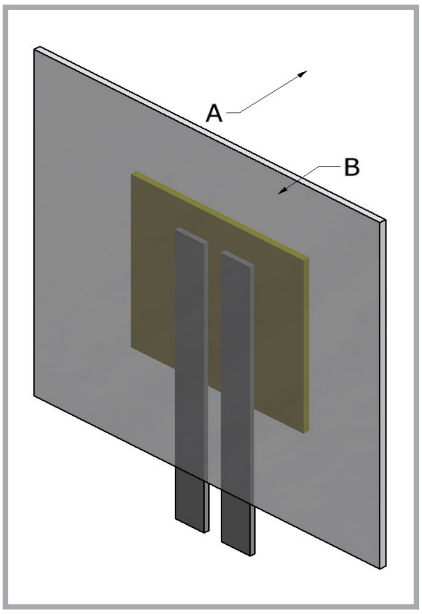


Figure 10. Proposed textile sweat sensor with waterproof, semi-permeable protection layer: A – to human body, B – waterproof semipermeable layer.

the hypothesis of a significant impact of the kind of liquid on the sensor's resistance. Examples of mean values obtained are shown in ***Figures 8*** and ***9*** (see page ...).

The results above were collected with new and unused sensors to make sure they were not affected by any other factors. As can be seen from ***Figures 6*** to ***9*** (see page ...), rainwater makes the resistance of the sensors similar to that for sweat. Additionally the large values of standard deviations (SD) collected for the different liquids which may indicate a large dispersion of results. Therefore it is necessary to protect the sensor from rainwater and other outer liquids with a watertight textile layer. This layer should be semi-permeable, stopping rainwater and outer liquids, while being permeable the sweat through. For example, this layer could be made from a *Gore-Tex®* material. The upgraded version with an additional protection layer is shown in ***Figure 10***. It is under development now and will be tested in the future.

Conclusions

In this article a simple sweat sensor with a specified cotton and polyester substrate was described and tested. The main novelty of the sensor proposed is that it is based only on textile materials. The sensors proposed are designed to detect the presence of sweat and not for precise measurements of sweat properties. This sensor, using the simple resistance drop effect, is sensitive to different kinds of sweat, differing from other liquids like water or rainwater, and when non-wetted it stays nonconductive.

A test of two different materials (cotton and polyester) used as a substrate of the sensors was performed to find information if the substrate materials affect the sensors' behaviour. Even cotton and polyester - based sensors behaviour similarly and are capable enough to detect the human perspiration effect. The PES-based sensor collects resistance data over time more stably than the cotton sensor, which fluctuated more easily as time passed. Therefore it seems that the polyester substrate, due to its stability, is more suitable as a substrate of sensors. The sensor is itself a standalone part of a measurement system. However, the measurements depended on what measuring devices were used, with the object of research being just the sensor. The sensor could be used many times, but a conservation and drying process is needed before any subsequent usage. The main advantages of the sensors proposed are the build simplicity, fully textile form and elasticity, which makes them user-friendly. It is entirely safe for the user, because of low, harmless current flow and no direct contact from the nickel parts with the body. Furthermore the sensors proposed have a low cost of manufacturing and can be made in any sewing room.

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