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Research Article

Evaluation of the impact of printing and embroidery parameters in the process of obtaining utility comfort sensors used in protective clothing dedicated to premature babies

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ABSTRACT

Biophysical comfort is one of the most important criteria for evaluating children's clothing products, as it contributes to maintaining to the thermal balance between the human body and the surrounding environment in which the newborn resides. This article describes the influence of screen printing and machine embroidery on the development of sensors designed to measure skin parameters such as temperature and humidity using a paste containing carbon nanotubes and four different electrically conductive yarns. An additional parameter examined was the embroidery (density, with two variants: 80 % filling and 60 % filling). The experimental part of the research involved testing surface mass, material thickness, air permeability, heat resistance and water vapor resistance as well as assessing sensory and conductive properties. All prints and embroideries discussed in the study were applied to the author's original three-layer system which has thermal resistance and water vapor resistance properties at levels that ensure the safety of prematurely born children by protecting them from excessive moisture loss and maintaining thermal comfort when they are outside the incubator. The resistance of all electrodes was below 12.22 Ω, both for samples after the washing and sterilization processes.

1. Introduction

Global statistics reveal a consistent increase in preterm births. American researchers have observed that, although the percentage of newborns delivered before 32 weeks of pregnancy has remained stable in recent years, the number of children born between 34 and 36 weeks has steadily risen. These late preterm newborns represent over 70 % of all premature births [1,2].

Premature infants are particularly vulnerable to heat loss due to their large external surface area relative to body weight, thin and immature skin, absence of a stratum corneum, lack of an adipose layer and brown adipose tissue, inefficient shivering, and poor vasomotor responses. Studies indicate that preterm babies with low birth weight can lose up to 150 ml of water per kg of body weight, within the first 24 h, leading to potential electrolyte imbalances. In contrast babies born after t30 weeks experience a significantly lower, water loss, around 12 ml/kg/day [3]. For optimal development, maintaining a stable temperature and humidity in the infant's microenvironment is essential. A thermally neutral environment, with temperatures between 36.5̊C and 37.5̊C, minimizes oxygen and caloric consumption [4]. This stable environment is crucial to maintaining the baby's thermal balance [5].

Neonatal hypothermia has been linked to increased mortality rates in preterm infants [6–8]. Research also shows a strong correlation between neonatal hypothermia and serious neonatal conditions such as intraventricular hemorrhage sepsis, severe retinopathy of prematurity, necrotizing enterocolitis, bronchopulmonary dysplasia and neurodevelopmental disorders [6–11]. Infants with extremely low birth weight are particularly at risk, as every 100-g decrease in birth weight correlates with a 0.04°C drop in admission temperature [8].

The immaturity of the skin's permeability barrier in preterm infants results in:

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- increased water loss through evaporation, exposing the infant to risks of dehydration, particularly hypernatremia,
- significant energy loss through evaporative heat, with 0.58 kilocalories (kcal) consumed for every milliliter (ml) of water evaporated [12,13].

Therefore, optimal care for preterm infants involves compensating for skin water loss to maintain fluid and electrolyte balance and ensuring in a thermally neutral environment to direct caloric intake towards growth rather than heat production [14].

Achieving a neutral thermal environment is a key physiological challenge for newborns. Careful management of this environment, to the temperature in the delivery room to the use of polyethylene occlusive skin compresses, can improve clinical outcomes and survival rates. Despite the importance of this issue, these interventions are not widely studied in research [15–17]. Newborns, particularly preterm and sick infants, struggle to regulate their body temperature. They rely on incubators to stabilize their thermal environment, monitor vital parameters, and promote their growth and survival. Heat and mass transfer between the newborn and the surrounding environment are critical to their development. Researchers use various methods to better understand neonatal heat loss and body-environment interactions in maintaining thermal neutrality, the ideal thermal environment for newborns [18].

Continuous monitoring of vital signs is usually carried out using various in preterm infants is essential for their survival and well-being. Non-contact monitoring methods are ideal for long-term observation [19]. Current monitoring devices, include pulse oximeters, electrocardiograms, bed mattresses, breathing belt transducers, nasal thermocouples and piezoelectric transducers [20]. Traditional devices with adhesive sensor directly attached to the skin can damage the fragile skin of preterm babies [18,21]. New and experimental, such as magnetic induction, phonocardiograms, and thermal imaging, offer alternative methods for remote monitoring [18–29].

Magnetic induction methods detect impedance changes from the mechanical actions of the heart and lungs, but are highly sensitive to movement between the body and sensors [30–33]. Thermal imaging captures vital signs by measuring heat differences due to blood flow but is also prone to noise, motion artifacts, and low resolution limiting its detection capabilities [34–36]. These technologies require significant investment and specialized equipment, which making them expensive [19,36].

Research on monitoring infants in neonatal intensive care units (NICU) remains limited despite significant progress in adult monitoring technologies. Existing methods and datasets are primarily designed for adults, and there is currently no publicly available database specifically for preterm infants that can support the development of deep learning models [37,38]. In light of this, the authors of this study, who are working on the development of protective clothing for preterm infants, decided to explore how integrating temperature and humidity sensors into innovative textile structures could improve neonatal care. They aim to assess the impact of material modifications—using printing and embroidery techniques on the biophysical and properties of fabrics intended for preterm infant clothing (Total Hand Value (THV)) [5].

Biophysical comfort is crucial for evaluating clothing, as it influences the heat and moisture exchange between the human body and the user's environment. The results of the heat balance are due to the correct regulation of the temperature of the human body and the correct exchange of heat and moisture between the human skin and the environment. This exchange, which also occurs through clothing, is vital for maintaining thermal balance. Key clothing properties that determine physiological comfort include thermal insulation, moisture absorption, water vapor permeability and air permeability [39,40].

Sensory comfort, on the other hand, is related to the mechanical properties of clothing and is evaluated through the Total Hand Value (THV), a dimensionless parameter that measures how the material feels against the skin [41].

The clothing's biophysical properties, such as thermal insulation, thermal resistance, water vapor resistance, and water vapor permeability, are typically evaluated through experimental research, sometimes supported by theoretical simulations of physical phenomena within fabrics [2–13,41–43]. One of the factors affecting both the biophysical and sensory comfort of clothing is surface modification. There are many reasons why the surfaces of clothing textiles are modified. One of the goals of the modification is to improve the parameters of functional clothing, affecting the safety of a selected group of users and protecting human health and life by monitoring through wearable devices [19,37,38,44–47].

Recent advances in wearable sensors, including accelerometers, smart fabrics and actuators, wireless communication networks and power supplies, and data capture technology for processing and decision support for clinical trials and health monitoring [48–52]. Health monitoring is an essential application of wearable sensor systems, especially for infants. Recently, with advances in sensor techniques, wireless communication, and power technologies, wearable sensor systems have enabled a new generation of continuous health monitoring for infants. For example, the development of a sensory vest for infants containing fully integrated sensors can monitor electrocardiography, respiration, temperature and humidity, allowing for early detection of life-threatening conditions [50]. Conductive textiles and innovative designs improve infant comfort while providing accurate health monitoring [51].

This study focuses on evaluating the biophysical and sensory comfort of newly developed textile sensors, created through screen printing and machine embroidery using paste with carbon nanotubes and four different electrically conductive yarns. The ongoing work is a very innovative solution for several reasons. Firstly, they are focused on integrating sensors into the bowl for premature babies, not just newborns and infants. In addition, the sensors are made on a new, innovative three-layer material, which on the one hand provides adequate thermal comfort, and on the other hand prevents excessive moisture loss by prematurely born children [5,53]. These research also assesses whether these material modifications negatively impact the delicate skin of preterm infants and maintains the accuracy of data collected from the skin surface. Additionally, the materials' conductive properties are tested before and after conservation and sterilization processes. The content of chemical elements in electroconductive yarns was also determined in order to verify their safety for use with infants. The conductive materials integrated into the structure of protective clothing function by ensuring continuous monitoring of physiological parameters like temperature and humidity. In the case of the application methods employed, screen printing uses carbon nanotube pastes which allow for flexibility and minimal thickness of the conductive layer. In contrast, machine embroidery with conductive yarns, although slightly thicker, enhances durability and ensures better embedding within the textile structure. Both methods enable consistent data transmission, though the durability and resistance to wear differ between printed and embroidered components.

2. Materials and methods

2.1. Materials

The subject of this research was a three-layer material assembly consisting of polypropylene non-woven fabric, polyethylene film, and cotton knitwear. The three-layer system is an original development protected by a patent [53]. The systems were tested both before and after the printing and embroidery modification processes. Their properties were verified at various stages before washing and sterilization, after washing and after the ethylene oxide sterilization. As the material is intended for contact with human skin, all selected materials are certified under OEKO-TEX® STANDARD 100, ensuring that no harmful substances are released that could adversely affect the user's health.

The work assumed that screen printing and machine embroidery would allow for obtaining textile temperature sensors that would be durable in use processes. For this purpose, samples were developed in sizes of 2 × 4 cm, in two embroidery densities of 80 % and 60 % and made using the screen printing technique according to Fig. 1.

The aim of the project was to determine the best method for manufacturing sensors using textile techniques that would be durable in use processes.

All test samples were prepared in dimensions of 32 cm × 32 cm. This was determined by the size of the heating plate on which the thermal resistance and water vapor resistance tests are conducted. On no such sample were embroideries or prints made in the amount of 9 pieces. In this research, we have used one printing pastes with conductive properties, aqueous dispersion of carbon nanotubes (CNTs) from Nanocyl under the trade name AquaCyl AQ0301, which included NC7000TM series multiwalled carbon nanotubes (MWCNTs) with a diameter of 9.5 nm and a length of 1.5 µm, amounting to of 3 % by weight. Surfactants were added to improve dispersion and stability. Four electrically conductive yarns containing silver particles were used for modification process using the embroidery technique. It was assumed that the yarns should be characterized by good electrical conductivity and antibacterial properties. The first yarn selected was produced by Statex Productions+ Vertriebs GmbH marked as Shieldex. This polyamide multifilament yarn is coated with silver, offering both electrical conductivity and antibacterial properties, which may be necessary in various applications. It is characterized by an electrical resistance of less than 300 $\Omega \cdot m^{-1}$.

The second yarn used was the is a Noble yarn under the trade name X-Static. This polyamide thread is coated with silver particles with a content of up to 15 % by weight, and is produced in multifilament form, comprising 3–34 filaments. It is ideal for electrical applications as there are no charge losses due to the presence of individual filaments as is the case with staple fibre products. It is characterized by an electrical resistance of less than 400 $\Omega \cdot m^{-1}$.

The third material used was a silver-coated polyester-polyamide hybrid yarn under the trade name Silver-tech by Amann. Silver-tech is a specialised sewing and embroidery thread suitable for creating conductive seams and surfaces, textile electrodes that can be used as sensors and actuators. Due to its antibacterial properties, Silver-tech is also used to create components that require antimicrobial properties. It is characterized by an electrical resistance of less than 530 $\Omega \cdot m^{-1}$.

The fourth yarn used was Silver-tech+, also from Amann. This silver-coated continuous polyamide filament is designed for smart textiles as well as for medical textiles. It is characterized by an electrical resistance of less than 200 $\Omega \cdot m^{-1}$.

Table 1 summarises the characteristics of these yarns.

The material was embroidered with two different filling densities 80 % and 60 %. These percentages indicate the density of the stitching used to create the embroidered pattern.

The authors conducted the washing process according to the hospital guidelines to ensure that the tested material met the standards required in a medical environment. The application of the hospital washing guidelines aimed to verify that the material retained its properties (such as biocompatibility and structural integrity) after passing through a standard washing and disinfection cycle used in medical facilities. Since garments used in hospitals must be washed in appropriate conditions that meet hygiene requirements, it was important to test how the material reacts to these procedures. The washing process was carried out under conditions consistent with hospital laundering guidelines. It was carried out at a temperature of 40°C and a disinfectant for fabrics classified as medical devices (Ozonite BNL) was used for 5 washing cycles. The washing time for one cycle was 20 min. Rinsing five times was provided after each washing cycle. The authors relied on the guidelines for the ISO 6330 standard on textile washing methods and the EN 13795 standard on textiles used in a medical environment, which could be used to assess the washing and disinfection process of the material.

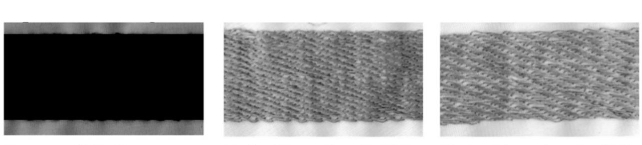

Fig. 1. Sample patterns prepared for testing.

Table 1
Characteristics of yarns.

Name yarn /tested parameter	Shieldex	X-Static	Silver-tech	Silver-tech+
Linear mass [dtex]	298.00 ± 3 %	312.00 ± 3 %	287.00 ± 3 %	331.00 ± 3 %
Specific strength [cN/tex]	368.24 ± 1,5 %	532.90 ± 1,7 %	457.65 ± 1,1 %	538.55 ± 1,9 %
Elongation at break [mm]	89.32 ± 6 %	107.21 ± 7 %	91.10 ± 5 %	102.15 ± 9 %
Electrical resistivity [$\Omega \cdot m^{-1}$]	< 300	< 400	< 530	< 200

The assumption of 5 washing cycles was developed based on consultations with pediatricians and production assumptions of three-layer systems on which temperature sensors are made. The three-layer system is made of, among others, a vapor-permeable membrane, which after 5 washing cycles undergoes minimal changes related to water vapor resistance. Since this indicator is extremely important in the case of prematurely born children, it was assumed that the durability of this type of product will last up to 5 washing cycles.

The sterilization process was carried out in several stages. Preconditioning was performed at a temperature of about 50°C and a humidity of about 57 %RH. The next step was conditioning at about 45°C and 60 % relative humidity. This was followed by exposure under the same conditions as conditioning, which lasted approximately 300 min. The final stage was the final degassing phase, which was carried out at 40°C for a specified period.

Conductive textiles in this study were employed in infant clothing through two methods: screen printing with conductive carbon nanotube pastes and embroidery using conductive yarns. Screen-printed sensors form thin layers that allow flexibility and a lightweight design, which contributes to ease of movement and comfort. However, they are more susceptible to mechanical degradation over time. Conversely, embroidered conductive components ensure greater durability due to their deeper integration into the fabric structure, though they are slightly stiffer. Both approaches ensure proper data collection and transmission of vital signals from the infant's body to monitoring devices, without compromising the fabric's softness.

2.2. Methods

2.2.1. Evaluation of chemical properties

Metal content testing was carried out in accordance with the internal testing procedure developed based on PN-EN 16711–1 (Textiles, Determination of metal content Part 1: Determination of metals using microwave mineralization) and PN-ISO 8288 (Water quality, Determination of cobalt, nickel, copper, zinc, cadmium and lead, Atomic Absorption Spectrometry (AAS) methods with flame atomization).

The metal content in the tested samples was determined by atomic absorption spectroscopy using the flame technique. The Thermo Scientific iCE 3500 AAS spectroscope was employed for the research.

The supplied samples underwent mineralization in 69 % nitric acid (Nitric acid for analysis EMSURE® ACS, Reag. Ph Eur by Sigma Aldrich - cat. no. 1.01799). Process of mineralization of yarns was conducted using the Milestone Start D digestion system for 15 min at 200 °C. Due to the high chemical resistance of carbon nanotubes, the process of mineralization of the carbon nanotube paste was not possible. For the carbon nanotubes paste dried to a solid mass, the extraction process was carried out with use Ertec Magnum II digestion system at 200 °C for 10 min. The extraction process was carried out in 69 % nitric acid. For preparation of calibration curves multi-element standard solution was used (Certipur ® ICP multi-element standard solution IV - 23 elements in diluted nitric acid at concentration 1000 mg/l by Sigma Aldrich - cat. no. 1.11355).

Nickel was determined at 232 nm using an acetylene-air flame.

Cobalt was determined at 240.7 nm using an acetylene-air flame.

Copper was measured at 324.8 nm using an acetylene-air flame.

Lead was measured at 217 nm using an acetylene-air flame.

Cadmium was determined at 228.8 nm using an acetylene-air flame.

Chromium was determined at 357.9 nm using an acetylene-nitrous oxide flame.

2.2.2. Determination of surface mass

The surface mass of the samples was determined accordance with the PN-EN 12127:2000 standard. Samples measuring 32 × 32 cm were prepared and acclimatized before testing.

The samples were weighed in normal climate conditions using the PS 750/X electronic balance. The accuracy of the balance was 0.001 g.

2.2.3. Determination of the thickness

The thickness of the acclimatized samples was measured under standard climate conditions using acclimatized samples. The test was performed in accordance with the PN-EN ISO 5084:1999 standard using a J-40-V thickness gauge. The gauge's shape and pressure met the requirements of EN ISO 5084.

2.2.4. Determination of air permeability

Air permeability measurements of the tested assembles were conducted in accordance with PN-EN ISO 9237:1998 under standard climate conditions: relative humidity – RH= 65 %, air temperature – T_a= 20°C, and air pressure – p_a= 1013.25 hPa. An FX 3300air permeability tester from Textest Instruments in Switzerland. The air permeability of each assembly was determined as an average of 10 independent measurements at a pressure difference of 100 Pa. The surface area of the sample was 20 cm^2.

2.2.5. Determination of thermal and water vapor resistance

The purpose of this experiment was to evaluate the thermal and water vapor resistance using a measuring stand constructed by Measurement Technology Northwest called Sweating Hotplate 8.2 according to PN-EN ISO 11092:2014–11. The parameter related to the evaluation of the thermal resistance is calculated according to the following formula [54]:

$$R_{ct} = \frac{(T_m - T_a) \bullet A}{H - \Delta H_c} - R_{ct0} \quad (1)$$

where: T_m - heating plate temperature [°C]; T_a - air temperature [°C]; A - surface of the measuring plate [m^2], H - heating power supplied to the measuring plate [W], ΔH_c - heating power correction in case of measuring thermal resistance [W], R_{ct} - instrument constant for measuring thermal resistance, [m^2·°C·W^{-1}] and the parameter related to the assessment of water vapor resistance R_{et} [m^2·Pa·W^{-1}] is calculated according to the formula [54]:

$$R_{et} = \frac{(p_m - p_a) \bullet A}{H - \Delta H_e} - R_{et0} \quad (2)$$

where: p_m - saturated water vapor partial pressure [Pa] at the surface of the measuring plate at the temperature T_m; p_a - partial pressure [Pa] of water vapor in the air in the measuring chamber at the temperature T_a; A - surface of the measuring plate [m^2], H - heating power [W] supplied to the measuring plate; ΔH_e - heating power correction [W] in the case of measuring the water vapor resistance, R_{et} - instrument constant [m^2·Pa·W^{-1}] for the measurement of water vapor resistance according to PN-EN ISO 11092:2014–11. The tests were carried out consecutively under the following conditions: thermal resistance: T_a= 20°C, RH= 65 %, air flow speed 1 m·s^{-1}; water vapor resistance: T_a= 35°C, RH= 40 %, air flow speed 1 m·s^{-1}.

2.2.6. Total Hand Value (Kawabata Evaluation System)

The Kawabata Evaluation System (KES) instruments quantify garment material tactile qualities through objective measurement of the mechanical properties related to comfort perception. With low forces applied, as in manipulating / touching fabrics, the Kawabata instruments define the role played by tensile (stretch), shear stiffness (drape), bending rigidity (flexing), compression (thickness, softness), and surface friction and roughness (next to skin) on tactile sensations. This analytical power, combined with the capability to characterize energy loss in mechanical deformation and recovery processes, provides an unparalleled tool for use in fabric hand analysis. KES provides a unique capability, not only to predict human response, but also to provide an understanding of how the variables of fiber, yarn, fabric construction and finish contribute to perceptions of comfort. Each of the results obtained on the modules was saved thanks to the appropriate software and a thorough analysis was made. To determine the purpose of the tested materials, the KN-201-MDY equation was selected, referring to textiles used for women's clothing of medium thickness (summer clothes). Thanks to this, in addition to the assessment of the total grip, the results related to the feeling of stiffness, smoothness, filling and softness (Koshi, numeri, fukurami, sofutosa, respectively) were obtained. Kawabata's team assessed various grip characteristics for groups of materials used in selected clothing assortments, e.g., men's summer and winter clothes, women's thick and thin coats. The basic features determining the suitability and quality of specific materials include stiffness, smoothness, and filling [54]. Stiffness (from Japanese Koshi), a sensation primarily related to bending stiffness. This feeling is enhanced by the elastic properties of the material, i.e., all fabrics characterized by high density, or fabrics made of elastic and elastic yarns. The feeling of smoothness (from the Japanese Numeri) is related to the sum of the features defining smoothness, softness, and curling. The filling (from the Japanese Fukurami) is created by bulk, it is closely related to the elasticity of materials subjected to compressive deformations, thickness, or the feeling of a warm touch. The feeling of softness (from the Japanese Sofutos) is associated with the interaction of three features - flexibility, plumpness, and smoothness. To properly assess the quality of textile products according to the method proposed by the Hand Assessment Committee (HESC), the material must be correctly assigned to a given group. As a result of the conducted research, a library of patterns was developed for each of the basic features, depending on the intensity of sensations. According to such a scheme, the total grip is assessed. A rank of 5 was assigned to materials with an ideal grip, while samples that were not suitable for a particular type of clothing were assigned a value of 0 [54].

2.2.7. Surface resistivity testing

The surface resistivity of the samples was tested in accordance with the PN-EN 1149–1:2008 standard, with the use of previously acclimatized samples. To conduct the test, a Keithley laboratory multimeter and a dedicated program installed on a laptop were used.

3. Results

This section presents the results of metal content determinations and their content limits (Table 2).

Based on the conducted tests, it was shown that the analysed samples of electrically conductive yarns do not contain metals in amounts exceeding the limits specified in the OEKO-TEX® STANDARD 100for

Table 2
Characteristics metal content of yarns.

Type of past/ yarn	Content in the sample [mg·kg^{-1}]						
	Ni	Co	Cu	Pb	Cd	Cr	Ag
Past carbon nanotubes	0.76	217.21	0.11	0.27	0.00	0.34	1.47
Shieldex	0.00	0.00	22.03	0.00	0.00	0.51	29935
X-Static	0.00	0.00	1.98	0.00	0.00	0.83	60286
Silver-tech	0.00	0.23	1.20	0.00	0.00	0.78	8211
Silver-tech+	0.00	0.00	3.48	0.00	0.00	0.07	32741
Requirements*	1.00	1.00	25.00	0.20	0.10	1.00	nd

* extractable metal content limits according to the OEKO-TEX® STANDARD 100for textile products intended for children

textile products intended for children. In case of past with carbon nanotubes the concentration of cobalt may seem disturbing, but in case of 100 % screen printing the content of pasta in material is only about 1,4 %. Moreover, the conductive print will be performed as a small pattern on external layer of three-layered material and it will not contact with the skin.

The tested material samples were characterized in terms of surface weight and thickness. The tests were carried out for a sample of a three-layer material consisting of a polypropylene non-woven fabric, a vapor-permeable polyethylene film and a cotton knitted fabric with a total area weight of about 138 g·m^{-2}. Rectangles of the same size, 2 × 4 cm, with printing and two different densities of embroidery were embroidered and printed on the prepared material. The first density was 80 %, which meant filling the embroidered rectangle in 80 %, the second filling was 60 % coverage of the material with the embroidered yarn. The results regarding the surface weight and thickness of the tested samples are presented in Table 3 and Figs. 1–2.

Analysing the results of the surface mass tests, it can be observed that as the embroidery density increases, so does the surface mass. This is due to the additional material that appears in the structure of the system in the form of electrically conductive yarn. However, this increase is approximately 1 %, so it is not a significant change. A slight increase in surface mass can also be observed for samples subjected to washing processes. For example, three-layer system sample embroidered with X-Static yarn at 80 % coverage had a surface mass of 139.49 g·m^{-2} Before washing, and after the washing process the surface mass increased to 139.78 g·m^{-2}. In all tested cases, the increase in surface mass after washing did not exceed 1 %. This increase may be related to shrinkage, which was approximately 0.8 % after five washing cycles. A similar effect was observed for samples subjected to the sterilization process, but the increase was even smaller than that observed for the washing process. Therefore, it can be concluded that neither the washing nor the sterilization process significantly affect the surface mass of the tested three-layer systems with embroidery. In analysing the test results for printed samples, a slight increase in surface mass can also be observed, caused by the application of an additional aqueous printing composition containing carbon nanotubes. These changes are within 1 % for both unmodified samples and those subjected to sterilization and washing processes.

Reading the thickness tests, it was observed that, for printed samples, the thickness at the printed area increased by about 12 %. When examining the thickness at the embroidery points, an increase of over 100 % was noted. For example, the thickness for Shieldex yarn with 80 % embroidery is thickness was 1.741 mm, compared to 0.770 mm before embroidery. The variation in thickness for different embroidery densities is not as significant for Silver-tech+ yarn: at 60 % embroidery density the thickness was 1.749 mm, and at 80 % it was 1.753 mm. This difference is due to the dancer packing of the yarns the embroidered areas. For samples subjected to washing processes, a minimal increase in thickness was observed, which, similar to surface mass, could be attributed to slight shrinkage. A similar situation occurred after the sterilization processes. Both the washing and sterilization processes were carried out at a temperatures above 40°C, which could lead to minimal shrinkage of the three-layer system on which the electro-conductive printing and embroidery were applied.

Biophysical properties

Table 4 and Figs. 1 and 2 present the results of tests on biophysical properties, including air permeability, heat resistance and water vapor resistance before and after the printing and embroidery processes with various densities and using different yarns.

One of the most important parameters of interest to the authors was the water vapor resistance within the range of 150÷350 m^2·Pa·W^{-1}. This range was established in previous studies referenced in the article [5]. It is critical need to maintain the correct level of moisture inhibition in the bodies of prematurely born infant who lack the natural barrier, of fully developed skin. Based on the results in Table 4, it can be seen that the washing process increased the water vapor resistance by approximately 50 m^2·Pa·W^{-1}, likely due to the slight shrinkage of the sample. The sterilization process had a much smaller effect on the water vapor resistance. However, the embroidery process significantly reduced water vapor resistance. For example, the reduction decrease was observed in samples embroidered with Silver-tech yarn, where the resistance decreased by about 40 m^2·Pa·W^{-1}. This may be because Silver-tech yarn more effectively filled the spaces between the needle punctures and the three-layer material. In embroidered systems, an increase in water vapor resistance was observed after the washing process, though it was not as pronounced as in the non-embroidered sample. The sterilization process had a much smaller effect on the water vapor resistance of embroidered samples, regardless embroidery density. It is important to note that all embroidered samples subjected to washing and sterilization processes remained within the acceptable range of water vapor resistance.

Analyzing the test results in Table 4 and Fig. 3, it can be observed that the embroidery process caused an increase in thermal resistance.

Table 3
Parameters of fabric embroidered with different density and non-embroidered.

Screen printed/ Embroidery density	Type of yarn/ past	New		After 5 washing cycles		After sterilization	
		Surface mass [g·m^{-2}]	Fabric thickness [mm]	Surface mass [g·m^{-2}]	Fabric thickness [mm]	Surface mass [g·m^{-2}]	Fabric thickness [mm]
100 %	**Carbon nanotubes**	140.34 ± 0.006	0.968 ± 0.16	140.21 ± 0.004	0.999 ± 0.16	141.02 ± 0.004	0989 ± 0.16
60 %	**Shieldex**	139.99 ± 0.002	1.729 ± 0.18	140.65 ± 0.003	1.732 ± 0.16	140.12 ± 0.002	1.732 ± 0.18
80 %		140.09 ± 0.003	1.741 ± 0.17	141.32 ± 0.002	1.746 ± 0.17	140.35 ± 0.002	1.744 ± 0.17
60 %	**X-Static**	139.41 ± 0.004	1.740 ± 0.16	139.56 ± 0.002	1.748 ± 0.16	139.46 ± 0.002	1.744 ± 0.16
80 %		139.49 ± 0.006	1.750 ± 0.16	139.78 ± 0.006	1.755 ± 0.16	139.98 ± 0.006	1.753 ± 0.16
60 %	**Silver-tech**	138.99 ± 0.006	1.739 ± 0.16	139.23 ± 0.006	1.759 ± 0.16	139.47 ± 0.007	1.742 ± 0.15
80 %		139.59 ± 0.006	1.758 ± 0.16	139.74 ± 0.006	1.762 ± 0.15	139.59 ± 0.006	1.761 ± 0.16
60 %	**Silver-tech+**	139.16 ± 0.001	1.749 ± 0.15	139.79 ± 0.001	1.752 ± 0.15	139.23 ± 0.003	1.752 ± 0.15
80 %		139.71 ± 0.005	1.753 ± 0.16	139.92 ± 0.005	1.757 ± 0.16	139.65 ± 0.004	1.757 ± 0.15
without embroidery		138.43 ± 1.67	0.77 ± 0.01	138.60 ± 0.68	0.87 ± 0.01	138.73 ± 1.39	0.88 ± 0.01

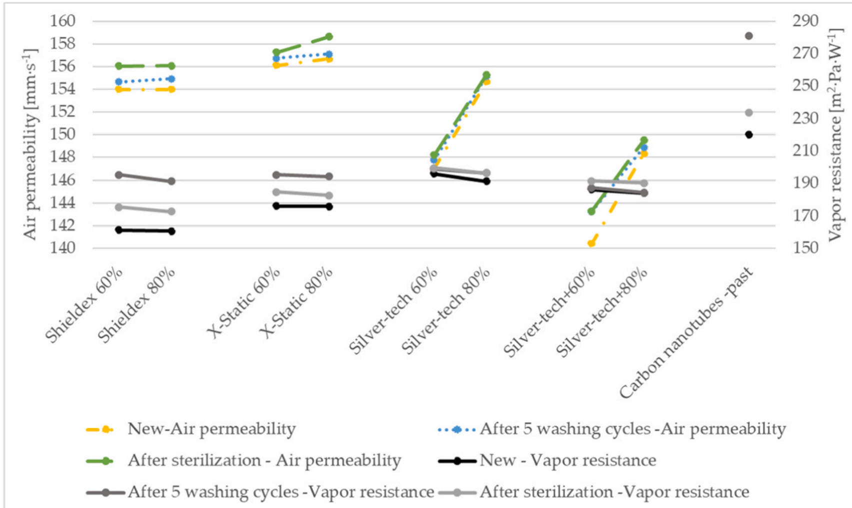

Fig. 2. Air permeability and vapor resistance of modified fabrics. Analysing the data c in Table 4 and Fig. 2, it can be observed that as the density of the embroidery filling, the increases air permeability also increases, while water vapor resistance decreases. This is because higher embroidery density, results in more needle punctures in the three-layer system on which the embroidery is applied. These punctures increase air permeability, as illustrated by the comparison between the unembroidered material - 0.51 mm·s^{-1}, and the material embroidered with Silver-tech yarn, where air permeability was 147.00 mm·s^{-1} for 60 % embroidery density and −154.67 mm·s^{-1} for 80 %. In the case of printed samples, no significant effect on biophysical comfort properties was observed, as both air permeability and thermal and water vapor resistance changed only slightly. This is because printing is a surface modification that does not affect the internal structure of the three-layer system.

This is due to the addition of extra material to the structure of the tested system. The degree of compaction as well as the conservation and sterilization process did not significantly affect the thermal resistance properties. The type of yarn used for embroidery was most significant factor, as in the case of samples embroidered with Silver-tech yarn, the increase in thermal resistance was 0.002 m^{2}·°C·W^{-1} for 80 % embroidery coverage. The largest changes in thermal resistance were for 80 % embroidery coverage using with Silver-tech yarn with an increase 0.011 m^{2}·°C·W^{-1}. Analyzing the results in Table 4 and Fig. 2, the printing process caused only a minimal increase in thermal resistance. The optimal variant for ensuring biophysical comfort, as measured in accordance with the PN-EN ISO 11092:2014–11 standard, is a product that provides thermal resistance in the range of 0.05–0.10 m^{2}·°C·W^{-1} . Therefore, the developed materials meet the assumed requirements.

3.1. Total Hand Value

Table 5 and Fig. 4 present the results of the Total Hand Value tests before and after the printing and embroidery processes with different densities and yarns types.

Analysing the data in Table 5, the highest stiffness among the embroidered materials was observed in the sample with 80 % coverage using X-Static yarn (8.51), the sample with 60 % coverage made using Shieldex yarn (8.01), and the printed sample (8.13). The sample before printing and embroidery processes had a stiffness index of 6.11, which increased to 6.88 after the washing process. The sterilization process had a minimal effect on the stiffness index. A similar trend occurred for printed and embroidered samples, where stiffness increased after the washing process, and to a minimal extent after sterilization. The highest smoothness index was observed in the sample with 80 % embroidery coverage, using Silver-tech yarn after sterilization process (8.75), while the lowest by the sample without embroidery after the washing process (6.35). It was noted that the conservation process had a negative effect on the smoothness index, causing a decrease, while the sterilization process increased, it. Additionally, both printing and embroidery increased the smoothness index. The results indicate that the smoothness index is at a high level, which positively affects the sensation of the fabric when in contact with the skin. Considering that these products are intended for premature babies, this is a crucial factor.

Another important parameter is the filling index, which contributes to a pleasant and warm sensation on the skin. The increase in this index after the embroidery processes is a positive outcome. The highest filling index was observed in the sample 100 % with embroidery coverage, made using X-Static yarn after sterilization (9.85), and the lowest in the sample without embroidery before the washing and sterilization processes (8.50). Both the sterilization and the washing processes had minimal impact on the filling index. Analysing the data c in Table 5 and Fig. 3, it was observed that the total hand value (THV) was highest for the sample with 80 % embroidery coverage using X-Static yarn (4.86), though the printed sample also had a high THV (4.66). The embroidery density slightly influenced the THV index, with 60 % Silver-tech+ yarn embroidery yielding a THV of 4.27, and 80 % yielding a THV of 4.53). The embroidery and sterilization processes had a negative effect on the grip sensation, likely due to the increase in stiffness after these processes. However, the research findings suggest that embroidery has a generally positive effect on the grip sensation and the equation used to assess the tested materials appropriate, as all tested indices were at a high level. The authors regret that the Kawabata Assessment System does not have equations developed specifically for assessing products for children and infants, necessitating the use of an equation designed for delicate women's clothing.

The presence of printed conductive layers in close contact with the infant's skin showed minimal impact on thermal comfort. Heat dissipation across the printed sections remained consistent over prolonged monitoring sessions. Although the conductive ink slightly altered the surface properties, this did not result in discomfort as confirmed by Total Hand Value (THV) tests. The materials demonstrated stable temperature profiles over time, ensuring that heat transfer between the infant's skin and the environment was not disrupted.

3.1.1. Electrically conductive properties

Fig. 4 presents the results of conductivity tests after embroidery processes with different densities and different yarns.

Analysing the data in Fig. 5, the best conductive properties were observed in the sample embroidered with of Silver-tech+ yarn, which is directly related to the yarn's electrical resistance of $< 200\ \Omega\ m^{-1}$. The sample with the worst conductive properties was the one using a carbon nanotubes- based ink composition. It was also observed that the washing

Table 4
Biophysical properties of unmodified and modified materials.

Screen printed/ Embroidery density	Type of yarn/past	New			After 5 washing cycles			After sterilization		
		Air permeability [$mm\cdot s^{-1}$]	Thermal resistance [$m^2\cdot °C\cdot W^{-1}$]	Vapor resistance [$m^2\cdot Pa\cdot W^{-1}$]	Air permeability [$mm\cdot s^{-1}$]	Thermal resistance [$m^2\cdot °C\cdot W^{-1}$]	Vapor resistance [$m^2\cdot Pa\cdot W^{-1}$]	Air permeability [$mm\cdot s^{-1}$]	Thermal resistance [$m^2\cdot °C\cdot W^{-1}$]	Vapor resistance [$m^2\cdot Pa\cdot W^{-1}$]
100 %	**Carbon nanotubes**	0.55 ± 0.02	0.0592 ± 0.002	220.25 ± 0.03	0.67 ± 0.04	0.0598 ± 0.002	281.24 ± 0.001	0.59 ± 0.02	0.0561 ± 0.001	233.66 ± 0.003
60 %	**Shieldex**	154.00 ± 9.27	0.0641 ± 0.001	161.17 ± 0.01	154.67 ± 7.65	0.0652 ± 0.001	195.33 ± 0.001	156.04 ± 8.25	0.0633 ± 0.001	175.33 ± 0.002
80 %		154.06 ± 2.83	0.0651 ± 0.001	160.65 ± 0.01	154.92 ± 1.76	0.0661 ± 0.001	191.23 ± 0.001	156.08 ± 2.34	0.0638 ± 0.001	172.66 ± 0.001
60 %	**X-Static**	156.11 ± 8.18	0.0661 ± 0.001	176.07 ± 0.03	156.75 ± 8.02	0.0671 ± 0.001	195.25 ± 0.001	157.25 ± 6.25	0.0652 ± 0.001	184.78 ± 0.002
80 %		156.67 ± 10.62	0.0663 ± 0.001	175.76 ± 0.02	157.12 ± 6.69	0.0673 ± 0.001	194.14 ± 0.003	158.65 ± 8.61	0.0655 ± 0.001	182.58 ± 0.003
60 %	**Silver-tech**	147.00 ± 4.90	0.0665 ± 0.001	195.91 ± 0.03	147.76 ± 3.75	0.0671 ± 0.002	198.88 ± 0.001	148.20 ± 3.54	0.0660 ± 0.001	199.47 ± 0.001
80 %		154.67 ± 7.41	0.0673 ± 0.001	191.23 ± 0.03	155.14 ± 4.43	0.0679 ± 0.001	196.36 ± 0.003	155.27 ± 5.98	0.0665 ± 0.001	196.35 ± 0.003
60 %	**Silver-tech+**	140.39 ± 6.94	0.0568 ± 0.001	186.19 ± 0.03	143.25 ± 4.47	0.0577 ± 0.001	187.23 ± 0.001	143.27 ± 5.47	0.0550 ± 0.001	191.55 ± 0.003
80 %		148.33 ± 3.40	0.0589 ± 0.001	184.12 ± 0.03	148.88 ± 4.42	0.0592 ± 0.001	184.22 ± 0.001	149.53 ± 3.54	0.0559 ± 0.001	190.28 ± 0.002
without embroidery		0.51 ± 0.02	0.056 ± 0.001	229.62 ± 0.01	0.65 ± 0.004	0.0569 ± 0.001	280.23 ± 0.002	0.58 ± 0.008	0.0555 ± 0.001	238.54 ± 0.001

process negatively affected the conductive properties of the tested samples. The sample with 60 % embroidery coverage using Silver-tech yarn had a surface resistance of 10.12 Ω before washing 12.22 Ω after washing and 11.06 Ω after sterilization. In the case of printed samples, the resistance before washing was 50.7 Ω increasing to 71.1 Ω after washing and then decreasing to 51.06 Ω after sterilization. The washing and sterilization processesWere performed on separate samples. For printed samples, the washing process had a negative effect due to the intensive action of mechanical forces, detergents and water, leading to partial degradation of the conductive surface. Sterilization, however, only affected the sample via temperature, without the external forces in the form of friction, bending, etc., but only by temperature, therefore it does not negatively affect the conductive properties. It should be noted, however, that neither the sterilization nor the washing process significantly worsened the conductive properties of the embroidered samples, while for the printed sample exhibited a deterioration over 40 % after washing

Continuous monitoring of temperature through printed sensors indicated minimal disruption to body contact due to the thin layer of printed conductive material. Our findings suggest that while the presence of printed layers slightly increases thermal resistance, the material's ability to dissipate heat remains effective, ensuring comfort during prolonged wear. This balance is essential, especially important when monitoring over extended periods.

4. Discussion

The aim of this study was to assess the impact of the sensor development process using printing and embroidery techniques on materials for the production of protective clothing for premature infants. The purpose of protective clothing for premature babies is to prevent heat and moisture loss protecting them from hypothermia. In addition, it is important to monitor parameters such as the temperature and humidity of the infant's body. The aim of the study was to develop a clothing system that would provide both biophysical and sensory comfort at an optimal level, while also enabling the measurement of parameters such as temperature and humidity. Recent advancements in textronic have contributed to the creation of specialized sensors for monitoring vital signs, which are now used in everyday clothing. Body temperature is one of the key parameters in newborns that requires constant monitoring. It serves as an indicator of infection and overall stability of the infant, and it is used to determine the appropriate ambient temperature for optimal growth and development. Our study emphasizes the seamless integration of sensors into protective clothing for premature infants. The use of conductive yarns and printed sensors allows for effective non-invasive monitoring while ensuring thermal and sensory comfort. The results confirm that conductive materials, whether printed or embroidered, can be successfully incorporated into garments without compromising the skin health of infants or the accuracy of collected data

The detection of abnormalities in the functioning of a small child is essential, because their systems are not yet fully developed. Multi-parameter monitoring provides comprehensive, safe, reliable, and accurate healthcare, especially for premature infants in the ICU.

Traditional sensors used to measure temperature, such as thermocouples, thermoresistors or thermistors, can have large dimensions and are rigid elements that can cause discomfort or irritate the baby's skin.

Based on the results presented in this article, the authors developed a textile sensor for monitoring the body premature infants. The sensor is integrated into a three-layer material system characterized by conductive and diffusion properties, and created via machine embroidery. This flexible textile sensor does not compromise the comfort of the final product and is made from polymer yarns containing 99 % pure silver particles. The yarns used for the embroidery meet the requirements of DIN EN ISO 9001:2015 as well as REACH and RoHS standards and are OEKO-TEX® STANDARD 100 certified. The second type of sensor developed is a printed temperature sensor using an ink composition in

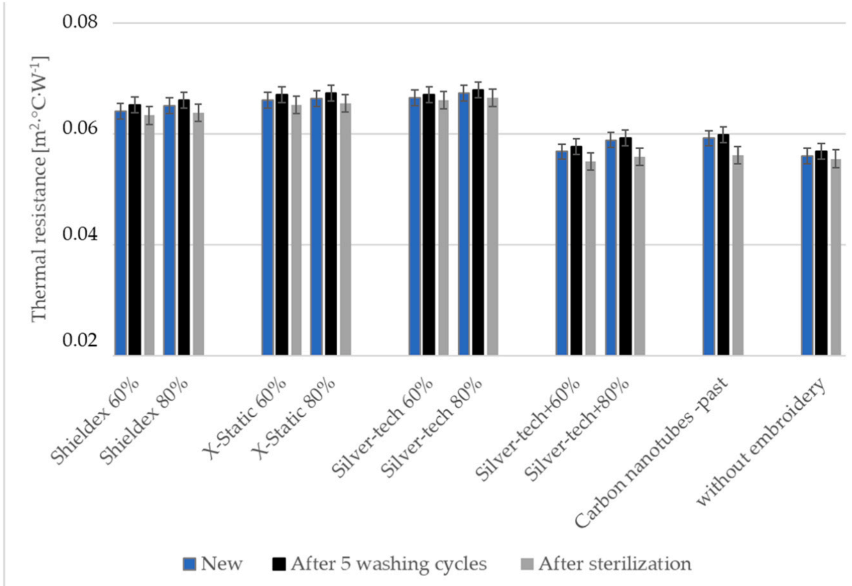

Fig. 3. Thermal resistance of modified fabrics.

Table 5
Total Hand Value of unmodified and modified materials.

Screen printed/ Embroidery density	Type of yarn/ past	New				After 5 washing cycles				After sterilization			
		Koshi	Numeri	Fukurami	THV	Koshi	Numeri	Fukurami	THV	Koshi	Numeri	Fukurami	THV
100 %	**Carbon nanotubes**	8.13	7.98	9.63	4.66	9.03	7.68	9.71	4.29	8.17	8.01	9.79	4.10
60 %	**Shieldex**	8.01	8.50	9.04	4.53	8.56	8.44	9.15	4.22	8.11	8.70	9.20	4.11
80 %		8.23	8.85	9.11	4.57	8.81	8.69	9.22	4.25	8.25	8.94	9.28	4.14
60 %	**X-Static**	8.11	8.24	9.57	4.82	8.42	8.12	9.58	4.56	8.18	8.46	9.64	4.26
80 %		8.51	8.66	9.72	4.86	8.95	8.56	9.75	4.60	8.59	8.87	9.80	4.29
60 %	**Silver-tech**	8.14	8.64	9.42	4.40	8.56	8.29	9.56	4.21	8.20	8.70	9.64	4.01
80 %		8.23	8.67	9.55	4.47	8.88	8.56	9.69	4.25	8.29	8.75	9.80	4.05
60 %	**Silver-tech+**	8.05	7.08	9.22	4.27	8.54	7.01	9.33	4.12	8.10	7.24	9.42	4.01
80 %		8.09	7.70	9.57	4.53	8.95	7.54	9.65	4.26	8.15	7.79	9.70	4.06
without embroidery		6.11	6.50	8.50	3.98	6.88	6.35	8.65	3.88	6.15	6.70	8.71	3.81

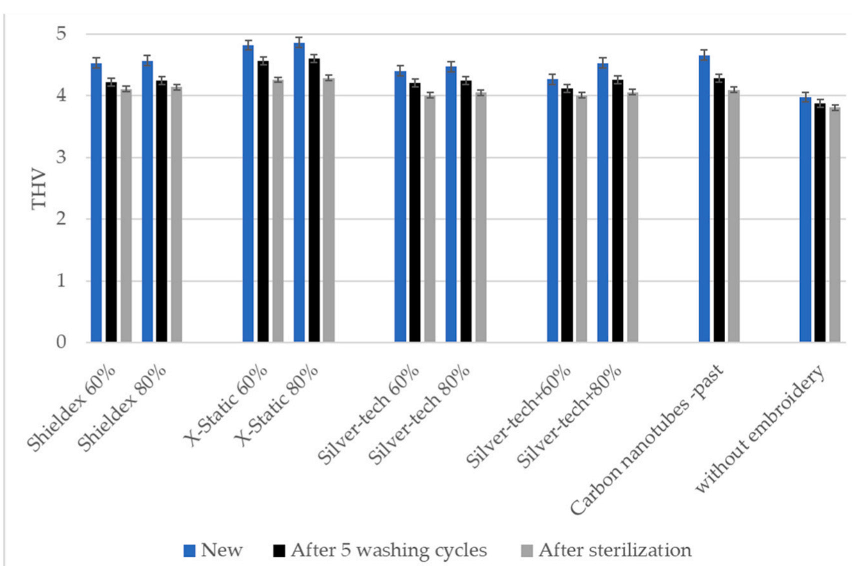

Fig. 4. Total Hand Value of unmodified and modified fabric.

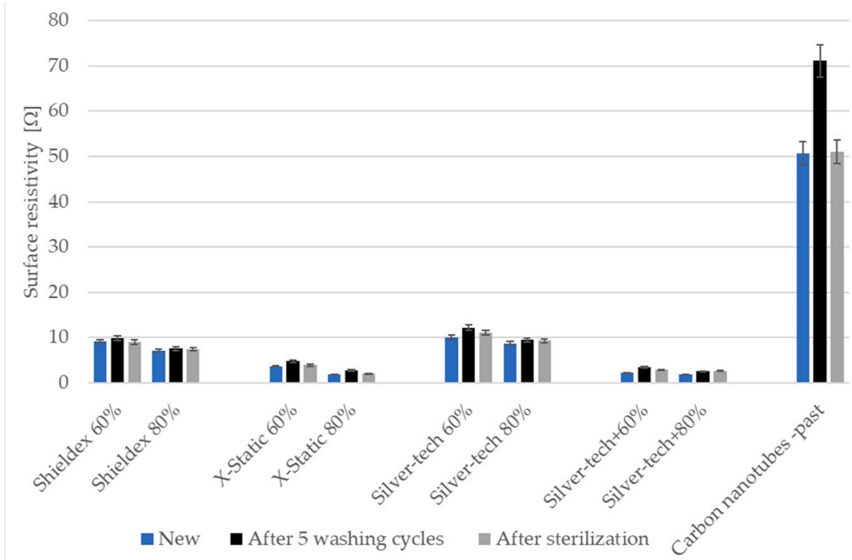

Fig. 5. Electrically conductive properties of unmodified and modified fabric.

the form of a printing paste containing 3 % carbon nanotubes. Unfortunately, in tests carried out using Atomic Absorption Spectrometry (AAS), an analytical technique for determining of chemical elements, revealed that these inks contain cobalt in amounts exceeding the permissible level of 217.21 mg kg^{-1}. As a result, the authors concluded that this paste cannot be used in products for children. However, the authors believe that these temperature sensor pastes could be used in other application, such as monitoring environmental parameters at home, or in workplaces, etc.

The textile sensor is integrated into the clothing at chest height and provides electrical resistivity that allows for the accurate detection of temperature changes due to high sensitivity.

A change in the wearer's body temperature alters the electrical resistivity of the sensor. The developed sensors were calibrated based on this principle (an example of calibration show in Fig. 6, which presents the changes in the sensory coefficient in response to temperature. The sensory coefficient is calculated using the formula $S_f = (\Delta R / R_o)$ x 100 %; where: S_f - sensory factor, ΔR - absolute change of the electrical resistance of the tested sensor, $\Delta R = R\text{-}R_o$, R - resistance of the tested sensor under the influence of temperature, R_o - resistance of the tested sensor before the test, measured at ambient temperature.

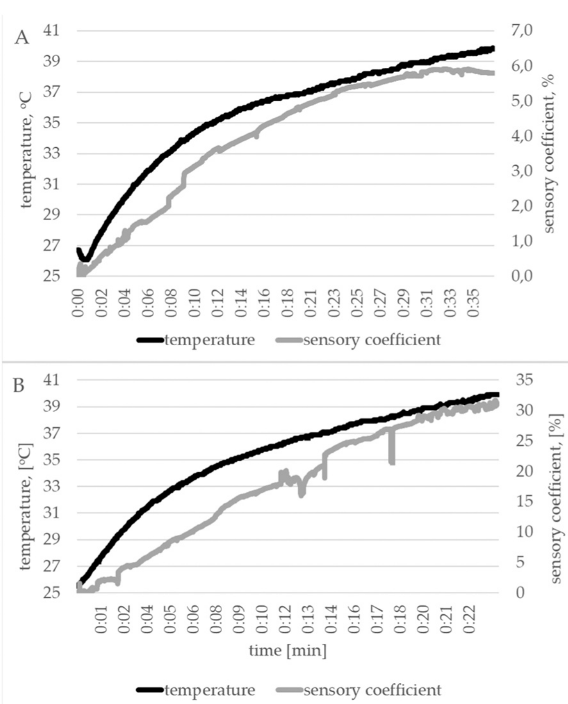

Fig. 6. Graph of changes in the sensory coefficient depending on temperature changes A) embroidered sensor, B) printed sensor.

5. Conclusions

This article presents the results of the evaluation of biophysical, sensory and conductive properties of three-layer material systems with carbon nanotube-based printing and embroidery using four different electrically conductive yarns. The developed materials are intended for use in clothing products for prematurely born infants, and thus, they must meet specific requirements including thermal resistance at least at the level above 0.05 $m^2 \cdot {}^\circ C \cdot W^{-1}$, and water vapor resistance at least 150 $m^2 \cdot Pa \cdot W^{-1}$. All the developed materials containing electroconductive sensors produced by screen printing and machine embroidery, met these requirements.

The development of textronics and rapid technological advancements in electronics have enabled the creation of modern systems combining textile and electronic applications. Such innovations can protect chronically ill individuals and support healthcare workers, thereby directly improving the quality for life of many people. Unfortunately, as of today, there are limited solutions of this kind for infants, and no dedicated clothing for premature babies, only medical plastic bags.

Therefore, textronic systems should be developed using materials that meet high standards in terms of both biophysical and Total Hand Value as well as chemical and biological purity. In systems using printed carbon paste and machine embroidery, the type of yarn selected for embroidery is crucial of the final properties of the product, as is the density of its embroidery. In the case of printed pastes, the size of the print has a significant impact on the functional properties and biophysical comfort.

Each textronic product should undergo a series of operational tests to confirm its usability in real world conditions, and to demonstrate how the product will behave during use. All created textronic systems should provide users with skin comfort, low mass high flexibility, and reliable integration of electronic systems.

The authors of this article conducted innovative research aimed at developing a temperature sensor and, eventually, a skin moisture sensor for premature infants. For this purpose, they selected electrically conductive yarns that meet the requirements of DIN EN ISO 9001:2015, REACH and RoHS, and that are OEKO-TEX® STANDARD 100. Additionally, they conducted metal content tests to verify whether these yarn meet the safety requirements for children's products. The second type of sensor developed was a printed temperature sensor using an ink composition with 3 % carbon nanotubes. Unfortunately, tests using Atomic Absorption Spectrometry (AAS), an analytical technique allowing for determining of chemical elements, revealed that these inks contain cobalt in quantities exceeding the permissible limit of 217.21 mg kg-1. As a result, the authors concluded that this paste cannot be used in products for children. Nevertheless, the authors believe that pastes for temperature sensors can be used for applications, such as monitoring environmental parameters at home or workplaces.

The experimental part of the research included testing the surface mass, material thickness, air permeability, heat resistance and water vapor resistance of the tested materials, as well as their sensory properties (Koshi, Numeri, Fukurami and THV) and conductive properties. The research showed that all selected yarns, and the textronic elements produced, meet the stringent material requirements for premature babies and exhibit high sensory sensitivity. However, it is important to determine optimal parameters for embroidery, density pattern and size before finalizing the design of temperature or humidity sensors. The developed textronic materials should in no way compromise the comfort of use for premature infants. This research successfully integrates conductive sensors into the textile structure of infant protective clothing through both printing and embroidery techniques. These conductive elements enable continuous monitoring of vital signs, such as temperature and humidity, while maintaining a balance between comfort, safety, and functionality. The use of specialized conductive materials allows for real time data transmission without compromising the physiological needs of premature infants. The results confirm that the textile structure enables seamless operation in infant care environments while preserving thermal and biophysical comfort.

Patents

Krucińska I., Kowalski K., Skrzetuska E., Komisarczyk A. Material for a baby clothing for prematurely born infants, No. Pat.231994. Skrzetuska E., Wilgocka K. Textile sensor for monitoring body temperature, especially of premature babies, intended to be placed in clothing, Patent Application No. P.448048.

Author statement

We confirm that neither the manuscript nor any parts of its content are currently under consideration for publication with or published in another journal. All authors have approved the manuscript and agree with its submission to Computational and Structural Biotechnology Journal.

CRediT authorship contribution statement

Wilgocka Karolina: Data curation. **Skrzetuska Ewa:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Szparaga Grzegorz:** Writing – original draft, Data curation.

Declaration of Competing Interest

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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