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Textronic Sensor for Monitoring Respiratory Rhythm

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Abstract
This paper describes the design of a textronic sensor for monitoring respiratory rhythm. The sensor, made of electroconductive materials, has a fabric structure and is knitted into a shirt.Tests were performed on a measuring stand and on volunteers. This paper presents characteristics of the sensor and curves of the input voltage of the sensor

Key words: *textronics, breathing sensor, measuring respiratory rhythm, electroconductive fibre.*

Introduction

The measurement of respiratory rhythm is one of the most important human physiological indicators. This work presents a prototype of a textronic sensor for monitoring the frequency of breathing. The sensor has a textile structure, consisting of electroconductive fibres. These types of interactive designs, hybrids of textile products and elements of electronics, are called textronic products [1, 2]. The solution presented has been designed and constructed in the past few years at the Department of Clothing Technology and Textronics and is now one of the solutions for sensors to monitor respiratory rhythm. The article briefly presents the way of designing such sensory products, as well as research and tests of the whole textronic system. The article also describes the physiological mechanism of breathing, which is necessary for designing these kinds of products.

Nowadays, respiratory rhythm is measured by specialised medical devices monitoring certain physiological quantities of the human. On the market there are many commercial solutions for measuring devices, so called spirometers. However, none of them is fully integrated with clothing nor is a part of it. Attempts at constructing mobile measuring systems have been made; however these constructions are based on conventional sensory systems, such as:

- The Textro-monitoring™ system by Textronics™ Inc, used to monitor human biophysical parameters, for example respiration rhythm and heart rate [3].
- The Ultima Respiratory Effort Sensor, introduced by the Braebon company, based on piezoelectric crystals which generate electric charges by deformation during breathing. The signal is send to an amplifier without any external current sources [4].

Also the optoelectrical sensor , which uses optical fibres in its structure, creates a hybrid structure with clothing [2, 4].

The aim of this research was to extend the functionality of traditional clothing with new functions not yet seen in conventional clothing solutions. Taking into consideration the fact that clothing is directly connected with the human body, attempts have been made to construct a textile clothing interface which adds a new function – interactive adaptation for external impulses.

Following the existing trend of manufacturing textronic clothing equipped with systems measuring physiological quantities of the human, a prototype of a textile sensor monitoring the frequency of breathing has already been elaborated [5] using the concept of mass-customisation, which concentrates directly on the user. Particular stages of the design process, presented in ***Figure 1***, are the following: identification of functions of newly created clothing, adjustment of the clothing and user by scanning the figure, and the design of clothing with the use of specialised software. The production process was performed on numerical knitting machines, obtaining a knit and wear clothing product. The whole process ends with verification tests of the textronic system.

Clothing which is in contact with the human body is called the clothing interface [6]. If it executes only one basic function, this is protects the human body from environmental influences; this is called a one-dimensional clothing interface. Moreover, clothing has to satisfy the human's individual requirements,

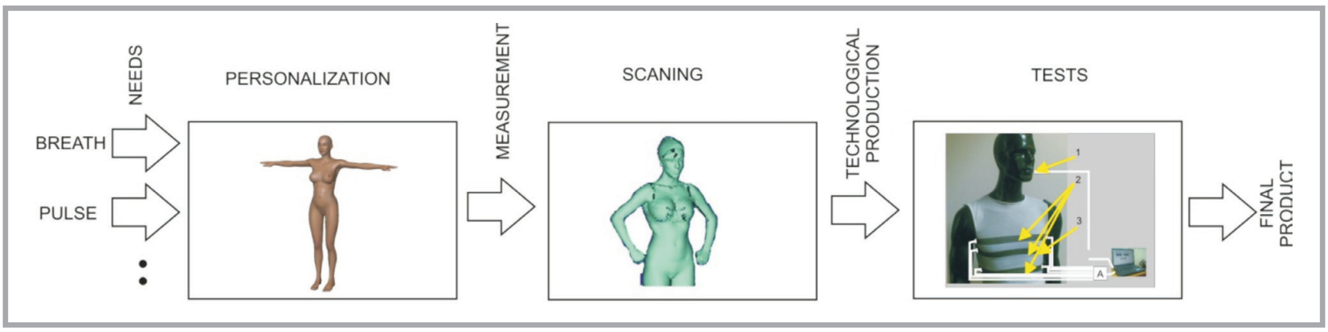

Figure. 1. *Simplified scheme of the technological process of producing textronic clothing products to monitor the frequency of respiratory rhythm.*

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taking into consideration their physique, fashion trends, financial possibilities, aesthetic feeling etc. When adding a new function to clothing (besides functionality and aesthetic), interactive adaptation to external signals causes the creation of a three-dimensional clothing interface [6]; such a product is a prototype of textronic clothing.

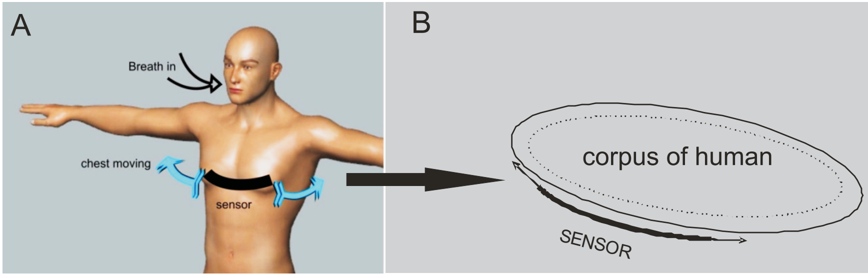

Figure 2. *A) Simplified scheme of the breathing mechanism; B) Simplified scheme of changes in the chest's dimension.*

Respiratory rhythm as a physiological parameter

The volume of rib cage changes in the breathing cycle due to an increase in the following three dimensions: anterior-posterior, transverse and superior-inferior (***Figure 2***). The anterior-posterior dimension increases due to the sternum standing off from the spine, thanks to muscles acting which raise the sternum by lifting the first rib connected to the sternum by synchondrosis. An increase in the transverse dimension is the result of lifting the down-curved middle ribs. An increase in the superior-inferior dimension of the rib cage is the result of lowering the diaphragm muscle. During the contraction, the diaphragm muscle presses the organs in the abdominal cavity, and therefore a rhythmic emphasis of the walls of the abdominal cavity is observed during the breathing process [7]. In normal conditions exhalation is the passive phase of breathing. The main inspiration muscle is the diaphragm, separating the rib cage from the abdominal cavity. Other breathing muscles are less important and are activated during more intensive effort. Inspiration is the active phase of external breathing. Rib cage and lungs previously widened come back to their "initial" dimensions thanks to a phenomenon called elastic deformation [7]. During breathing at rest, there are 14 – 18 cycles per minute for a healthy man, which is equal to 8 litres of air. At every breath, 350-500 ml of air flows into the lungs, called breathing air, and the process – a minute ventilation. The number of inspirations and expirations changes with regard to the body's activity, for example while exerting effort, it can be from several to over twenty times higher than the minute ventilation during rest [7, 8]. These parameters were taken into consideration while constructing the textronic clothing.

Hypoxia increases the level of adrenaline and noradrenalin, which increases the heart rate and blood pressure. Severe hypoxia may lead to death. Dangerous situations occur in the professional activity of soldiers, policemen, firefighters, rescue workers, as well as people going through convalescence at home, creating possibilities for potential applications of textronic sensors monitoring the respiratory rhythm. The most important function of the prototype sensor described is an increase in human safety, which can be achieved by early detection of danger and effective prevention. Monitoring the work conditions and state of health is the basis for realisation of this function, which must be completed with a control system containing systems of automatic regulation, storage and transmission. This kind of activity, focusing on the protection of human health, is called e-medicine or telemedicine, which over the past few years has been developing in a very dynamic way [9]. The basic element of the monitoring system is the breathing sensor.

A textronic system monitoring the frequency of respiratory rhythm can be also used for monitoring the breathing rhythm of people suffering from sleep apnea, which is a very dangerous, life threatening disorder. A similar phenomena is observed in infants, therefore all kinds of products monitoring the breathing rhythm of infants are manufactured. The monitoring of work conditions and state of health is the basis for realisation of this function.

Knitted resistance sensor

Electroconductive fibres or yarns have sensory properties since the distortion of a fibre is accompanied by a change in the electrical resistance R. The resistance depends on the fibre or yarns, particularly

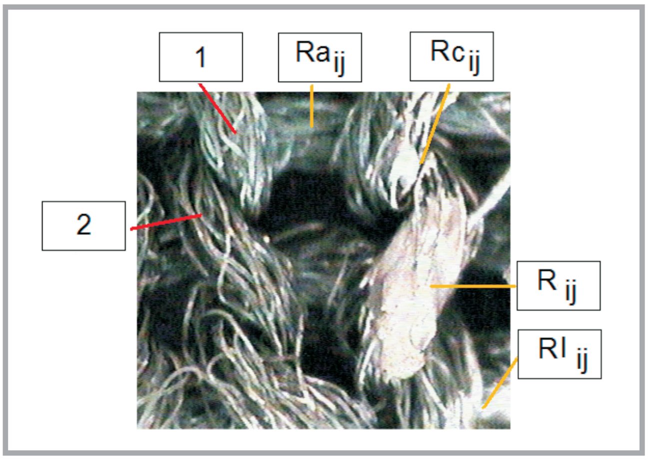

Figure 3. *Fragment of the knitted sensor's structure [1]; 1 - segment 1, 2 - segment 2.*

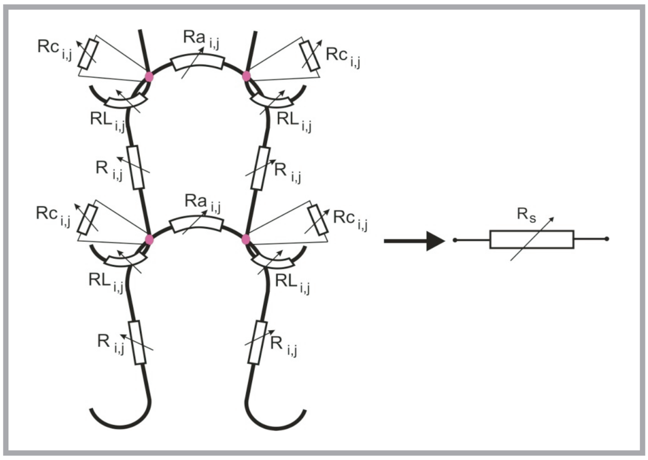

Figure 4. *Equivalent resistance scheme of the knitted sensor subjected to stretching.*

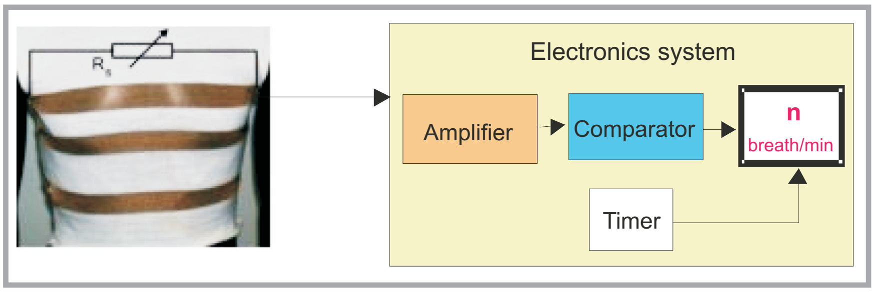

Figure 5. *Block diagram of a system for measuring the respiratory rate (n = indicator).*

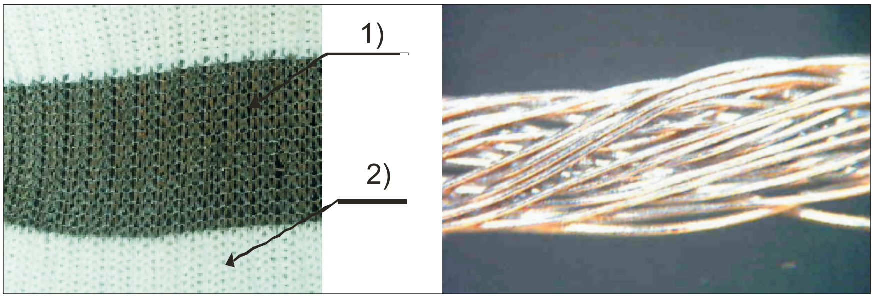

Figure 6. *Textile sensor used in this research; A) general view of part of the sensor, B) microscopic photo (10 ×) of Xsilver yarns used for sensor construction [12]; 1 - cotton yarn, 2 - silver yarn.*

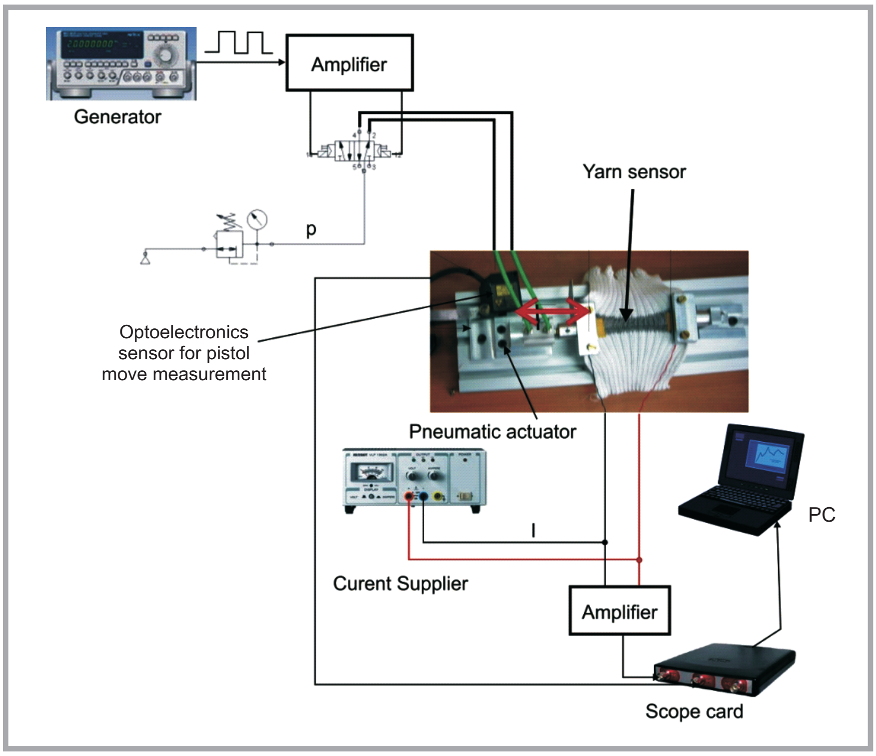

Figure 7. *Scheme of measuring system.*

on their conductivity γ and geometrical dimensions. This property was used in the construction of a sensor knitted in a shirt for monitoring the breathing rhythm frequency.

A breathing frequency sensor can take the form of a tight-fitting knitted shirt, which contains a small fragment in the form of a strip made of electroconductive yarn. During breathing, the rib-cage deforms, which leads to the stretching and shrinking of the shirt (***Figure 2.B***). The sensory properties of a knitted fabric produced from electroconductive yarn result from its structure, presented in ***Figure 3***, where $Ra_{i,j}$ is the resistance of the needle arc of a loop, $Rc_{i,j}$ - the resistance of connection points between the threads forming the loop, $R_{i,j}$ - the resistance of a fragment of the generating line of the loop, and $Rl_{i,j}$ is the resistance of the arc of the loop [3, 10].

The resistance model presented in ***Figure 4*** represents the structure of electroconductive knitted fabric.

An equivalent scheme consists of resistors representing the connections between the knots of the loop and the resistance of connection points between the connectors of loops in the structure of a knitted fabric. The resistors between the loop knots are connected in series and parallel. During a breath, the knitted sensor is stretched and shrunk, therefore the resistances of the arc of the loop change their values. The resistances of connecting points also change during a breath because the contact line between two yarns changes its length, and therefore the pressing force changes [4]. Analysis of the circuit of an electric sensor made of a knitted fabric is very complicated, as it consists of a hundreds of loops, similar to woven structures [11]. Moreover, it is difficult to determine the resistances of the resistors presented in ***Figure 4*** (see page 75). The substitute resistance of sensor R_s changes during breathing. The resistance of the sensor is an element of voltage divider connected to the inlet of an amplifier, being part of the electronic measuring system (***Figure 5***), which also consists of a comparator, gating circuit and one-minute timer.

Testing a sensor element

An electroconductive knitted sample is an element of a respiratory frequency sensor. In the first part of the research, samples of sensorial knitted material were formed consisting of two parts, as shown in ***Figure 6***, one of which was manufactured from typical cotton yarns of 32 tex, and the second from electroconductive yarns – polyester yarns of 156 tex coated with silver (20%). The sensitive part had dimensions of 90 × 30 mm. Another important requirement for underwear monitoring of human parameters is its tight fit to the body. In order to ensure a comfortable unit pressure for the user, it should be within the range of 2 - 4 kPa, in the relaxation zone [9].

In this research the static characteristic of the sensor was determined and tests using a mechatronic stand were performed (***Figure** 7*), where a knitted fabric was stretched and its substitute resistance measured, shown in ***Figure** 8*. The static characteristic of the textile sensor, made in the form of a knitted strip, is presented in ***Figure** 7*.

The mechatronic stand consisted of a pneumatic actuator, whose piston rod moves over a length of 25 mm. A holder was mounted at the end of the piston rod, where a sample of the yarn sensor was inserted. The displacement of the holder was measured using an optoelectronic sensor. The generator was controlled by a power amplifier and pneumatic distributor fed by the pressure p of the pneumatic actuator. The actuator was controlled by a rectangular wave from the generator. The Frequency of the controlling signal from the generator was changed in the range of the physiological value. A square testing signal was used due to the two-position activity of the pneumatic actuator.

Tests of the sensor were performed on the measuring stand at a frequency range equal to the physiological range of a human. The selected courses of deformation and output voltage of the sensor amplifier (***Figures 9.A and 9.B***) for a frequency of 0.25 Hz, being equal to 15 breaths per minute, confirm the fact that the sensor produces a voltage wave according to changes in the deformation of the sensor. The shape of the sensor voltage differs from that of the square weave, which is connected with deformation, as the relaxation phase appears after stretching of the sensor's knitted fabric. It can be observed in the course of voltage, a fragment of which takes on an exponential shape as the voltage decreases.

The shirt tested has three electroconductive stripes knitted in, which is a result of different tests performed on volunteers of different sex, as women breath in a different way to men. All three stripes of the sensor meet the requirements of textronic constructions and are characterised by correct operation. The respiratory sensors are in the form of stripes fitted tightly to the body of the person being tested and are knitted in the structure of a textronic shirt. In the back part of the product the sensors are integrated with textile electronic connectors directly connected to the measuring system. In order to connect textile sensors of the respira-

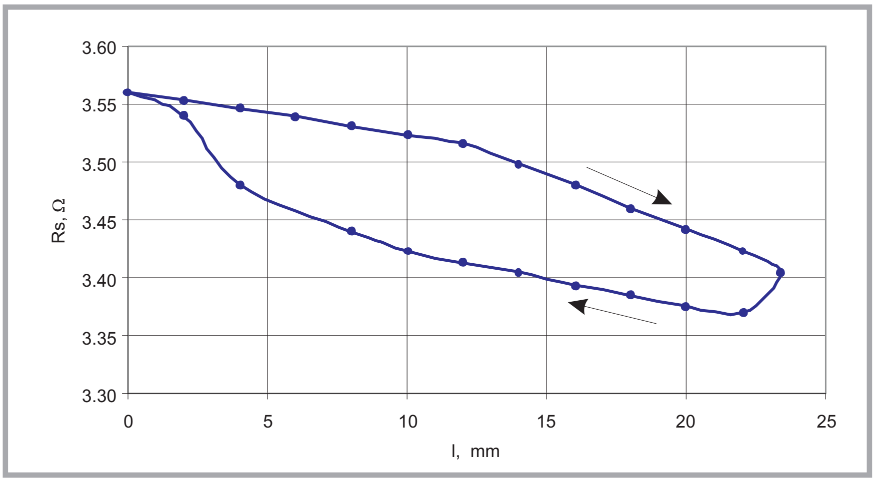

***Figure 8.** Substitute resistance of the knitted sensor in a deformation function.*

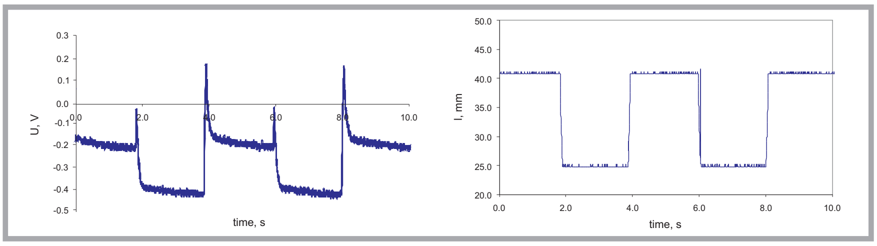

***Figure 9. A)** Voltage of the sensor subjected to temporary deformation at a frequency of 0.25 Hz; **B)** Displacement sensor elongated at a frequency of 0.25 Hz.*

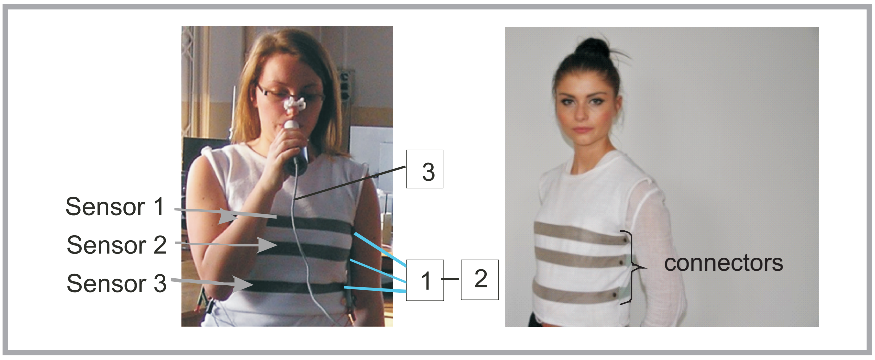

***Figure 10.** Electroconductive fibre sensor; 1 – electronic system (amplifier); 2- recording device (computer) 3- professional spirometer.*

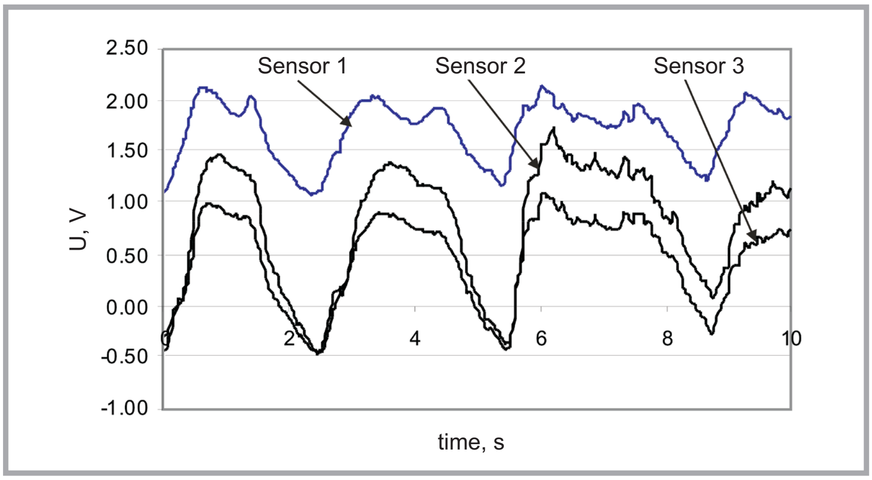

***Figure. 11.** Exemplary results of breathing rhythm frequency obtained using a textronic shirt.*

tory rate, the textronic contact junctions described in detail in [13] were used.

A prototype of textronic clothing for monitoring the respiratory rate is presented in ***Figure 10*** (see page 77). The real courses of the voltage of the sensor integrated with a shirt registered are presented in ***Figure 11*** (see page 77).

Discussion

The construction of textronic products requires changing the prevailing mentality of manufacturers of specialised clothing. First of all, the production of this kind of product requires the collaboration of a few branches of industry (textile industry, electronics, medicine), which means an increase in the expenditure of companies in order to change their production systems and develop technological lines. However, it seems as if continuous technological progress will force this kind of course of the development of the modern textile industry. Modern clothing with sensory characteristics is a new specialisation being developed at the Department of Clothing Technology and Textronics.

The textronic sensor described integrated with clothing allows to monitor the breathing rhythm frequency and can be inserted in different types of apparel (shirt or blouse).

The advantage of the sensors discussed is that they do not interfere directly with the human body and their textile form does not cause discomfort of use.

Conclusions

The textronic sensor for measuring the respiratory rate described can be applied in many different products due to its fibrous structure and elasticity. The sensor has a linear static characteristic. The tests performed showed that the sensor works correctly, as the output voltage of the sensor followed changes in its deformation. Moreover the real measurements of the respiratory rhythm using the test shirt confirmed that it works correctly.

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