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Elina Ilén

Decontamination of Wearable Textile Electrodes for Medical and Health Care Applications

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Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Konetalo Building, Auditorium K1702, at Tampere University of Technology, on the 26th of June 2015, at 12 noon.

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ABSTRACT

In the medical and health care environment ‘intelligent’ clothing must endure all the same treatments and procedures as standard hospital textile; that is laundry, disinfection and sterilization. The decontamination level depends on the end-use of the product. The smart garment system for long term body monitoring must be like any other technical underwear; fit well, be comfortable, elastic, vapor permeable, and have easy-care properties capable of enduring multiple cycles of laundry washing. Thus the use of man-made fibers, instead of traditionally used natural fibers, in a body monitoring garment would be more reasonable.

The research focuses on disinfected and sterilized textile electrodes which are applicable for long term body monitoring. As high elasticity, comfort and good vapor permeability are needed, the research concentrates on the electrical and mechanical properties of knitted sensors after sterilization, disinfection and water-repellent treatment. The most important mechanical features of elastic textile electrodes are elongation recovery and dimensional stability. Before sterilization the textile must be cleaned properly from body fluids like blood and sweat. Improving the easy-clean properties would consequently be desirable. By improving the stain repellent or easy cleaning properties, the need for washing can be decreased and a more protective, lower temperature program during laundry washing can be used. These factors not only save energy but also lengthen the lifetime of textile electronics.

The textile surface electric resistance, abrasion resistance, dimensional change and elastic properties following decontamination processes were studied, including the evaluation of water repellent-treated electrode properties. In addition, the mechanical properties of conventional knits and elastic woven bands were observed after treatment in order to assess their use in smart wearable systems.

In addition to electrodes, the research results can be applied to many other textile electronics components such as conductors, antennae, heat elements, switchers and detectors, because all these components can be achieved with same elements; conventional textile fibers combined with conductive fibers or coatings. The obvious application areas for body monitoring by using textile electrodes are hospitals, health care centers and medical research centers. The textile electrodes are more comfortable and invisible for long time body monitoring which is needed, for example, in rehabilitation after surgery or detection of chronic diseases, where they are more effective than conventional gel (Ag / AgCl) electrodes.

In conclusion it can be stated that silver-plated PA fiber in a knitted or woven structure with added repellent treatment provides a highly conductive and durable solution for wearable electronics in medical and health care applications. The steel fiber and textile mixture cannot tolerate mechanical stress caused by disinfection, washing, or repellent treatment. The knitted textile with silver coating cannot tolerate sterilization, either electrically or mechanically. Based on the results of the study, the use of woven bands as an electrode would be recommended instead of knitted material because they are dimensionally more stable. The electrode dimensional changes might negatively affect the measurement quality. On the other hand, the knitted electrodes have additional useful properties like softness and flexibility, thus compromises must be made in using textile electrodes in wearable technology. All materials in the study, woven and knitted, elastic and inelastic, coated and non –coated showed clear shrinkage in the sterilization process. However, using only one heat treatment makes them much more stable. For this reason it can be assumed that man-made fibers are more useful for medical products as they are more resistant to being sterilized or disinfected than are natural fibers. The elastane fiber can be used for improving bi-directional textile material recovery, but the unrecovered elongation as a function of sterilization must be considered. The variation in unrecovered elongation (stretching) might be extremely high and success depends on raw materials and textile structures.

Keywords: Decontamination, sterilization, wearable electrodes, conductive textiles

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Espoo, May 2015

Elina Ilén

LIST OF ABBREVIATIONS

ABS	Acrylenitrilebutadienestyrene
AC	Alternating current
Ag	Silver
AISI 316L	Ni 10-14% and Cr 16-18%
Al	Aluminium
AMOLED	Active-Matrix Organic Light-Emitting Diode
Au	Gold
C	Celsius
CB	Circuit Board
CIGS	Copper indium gallium (di) selenide
CNT	Carbon Nanotubes
CO_2	Carbon dioxide
COPD	Chronic obstructive pulmonary disease (Congestive heart failure)
CPU	Control Processing Unit
Cu	Copper
CVD	Chemical vapour deposition
DC	Direct current
EBI	Electrobioimpedance
ECG	Electrocardiogram
EEG	Electroencephalogram
EIT	Electroimpedance topograph
EL	Elastane (a.k.a. ‘Spandex’ or ‘Lycra’)
EMG	Electromyogram
EMI	Electromagnetic Interference
ESD	Electrostatic Shielding
GPS	Global Positioning System
GSR	Galvanic skin response

H_2O	Water
HIV	Human immunodeficiency virus
HR	Heart Rate
HRV	Heart rate Variability
ICP	Intrinsically or inherently conductive polymer
LCP	Liquid crystal polymers
LED	Light emitting diode
Ni	Nickel
OI	Output Interface
OLED	Organic light emitting diode
OTFT	Organic thin-film transistor
PA	Polyamide
PAc	Polyacetylene
PAN	Polyacrylicnitrile
PANI	Polyaniline
PCB	Printed circuit board
PEDOT:PSS	Poly(3,4-ethylene dioxythiophene):poly(styrenesulfonate)
PEEK	Polyether ether ketone
PES	Polyester
PEOC	Post exercise oxygen consumption
PFC	Perfluorocarbon
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid or perfluorooctane sulfonate
PFHA	Perfluorohexanoic acid
PP	Polypropylene
PPy	Polypyrrole
PT	Polytiophene
PV	Photovoltaics
PVA	Polyvinyl alcohol

PVC	Polyvinyl chloride
PVDF	Polyvinylidene fluoride
PZT	Zirconate titanate
QTC	Quantum Tunnelling Composite
RFID	Radiofrequency Identification
RST	Reactive surface treatment
SS	Stainless steel
Ti	Titanium
TiO_2	Titanium dioxide
TPU	Thermoplastic polyurethane
UI	User Interface
VOCs	Volatile Organic Compounds

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1 Introduction

The wearable electronics business generated over $14 billion in 2014, and this figure is predicted to increase to over $70 billion by the end of 2024. The dominant application area is currently and is expected to remain the healthcare sector, including medical applications, fitness and wellness. It is noteworthy that major companies from many sectors are all interested in wearable electronics. These companies include garment, software, mobile device and consumer electronics companies, such as Apple, Accenture, Adidas, Fujitsu, Nike, Philips, Reebok, Samsung, SAP and Roche, which have all launched new developments in this area. [181]

The aim of wearable textile electronic applications is to add, expand and improve the properties of the original textile applications. At the same time, these applications should not worsen the primary and already available properties of the textiles or clothing. Electronics embedded in textiles or clothing provide extra value to the user. The clothing or textiles have the ability to record, analyse, transmit and display data. These data can extend the user's senses, augment the user’s view of reality and provide useful information, anytime and anywhere. Textile materials are lightweight, flexible, elastic, comfortable and washable; thus, the same features are required from electronics in order to add value for the user. The development of these applications is moving rapidly in that direction; the availability of wireless communication technologies, the development and increased popularity of smart mobile devices, the on-going miniaturization of electronics and the remarkable progress of flexible, even stretchable, electronics and components enable the creation of even better useable wearable devices.

The use of conductive materials has enabled the development of smart textiles. As electronics continue to become smaller, lighter, thinner, more flexible, more stretchable, printable, less expensive, and more usable, user intelligence about and acceptance towards textile electronics and smart clothing are enhanced. [1] The development of these materials is now moving in a direction that will make wearable technology a part of everyone’s everyday life. Textile electronics-based body monitoring systems have already been a part of everyday life in sports, fitness and wellness for over a decade. Today, many companies, such as Polar Wearlink+ [2], Suunto Comfort Belt [3], Garmin Ant [4] and Adidas Micoach [5], provide textile-based heart rate monitoring straps. Garment-integrated wearable electrode solutions are available from Numetrex [6], Under Armour [7] and PureLime [8], among other companies. Myontec has launched a textile sensor-based application called MBody sportswear. This application measures the muscle load, balance and the efficiency and intensity of exercise [10].

The development of wearable technology is widespread, but due to system complexity and some unsolved commercial issues, the prediction of future progress is difficult. The futurist Elina Hiltunen forecasts that during the coming decades, textile-based wearable technology that is used to monitor vital body functions and communicate with the environment will be as much a part of everyday life as mobile phones are today. [11] It is also estimated that approximately 25 billion wearable devices will be in operation by 2020. However, power management is expected to remain the bottleneck for progress. [14] As a result of advances in software, apps and the internet, many emerging wearable technologies are rapidly proving to have greater value than the purposes for which they were originally intended. By as early as 2016, approximately 300 million body-worn wireless sensor-based gadgets are expected to be on the market, with Bluetooth Low Energy (BLE) technology in devices such as laptops and mobile phones having a major impact. [1]

A textile sensor is able to detect and measure the user and the environment. Consumer demand for “wearables" is on the rise, which will further accelerate technological developments in all kinds of fields. Electrodes made of textile fibre material are a competing technology for the old-school plastic-moulded electrodes. Textile electrodes are comfortable and soft during use, while a plastic electrode has a less flexible surface, which may also feel uncomfortable during skin contact. A textile electrode is lightweight, flexible, and even stretchable, and can be formed and shaped almost without limitations. This formability enables production in smaller lots because the variation required for different applications is easy to accommodate. The flexibility of an electrode is an important property e.g. in body-monitoring applications, where proper skin contact with the textile electrode is essential. [14] Application areas can be found in the professional, protective and fashion wear sector, the medical and health care sector, the sports, fitness and well-being sector, home interiors, and in the automotive, construction and gaming industries. In body monitoring, the textile electrode (i.e., the conductive textile) can be used to measure bio-signals, such as electrocardiogram (ECG), pulse, heart rate, stress level, sleep quality, physical pain, electromyogram (EMG) of muscle rate and balance, body motion, electroencephalogram (EEG) of brain function and vitality level, respiration rate and frequency, body composition, including fat content and fluid balance, which are obtained via bioimpedance measurement, temperature and conductivity of the skin and blood oxygen saturation. In addition to electrodes, conductive fibres and textiles can be applied to signal and power transfer, to heating elements, antennas, detectors and actuators and to electromagnetic interference (EMI)-shielding and static dissipation control. [72, 91]

The sports and fitness applications are not significantly different from the solutions for medical and health care. Wireless communication has become commonplace, and the exponential rise of smart phones and tablets has only expanded the range of available monitoring textile electronic applications. Product acceptance increases when the electronics are embedded and cannot be touched or felt. [1] One rapidly increasing field in healthcare applications is the combination of wearable home care monitoring solutions with mobile health applications, which is called mHealth. The smartphone-based fitness and mHealth device market is forecasted to generate 100 million US dollars by 2018. [15] The OMsignal shirt measures the heartbeat and breathing rate, while the user's mobile phone works as a display, allowing the user to follow remotely the health condition of family members. [16] According to Qualcomm Life, home-based remote monitoring will save $305 billion in the USA in the next decade as a result of increased productivity in the medical industry, in addition to a further $205 billion due to the widespread adoption of this technology. There are 300 million people in Europe and North America and 860 million people worldwide who have at least one chronic disease, and it is estimated that 25% of these individuals would benefit immediately from wireless home monitoring solutions. [14] To prevent and follow chronic diseases, long-term monitoring of patient vital functions is necessary, and the use of textile electrodes embedded in clothing is an obvious and relevant solution. However, health is in many ways a personal and sensitive issue. Therefore, especially for long-term body monitoring, clothing is a natural, comfortable and invisible platform for electronics. [14] Common plastic electrodes are not meant for continuous monitoring due to the risk of skin irritation. Long-term monitoring can be used for pre-emptive actions, such as detecting the breathing rate and breathing breaks in babies (e.g., in order to prevent sudden cot death syndrome [17]) or detecting or following patient health after surgery or injury. The possibility of home monitoring would lead to a shorter hospitalisation period for patients, which naturally appeals to both hospital personnel and the patient. It is estimated that approximately 10 million Europeans suffer from chronic heart failure (CHF). A significant number of these patients are admitted to hospitals regularly, and the mortality rate for these patients one year after diagnosis is approximately 20%. The Ohmatex electronic stocking monitors fluid retention in the legs and sends data to the hospital. This application was developed especially for heart failure patients and pregnant women, who are at risk of pre-eclampsia.

The incidence of pre-eclampsia has been estimated to be between 5% and 14% of all pregnancies globally. [18]

Textile electronics is an interdisciplinary science. This field combines fibre material science and textile and clothing technology with electronics, signal processing and computing. Textile electronics refers to products in which textiles and electronics are combined in order to improve or add properties and functionality, thus adding value by combining the strengths of different sciences. However, due to this interdisciplinary nature of the ‘wearable’ field, it is forecasted that the incompatibility of manufacturing practices in the textiles and electronics industries is expected to restrain the industry from attaining its full potential by 2020. Smart textiles will be used in a variety of end-use industries, and robust growth is expected in sports and fitness, protection and safety through personal protective equipment, and home health monitoring by the end of 2020. [13]

Textile body-monitoring systems are more expensive than plastic systems; thus, textile systems must be reusable to have an economic benefit. In order to use such systems in hospitals and medical health care, the whole system must not only be washable but capable of being disinfected and even sterilized, depending on the application. The lack of information concerning how the textile electrode should be sterilized and how the electrode will react electrically and mechanically to this treatment represents at least one barrier to product commercialisation for the medical sector. Before sterilization, the textile must be cleaned properly. In the hospital environment, for repellent textile materials would be beneficial. As the disadvantages or weaknesses of textile electronics are being discussed, the mechanical durability, cleaning effectiveness and manufacturing cost of these systems in comparison to plastic systems have emerged as important factors. Laundry washing is conceived as the best method for cleaning textiles. However, every washing cycle adds wear and affects the mechanical features and appearance of the product, thus shortening the lifetime of the product. By improving the stain repellence and cleaning effectiveness of the product, the need for washing can be decreased, and a more protective, lower temperature laundry program can be used. These factors not only save energy but also lengthen the lifetime of the textile electronics. A longer lifetime also decreases the cost per instance of use. On the other hand, the cost per piece of disposable plastic sensors might be low in comparison to textile electrodes, but these sensors produce much more waste, thus increasing the unit cost. The longer the lifetime of textile electrodes, the less waste is produced in comparison to disposables.

1.1 Motivation and research objectives

There is much research activity regarding textile electronics in the area of medical and health care, leading to progress in research and development. However, in the hospital environment, intelligent clothing must endure all of the same treatments and procedures as standard hospital textiles, especially disinfection or sterilization. The decontamination level (i.e., washing, disinfection or sterilization) depends on the end use of the product in the medical environment (details are discussed in Chapter 5). Before sterilization, the textile must be cleaned properly, primarily to remove blood and sweat. Improving the easy-clean properties of the textiles would consequently be desirable. Second, hospital textiles are made primarily from cotton and other natural fibres. The use of man-made fibres in a body-monitoring garment is more reasonable, as the aim is long-term body monitoring. The garment must be like any other technical underwear; the garment must fit well, be comfortable, be elastic, be vapour-permeable, have easy-care properties and endure several cycles of laundry washing. Natural fibres are inferior to man-made fibres with respect to technical properties during use, including the material drying speed after washing, surface pilling and moisture management. Researchers and hospitals have a need and a desire to make commercial applications available as soon as possible. This research represents one step in that direction, as the sterilization, disinfection and easy-care properties of textile electronics used for body-monitoring applications in hospitals and medical research are investigated. [19]

The most reasonable solution for positioning the body-measuring unit to measure vital functions is the shirt or the sleeve. The garment must also fit perfectly for technical reasons. The electrodes must find their correct places without any adjustment or knowledge of measurement on the part of the user. This placement is a huge advantage in comparison to conventional electrodes, for which the correct placement of electrodes requires knowledge and experience. In addition to the hospital environment, this feature also enables the use of these electrodes in home monitoring systems (e.g., for chronic or at-risk patients or for rehabilitation after surgery or injury). As these systems are complex and expensive, they must be reusable and recyclable from user to user. A vital function shirt would also be useful in medical research, for which large user groups would wear the shirt for a long period of time. Invisibility and comfort are therefore keywords. Exchange between users requires the disinfection or even sterilization of the product. In addition, sterilized exchangeable measuring systems would reduce the need for storage space and ensure the availability of the correct size [19].

Textile body-worn electrodes enable the use of even more complex body-monitoring systems (e.g., the simultaneous measurement of several vital functions), which is not possible with conventional disposable electrodes. In hospital applications, the most important measurable functions are heart rate, which is measured using ECG, lung function, which is measured using electroimpedancetomography (EIT), the respiration rate and frequency, which are measured using electrobioimpedance (EBI), brain function, which is measured using EEG, and skin temperature. Measuring the shape of the breastbone after an accident would also be essential. Technically, textile electrodes can be used for all of these measurements. The same electrodes in a system could even be used to measure different functions. [19] Hospitals produce a considerable amount of undesirable waste by using a large quantity of disposable products. A textile body-monitoring system naturally decreases waste in comparison to single-use electrodes.

Research results can be extrapolated to many other textile electronics components, such as conductors, antennas, heat elements, switchers and detectors, in addition to electrodes, because all of these components can be achieved using the same elements: conventional textile fibres combined with conductive fibres or coatings. In the end, the whole system, which is a combination of these elements, must be sterilized. The obvious application areas for body monitoring using textile electrodes are hospitals, health care centres and medical research centres. In those environments, it is essential that products can be sterilized before and after use and that products are easy to clean to remove secretions of the human body. An easy-clean property is a necessary feature in every application in which textile sensors are not covered or integrated invisibly.

The research objectives of this study are:

- *To determine the most efficient sterilization method for elastic knitted electrodes and woven fabric electrodes;*

- *To investigate how textile electrodes endure the disinfection process; and*

- *To identify a safe fluid-repellent treatment for elastic and inelastic conductive textiles in order to make the textiles easy-to-clean*

1.2 Scope of the research

This study concentrates on textile electrodes made of synthetic fibres and conductive metal fibres or coating. Man–made organic fibres are famously used for fitness and sports under wear applications due to specific properties, such as moisture management and a high washing endurance. Thus, this study does not include electrodes made of natural fibres.

In this study, conductive fibres are limited to highly conductive metal fibres, such as silver and stainless steel. Based on earlier research, high conductivity leads to a wider range of applications with silver [24]. The additional antibacterial property and good electrical stability during laundering of silver materials are beneficial advantages in medical and health care sector applications. Stainless steel has nearly the same conductivity as silver, and even if this material is not naturally antibacterial, it has a more competitive price than silver.

This study focuses on disinfected and sterilized textile electrodes, which are applicable for long-term body monitoring. As high elasticity, comfort and good vapour permeability are needed, this study concentrates on the electrical and mechanical properties of knitted sensors after sterilization, disinfection and water-repellent treatment. The most important mechanical features of elastic textile electrodes are elongation recovery and shrinkage, while all other mechanical properties are excluded. Textiles with antibacterial features are desired and essential, especially when the textile is used in hospitals or health care centres. However, the antibacterial effect of silver is not examined after repellent treatment. In addition, this study does not focus on analysing the repellence efficiency of different water-repellent treatments or chemicals but instead focuses on examining the impacts of certain C6 technology-based chemicals on conductivity and cleaning capability.

Based on a literature study (see Chapter 5.4) and interviews with the equipment supplier Getinge, textile products are commonly sterilized in an autoclave with hot steam. This method is simple and ecologically sound in comparison to other competing methods. Sterilization using gamma radiation (i.e., the ‘dry’ method) is suitable in theory but is currently used primarily for disposable products. In addition, this method requires a large space and is expensive. Different sizes and types of autoclaves are available at competitive prices, and autoclaves are currently the main type of sterilization equipment used in hospitals and health care centres. Sterilization can also be accomplished using formaldehyde, but this method has undesirable environmental impacts. Hydrogen peroxide is also an option, but suitable care must be taken to ensure safe evaporation, making the correct construction of the system essential in both of these cases. Due to these facts, the autoclave was chosen for sterilization, and other methods are excluded from this study. [26]

1.3 Methodology and structure of the study

The research methodology is based on the experimental study of cases. The textile material cases, decontamination methods and repellent treatments applied were chosen based on a theoretical study. The cases are tested under laboratory conditions (*in vitro*) using quantitative and qualitative methods. Quantitative methods are used to evaluate the electrical and mechanical properties of electrodes after treatments (i.e., disinfection, sterilization and water repellence) by utilizing comparative analysis to analyse the data. The results are calculated as a percentage of the change. Visual observation is used as a qualitative method to evaluate the repellence and cleaning effectiveness of the material. To draw conclusions from the results, causal explanation is used. The study can be construed to have an inductive nature, as it is based on cases from which extrapolations are made. However, the study also has a deductive nature, as the findings are obtained based on logical deductions from the results, using fact-based premises.

Figure 1 illustrates the overall structure of the thesis. Chapter 1 presents the background, motivation and defining research questions for the study, whereas Chapter 2 describes the terminology of the research area, which is illustrated with current applications of wearable textile electronics. Chapter 3 concentrates on describing the architecture of a wearable body-monitoring system, with applications and added discussion about wearable data processing and energy management in wearable systems. Chapter 4 broadly describes the solutions and application areas for conductive textiles that are under study here. Thus, Chapters 1-4 illustrate the arena and state of the art for current research, development and applications of wearable technology. The proper theoretical study is divided into three chapters according to the research questions. First, a detailed description of decontamination terminology and processes in medical and health care environments is provided in Chapter 5. Second, in Chapter 6, the different structures and materials used to produce textile electrodes are discussed. Third, Chapter 7 concentrates on the characteristics of textile fluid-repellent finishes. Based on the theoretical study, the selection of the textile materials under study, the decontamination methods and the repellent finishes to be applied to the textiles are described in Chapter 8. Chapter 9 presents the preparation of the material specimens, the testing methods and the results with analysis. The findings, which are organized according to the research questions, are discussed in Chapter 10. The conclusions (Chapter 11) are included with a summary of the study and a discussion of future research in this area.

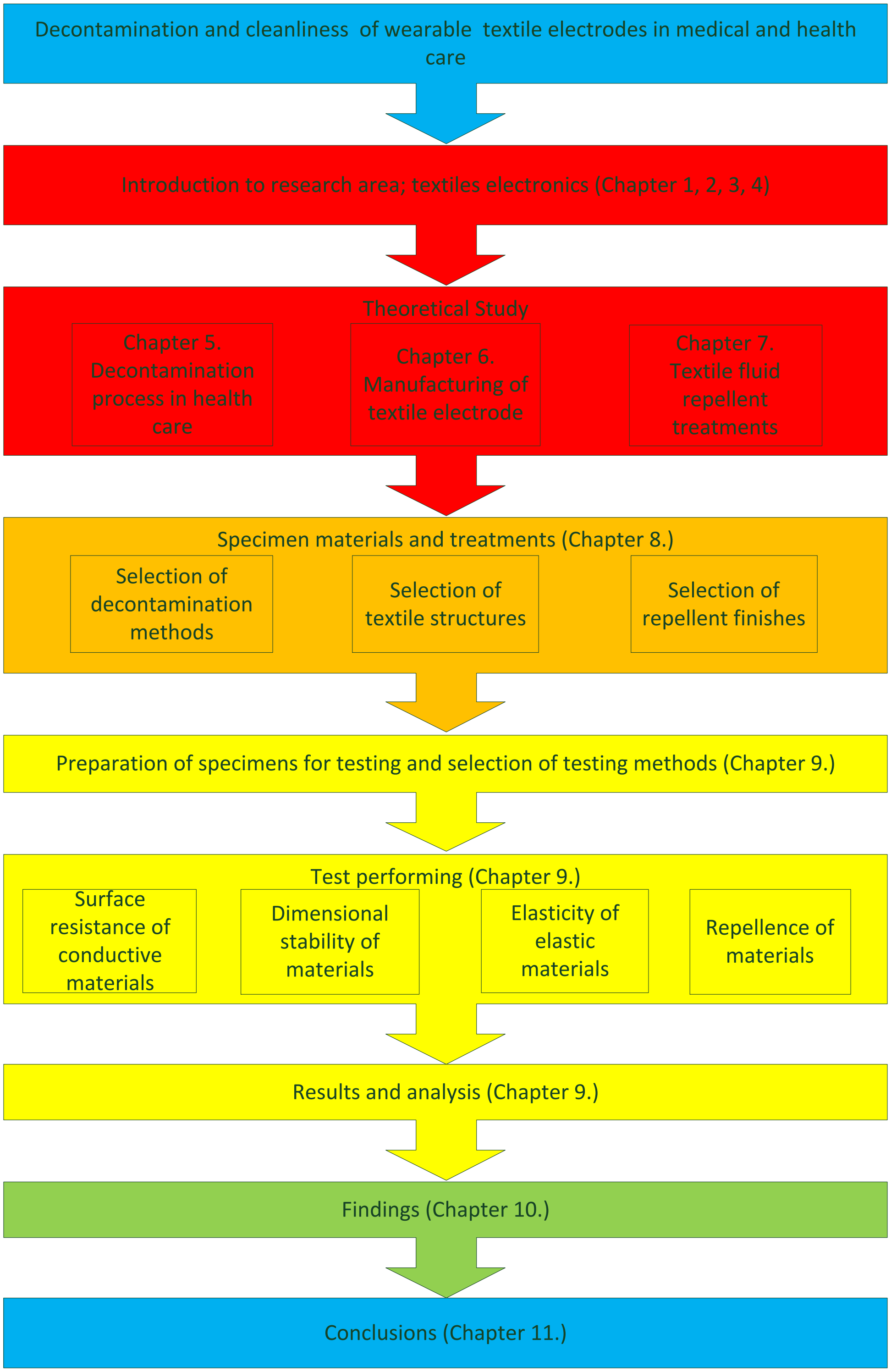

Figure 1: Study structure.

1.4 Research questions and contribution

The aim of this study is to determine whether textile electrodes are suitable for the sterilization and disinfection processes and to investigate the effects of those processes on the electrical and mechanical properties of textile electrodes. The textile must be clean before sterilization. The cleaning effectiveness could be improved by incorporating easy-clean properties into the electrode. In many medical applications used in the hospital environment, disinfection and sterilization are necessary. Textile properties, such as flexibility and elasticity, comfort and breathability, are important material properties in long-term body monitoring applications. These properties cannot be obtained with conventional plastic disposable electrodes. This study seeks answers to the research questions outlined below.

1.4.1 Impacts of decontamination on textile electrodes

Conductive textiles can be used for body monitoring. To apply these textiles widely in medical and health care environments, they must endure the textile sterilization process. The simplest, most common and most cost-effective way to sterilize textiles is autoclave sterilization, which is a hot and wet process. The steam temperature used for textiles is 121°C or 134°C, and the exposure time is 25-45 min [26]. This kind of treatment might change the properties of the textile.

> Q1: What is the effect of the autoclave textile sterilization process on the surface resistance of conductive textile materials?
> Q2: What is the effect of the autoclave textile sterilization process on the abrasion resistance of conductivity?

High temperature treatments, such as disinfection and sterilization, are not usually recommended for synthetic fibres, such as polyamide (PA) and polyester (PES), because in theory, these processes damage the fibres. However, PA and PES are the conventional and practical raw materials for sports and wellness applications, as well as body-monitoring electrodes.

> Q3: Does the autoclave textile sterilization process have an effect on the elastic properties of knitted textiles?
> Q4: Is there a dimensional change in autoclave-sterilized textiles?

Q5: Does the autoclave textile sterilization process have visual or hand-feel impacts on the textile?

The textile must be clean before the sterilization process begins. Thus, it is a real advantage if the textile can be cleaned easily to remove hard stains with the help of a water/stain-repellent treatment and if this property can withstand the sterilization process.

Q6: What is the impact of the laundering and sterilization process on the water/stain-repellent property?

Depending on the end use, disinfection might be an appropriate and adequate decontamination method for reusable clothing and textiles in the hospital and health care environment. In this case, the textile is disinfected after every use by laundering at 90-95°C [27].

Q7: What is the effect of the textile disinfection process on the surface resistance of the textile?

Textile body-monitoring systems consist of many materials. Disinfection and sterilization are always applied to the whole product; thus, the dimensional change of the material must be known.

Q8: Is a dimensional change in the textile electrode caused by the disinfection process?

1.4.2 Water-repellent finishing for textile electrodes

A water/stain-repellent treatment might behave as an insulating layer for the conductive textile structure. On the other hand, the layer can also be conductive and may even improve the surface resistance of a conductive fabric. Nano-scale treatments are known to have good properties, notably durability and softness.

Q9: What is the effect of a nanoscale water/stain-repellent treatment on the surface resistance of conductive textile materials?

The water/stain-repellent treatment makes the material surface hydrophobic, which forces liquid droplets into a spherical shape that minimizes contact with the surface. The drops roll off easily and carry away dirt, leaving the surface dry and clean. Water/stain-repellent treatments are typically used for outdoor textiles, for which the woven textile structure is often laminated or coated on the reverse side. For this reason, the water/stain-repellent treatment of uncoated/non-laminated knit structures has not been widely examined.

> Q10: How well is the repellent-treatment adapted to uncoated/non-laminated knitted textiles?

When the textile is used in contact with skin in hospitals and health care environments or in wellness and sports applications, specific stains, such as blood, sweat and body lotion, occur. Hydrophobic water-repellent treatment presumably improves stain removal from textiles. PA and PES textiles are commonly recommended to be cleaned by washing at 40°C. Washing at 30°C saves energy, which makes the use of this approach more ecologically sound. Conventional hospital textiles and cloths should withstand up to 250 cycles of laundry washing [27]. Every laundry washing cycle wears out the textile by decreasing its performance. Thus, finishing treatments, such as water/stain-repellent treatments, are removed from the textile during washing.

> Q11: Does the water-repellent treatment improve the cleaning effectiveness of textiles against blood, sweat, and body lotion?

The novel scientific contribution of this thesis is as follows:

- *This thesis provides essential information about the suitability of conductive textile electrode applications for mandatory textile-handling processes in medical environments (i.e., sterilization and disinfection).*

- *This thesis provides essential information about the impacts of stain-repellent treatments on knitted and woven textile electrodes, as visual cleanliness is a prerequisite for the sterilization and disinfection processes.*

2 Terminology of textile electronics

As a research and development area, wearable technology is fairly new. The first steps in this area were taken in the 1990s, but only in the early 2000s did this topic gain the interest of the general public, universities and companies as an emerging technology that should be researched further. [28] At an early stage, various types of terminology were used, until the terms gradually became more standardized. Wearable technology, wearable computing, wearable electronics, smart or intelligent textiles, fabrics or clothing, textile electronics, electronic textiles and E-textiles are some examples of this varying terminology. In common language, the brief form 'wearables' has become popular.

This chapter presents a description of terms, including their relationships and how they are understood in the research community. Figure 2 illustrates the interrelations of terms used in this area, and in the next sections (2.1, 2.2, and 2.3), the terminology is explained in detail with the help of some applications provided by the companies, research institutes or universities in this area. Many applications are being developed rapidly, and the applications presented in Chapters 1, 2, 3 and 4 were launched in the years between 2011 and 2014.

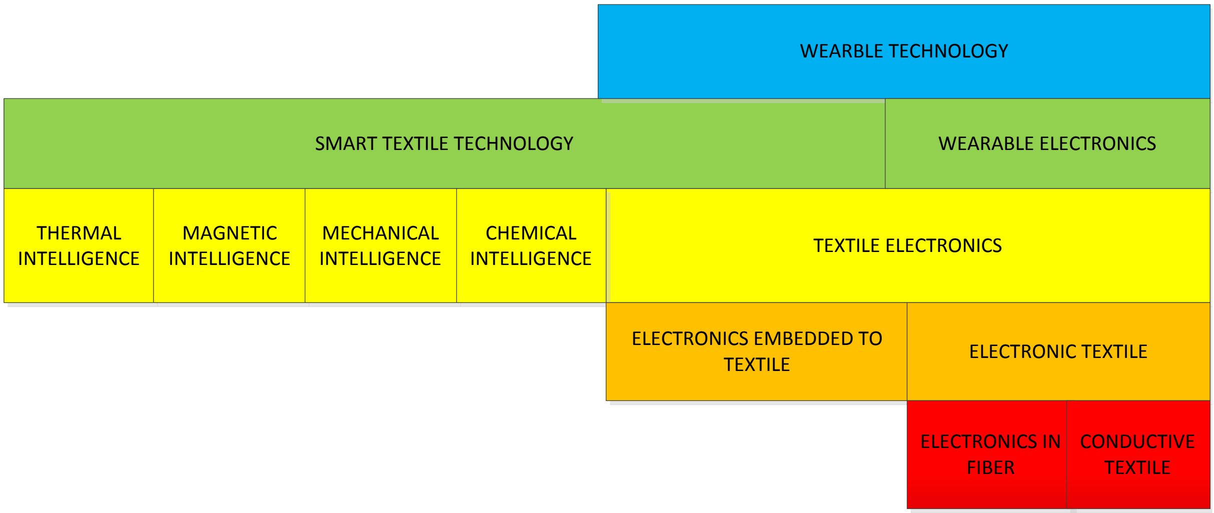

Figure 2. Interrelations of terms in smart textiles and wearables. [29]

2.1 Wearable technology

The term ‘wearable technology’ was created to cover all of the devices that are used by wearing or carrying. Garment-integrated wearable technology is an obvious application, but this approach is not necessary. There are many applications in which a garment or textile does not exist. These applications can also be called ‘wearable computing,’ which requires wearable electronics to become a reality. Intelligence can be achieved using electronics, mechanical or chemical technology, or a combination of these approaches. [29]

Smart watches, wristbands and bracelets, which are commonly called ‘wristables’, are an increasing sector in fitness and healthcare applications. Samsung produces the Galaxy Gear for activity tracking and communication. This device has standalone features with which the remote control of devices (e.g., when staying at home) is possible. [30] Another similar application with little variation in properties can be found in Nike’s Fuel Band, Polar’s Loop, Garmin’s Vivo Fit, LG’s Life Band and the fitness tracker Fitbit. Smart watches and bracelets are based primarily on Bluetooth technology for transferring data and optical sensors for activity tracking and body monitoring. The Sony Smartband Core is a product with fitness-tracking properties, as well as a connection to environment. This product has the ability to track photos and other events and will inform the user of incoming smart phone calls by vibrating. The GSM module, speaker and microphone and a connection to cloud-based software are integrated. [31]

Figure 3. Wristbands (i.e., ‘wristables’) from different brands: Samsung, Fitbit, Sony, and Polar Electro.

Recon Instruments of Vancouver, Canada has developed Heads-Up Display (HUD) Goggles for action sports. The collected data, such as speed, jump airtime and altitude, navigation and buddy tracking, as well as smart functions, are relayed instantly and directly to the eyes via a micro liquid crystal display (LCD) screen that is mounted inside the frame of the goggles. [32] Another goggle application was launched by Google. Google Glass has a glasses-integrated display, and commands are given by touching a bow or giving a voice command to the system. The main properties are navigation on the internet and messaging. [33]

Implantable medical devices are also included in wearable technology. Electronics can be either swallowed or implanted in the body. For example, such systems can monitor wound healing and disease progression and release drugs. Implantation enables more sensitive neural and cardiovascular sensors and stimulators to be used. [31]

2.2 Smart textile technology

Smart fabric or textiles are defined as fibre-based structures that can react to stimuli and are capable of interacting with the environment. The integration of electronics with textiles provides new concepts for lighting, heating, cooling, energy harvesting, communicating, sensing, measuring and monitoring. In addition to electronics, the smart fabric can also react to thermal, chemical, mechanical or magnetic stimuli. [1, 29, 36] Smart textile technology always includes a textile component that can change and adapt to changes, such as thermochromic materials, but such technology does not necessarily need to consist of electronics. Those smart textile applications that include electronics are used primarily to monitor the user or the environment based on output data that inform, support, take care of and indirectly protect the user. [29] Bekaert Textiles applied HeiQ’s adaptive technology. Adaptive® enables fabrics to respond dynamically to changes in temperature and moisture level in order to achieve optimal comfort and performance [37]. Wellsense Ltd., USA and M.A.P., UK developed a pressure-sensing mat for the prevention of pressure ulcers among bed-bound patients. The nurse can follow and react to a real-time colour display of pressure data to minimize areas of high pressure. It is estimated that in the UK alone, reducing or eliminating pressure ulcers would lead to an annual savings £154 million. [38] [39]

When a garment or a piece of clothing is involved as an integration platform, the combination becomes smart or intelligent clothing. The ‘intelligence’ of clothing does not have to be at the textile level; the textile can simply embed, cover and protect electronics to form intelligent clothing. In these structures, commercial electronic devices are attached or laminated to textile substrates. [29, 36] Smart clothing can be viewed as a sub-category of smart textiles, as the smart clothing is limited to smart textile applications that are worn around the body. Smart clothing is defined as a system formed by the human body, electronics and a garment, which adds value to the user by producing new properties. Today, the applications of this technology are mostly in sports and fitness, but medical and health care is a developing sector. However, as a great platform for wearable technology that utilizes textile electrodes to monitor vital functions, a garment or textile is the strongest scenario in medical and health care wearable applications. The use of smart phones and tablets as a display and for wireless communication between the devices is growing. Developed by Heapsylon, which is based in Redmond, Washington, USA, a T-shirt and bra carry out the real-time monitoring of heart rate, burned calories and breathing rate, among other parameters, by measuring ECG with textile sensors and collecting data via Blue Tooth technology. [40] [31] Intel Smart Earpuds provide biometric and fitness information by monitoring the user’s heart rate. The smart phone app tracks the running distance and the calories burned. The Edison has developed a SD (secure digital) card with built-in wireless to be used for smart consumer products and wearable computing. One application based on this technology is Mimo, which is produced by Rest Devices in Boston, Massachusetts USA. This technology is a monitoring system for sleeping infants, through which respiration, body motion and activity level can be measured. [31]

Bluetooth is a dominant technology for wireless communication between the wearable textile electronic, the input device and the output device display or smart phone. Runware, which is based in Sainte-Clotilde, France, is launching the Runalyzer chest strap for iPhone 5, which provides access to more than one hundred activity applications for walking, running, cycling and other activities. [45] [46] Wearable technology is viewed as beneficial for mHealth applications. [31] Hexoskin (see Figure 4) uses textile sensors to measure the heart rate (HR) based on RR Interval (distance between two beats of heart) and Heart Rate Variability (HRV) measurements, breathing rate and volume, heart rate recovery and estimated VO_2 max, while a smart device works as a data display. [48] A shirt produced by Citizen Sciences in Lyon, France enables the monitoring of temperature, heart rate, speed and acceleration with textile-embedded micro sensors. In addition, this product includes location information with the help of a global positioning system (GPS). [49] Electronic stockings that monitor fluid retention in the legs were developed by Edema, Denmark. These stockings benefit people suffering from chronic heart failure and pregnant women, who both have a risk of pre-eclampsia. The stocking detects leg volume changes by using an embedded textile strain gauge sensor. In addition, in this application, the data are transferred via Bluetooth to the mobile phone in real time, and an encrypted email is sent to the hospital. [32] [44]

Figure 4: Hexoskin textile heart rate-monitoring operation system. [48]

2.3 Textile electronics and electronic textiles

Wearable, electronic-based devices can be formed without textiles, but when a textile is incorporated, the system is defined as a smart or intelligent textile or textile electronics system. Textile electronics is a subcategory of smart clothing or textiles, but this field is a subcategory of wearable clothing only when the application is body-worn. The wearable application areas are fitness and sports, medical and healthcare, professional and work wear, and the fashion and gaming industries. In addition to wearable solutions, textile electronics and thus intelligent textiles can be found in the automotive industry, avionics, building construction and home interiors. If the electronic textile application is not wearable, it belongs to the main category of smart textile technology. [29]

The term textiles electronics includes all of the applications in which textiles and electronics are involved. Textiles can be used only as a pure platform for covering and embedding existing commercial electronics [50] by using textile and clothing technologies, such as lamination and welding, and textile-related materials, such as foams, and trimmings, such as snaps, hooks and zippers; alternatively, the textile can act as an electronic component within a system.

Electronic textiles, electrotextiles or E-textiles is a subcategory of textile electronics and is called “functional textiles.” These products have electronic features, such as conductivity, or miniaturized electronics can be even embedded within the textile fibre itself [51]. The textile is defined as conductive when the conductivity is $> 10^{-2}$ S/m ($<10^{4}\ \Omega\ \mathrm{cm}^{-1}$). E-textiles work as a component in a textile electronic device, as part of a ‘smart material system.’ The conductive textile can be used as an electrode, antenna, conductor, data transfer component, etc. [29] These products are replacing conventional hard plastic solutions by providing better comfort to the user. The most obvious applications are garment-integrated E-textiles for monitoring body vital functions, as well as the user’s environment or location. It is predicted that the E-textile market sales potential will reach 3 billion US dollars by 2024 [180].

Advanced Textile Research Group at Nottingham Trent University in the UK, and the advanced manufacturing division of Micro Electronic Textiles (MET) have managed to produce electrotextiles by embedding electronic micro-devices into the core of their yarns (see Figure 5) making the textiles machine washable with textile-like properties, such as tactility and flexibility. Technology allows the use of variable components, micro-electronic radiofrequency identification tags (RFIDs) or ultra-lightweight flexible photovoltaic films to add desirable features to the fabric (e.g., sensors, light-emitting diodes (LEDs) and comfortable displays). [51] [52]

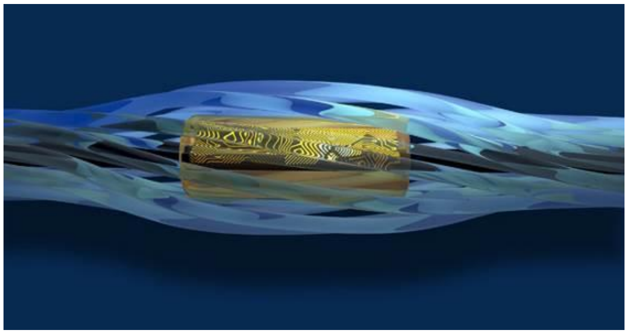

Figure 5: A fibre-embedded micro-electronic component. [51]

3 Architecture of a body-monitoring system

A wearable body-monitoring system must have a certain structure and architecture independent of the application. The principle of body-monitoring devices is that they always consist of a sensor or user interface (UI) for input, a control processing unit (CPU), a network for communication within the system, a power source and an output interface (OI). Depending on the application, an antenna for a positioning system (GPS) can also be included. The system architecture is illustrated in Figure 6. [54]

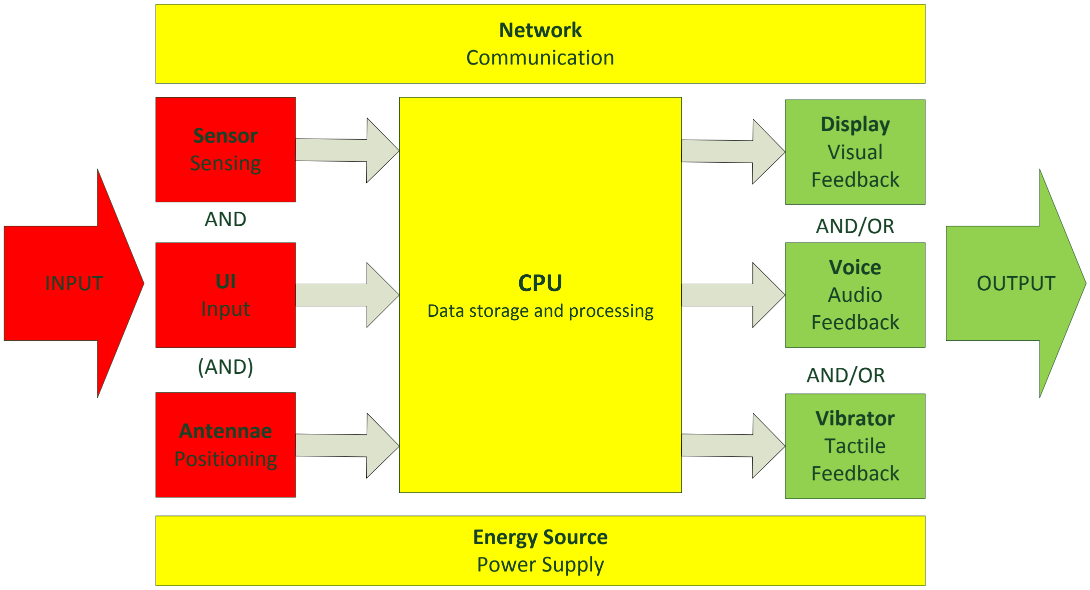

Figure 6: Architecture of a body-monitoring system.

Primarily, the system needs an energy source to power its functions. Input interfaces, a sensor and a user interface (actuator) are needed for sensing and for steering the system. Different types of sensors can measure the user or the environment. Both the user himself and the sensor can give the input required for the device to react. The CPU is the brain of the system. The CPU is needed to store and process the programmed data. This component converts data input to information output. A communication network is needed between all of the components involved in the system, between the system and the user and between the user and other people. This communication can be carried out using a regular conductor or using different kinds of wireless techniques. An output interface is needed to inform the user about the measurement results and the status of the system. The feedback can be visual using a display or light, or audio-visual, or tactile. [28] [54]

The dramatic development and increased popularity of touch display devices, such as smart phones and tablets, enables these device to act, at least in part, as the communicators, CPUs, displays and user interfaces of the system. Another benefit is that the smart phone uses its own battery for those functions. The rest of system elements need much less energy than the above-mentioned actions performed using a mobile device [41]. As previously noted, many types of sensors can be used to measure the human body and the environment. In addition to electrically conductive sensors, which are fully discussed in Chapter 6, thermal, light, sound, humidity, pressure, accelerator, strain, chemical, and biological sensors and combinations of these types of sensors can be used as a system input interface. [55]

In an ideal case, when fabricating unobtrusive, comfortable electronic-based smart clothing, all of the properties of the regular garment are maintained, such as flexibility, elasticity and breathability. The size of the electronic components should be micro- or even nano-scale, and the components should be invisible, senseless (i.e., the user is not constantly aware of their presence) and robustly integrated and embedded into the textile. Integration can be accomplished by using conventional textile techniques to attach materials to each other, as well as by using more sophisticated methods, such as welding and laminating. The laundering of the garment must also be considered, by making components either removable or machine-washable. Due to these requirements, there is a great interest in developing real smart fibres. This term refers to a fibre in which the electronic component is integrated into the fibre or yarn; the textile can then be produced by using conventional fabrication techniques. The direction of development is quite clear. The aim is to make every system component using textile material or materials with a textile-like nature so that the integration with the textile substrate or with a whole garment is seamless. Today, studies of textile electronics and applications of system components are common. The embedding of electronic components into fabrics should be accomplished without compromising the lifespan of the components and while making the manufacturing process flexible and cost-effective. Interconnection technology should allow textile manufacturers to place components into any step during the standard textile mill production process; alternatively, the component could be attached to the fabric or garment surface afterwards (e.g., by laminating). Textile properties, such as bending, flexing and stretching, are retained [56]. Using conventional textile technologies to produce textile electronics is desirable, because this approach facilitates the commercialisation of the product and helps meet the requirements set for the textile product. Textile electronics are viewed primarily as textile product-like electronics.

3.1 Wearable data processing and communication

The successful commercialisation of wearable textile electronic products requires flexible, stretchable, lightweight and washable components. The most challenging part of meeting these requirements is the data processing unit, including printed circuit boards (PCBs), LEDs, solar cells, transistors, capacitors, batteries and displays. The UK's National Physical Laboratory (NPL) developed a new technique for directly printing circuits onto fabrics to create robust, functional wearable electronics. This technique can be applied directly to finished garments with nano-silver bonding and encapsulating fibres as thin as 20 nm in diameter, which could be used for wearable sensors and antennas [104]. The properties of the printing ink determine the result and the capabilities of the printable circuits and electronic components. An ink that can be used robustly for almost any substrate would be desirable. Haydale, which is based in Ammanford, UK, is developing a metal-free graphene ink (HDPlasTM Graphene Ink Sc213) that can be applied to substrates via screen printing, flexographic techniques or gravure printing. This ink is not as conductive as silver, but it is cheaper and less volatile. Graphene ink is resistant to cracking; thus, this ink is suitable for flexible electronics and for large area prints to be used in chemical sensor electrodes.

For example, other research areas include flexible sensors, displays, thin-film photovoltaics, energy storage, transparent electrodes and catalytic devices. [77, 106] Peratech of Richmond and the Centre for Process Innovation (CPI) in County Durham have developed printing inks that can be used for pressure-sensitive switches and sensors. [79] The quantum tunnelling composite (QTC) material can be applied to textiles by using flexographic printing processes. This material also readily withstands washing. The QTC material can be used to print RFID tags on paper or plastic. Peratech is researching ways to print its QTC e-nose sensor, which can detect volatile organic compounds (VOCs), onto fabric. Certain VOCs can be used as early indicators of health issues. [79,108] Chinese researchers at Fudan University introduced a stretchable high-performance supercapacitor, which is often used for static random access memory (SRAM). The components of this supercapacitor are fibre-shaped and based on carbon nanotubes (CNTs). The elastic fibre is coated with an electrolyte gel and a thin layer of CNTs. This layer is followed by a second layer of electrolyte gel and another layer of CNT, which is covered by a final electrolyte layer. [56] Prototyping is an essential part of research and development. Georgia Institute of Technology (GT) in Atlanta, USA, the University of Tokyo, Japan and Microsoft Research in Redmond, Washington, USA have in collaboration managed to inject silver nanoparticle ink into an empty cartridge from an ink-jet printer to produce an instant ink-jet circuit for prototyping. This approach allows the printing of arbitrary-shaped conductors onto both rigid and flexible materials. In addition to circuit boards (CBs), this method can be used to make sensors, such as capacitive touch sensors, and antennas with little cost. [56] The development of flexible, lightweight displays is essential to body-monitoring applications for which a smart phone or tablet is not appropriate. In collaboration, Plastic Logic from Cambridge, UK and Novaled from Dresden, Germany are developing fully organic, plastic, flexible and unbreakable AMOLED displays, which consist of organic thin-film transistor (OTFT) and OLED materials. [31, 113, 114]

The researchers at the Fraunhofer Institute and the University of Heidelberg, Germany developed a stretchable polyurethane circuit board plaster, which will be used to test kidney function. With the plaster, a blue light-emitting diode (LED) and a detector, the doctor can monitor the test continually. In the traditional approach, a substance that only the kidney is able to break down is injected, and blood samples are collected every 30 min. In the plaster system, the injected substance is an organic colorant, and the blue LED causes the colorant to fluoresce. As the natural colorant is broken down by the kidney, the fluorescence also decreases. [115] The development of wireless body area network systems could lead to improvements in mobile health-monitoring applications. One solution is the use of ‘Zenneck surface waves,’ which are used as Radar systems to visualize the curvature of the Earth. Roke Manor Research in Romsey, UK developed a dielectric-coated conducting fabric, which enables worn devices to communicate wirelessly in a personal network. This material could enable the propagation of surface waves around the body without the need for repeaters, high powers or high-gain antennas. [31]

The most wearable and garment-like approach is to integrate electronics directly into the fibre or the yarn. Researchers at North Carolina State University (NCSU) in Raleigh, USA created metal-filled polymer wires that can be stretched up to eight times their original length while still functioning [117]. Miniature-sized electronics, such as thin-film temperature sensors, accelerometers and circuits, can be integrated into fabric by using plastic strips as a platform for components. The strips can be wrapped around the fibre or woven into or embroidered onto the textile surface. This method enables non-fibre based components to be integrated into the textile structure. [118] Forster Rohner Textile Innovations of St. Gallen, Switzerland developed E-broidery technology for the industrial-scale production of fabric embedded LEDs. The embroidery technology also enables the interconnection of sensors to be incorporated into the fabric. [66]

Instead of using mobile devices as a display, other types of solutions are also being investigated. Tactile displays (see Figure 7) and LEDs, OLEDs and AMOLEDs are also interesting ways to implement a flexible lightweight display for a wearable solution; this application is predicted to replace many traditional LED functions. The skin's sensitivity enables the use of wearable tactile displays for medium-level communication, such as for a navigational aid [119].

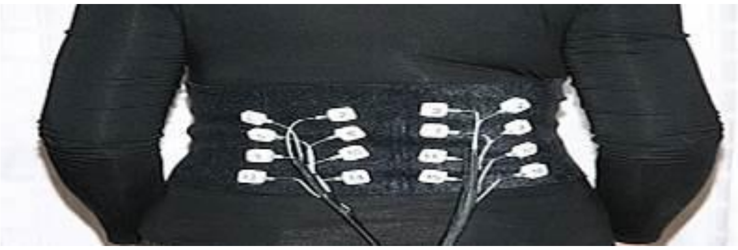

Figure 7. Application of a tactile UI. [119]

3.2 Energy management in wearable systems

Power management, specifically energy harvesting, is expected to be a bottleneck for commercial breakthroughs in intelligent clothing. However, several research groups are studying and developing technology for efficient, lightweight, wearable energy harvesting systems, and expectations of commercial solutions are high. These systems are employed primarily in various specialized applications, but none of these systems is yet ready for mass adoption. The development of power management lags behind the development of other components, and this field should aim to achieve the development level of other electronic components, such as semiconductors, displays and sensors. [9] The development of semi-conductor electronics is expected to significantly reduce the energy consumption of wearable technology solutions. Thin-film solar cells and supercapacitors made from graphene could provide relief for energy management in the future. [41]

For intelligent textiles, the best power source would be a self-powering, autonomous system. The hard and quite heavy battery pack is usually inserted into clothing. Current energy-harvesting and flexible battery technologies are not yet mature enough to supply sufficient power for smart textiles. [36] Sefar has developed a fabric-based electrode as part of a new thin-film solar cell that is based on the Grätzel cells that were invented by Michael Grätzel, a Professor at ETH Lausanne, Switzerland. Producing these electrodes is cheaper than producing conventional silicon cells, and these electrodes work efficiently even in diffused light. [77] Today, the thin-film solar cells developed by EMPA, the Swiss Federal Laboratories for Material Science and Technology, can achieve a 20.4% energy conversion efficiency using copper indium gallium (di) selenide (CIGS) solar cells on a flexible polymer substrate. Thin-film, lightweight and flexible high performance modules are attractive for portable electronics and can be produced more efficiently than standard silicon technology by using a continuous roll-to-roll process. [51]

Conventional printing technologies can also be used to fabricate flexible batteries. Imprint Energy has developed a rechargeable battery based on an ultra-thin zinc polymer cell structure, which can be printed onto textile substrates. [31] Pigments in the textile can convert light to electrical energy. TITV was the first to convert energy directly on modified textiles for applications (e.g., autonomously operated cost-effective textile sensors). Pigment-based solar cells supply energy for components with an energy consumption of up to 100 µW. [51] The rise of energy-autonomous products that can harvest energy from many sources is underway. In addition to pigment-based and thin-film solar cells, materials with piezoelectric properties are increasing. These materials have the ability to convert deformation into electrical voltage. The development of polyvinylidene fluoride (PVDF) thread would enable the integration of electrical components into a textile that could generate energy from the user’s own movement. CNT-based heated coatings can be manufactured without outage and used to store energy. [51, 182]

Several methods can be used to provide energy for electronic systems integrated into clothing. The alternatives that are currently in use are non-rechargeable primary or rechargeable secondary batteries and solar energy. [50] In addition to batteries and solar energy, the power can be harvested from the body movement of the wearer or from the temperature difference between the wearer and the environment. The kinetic energy of movement can also be converted to electrical energy. The kinetic energy can be generated by respiration and by the movement of the extremities. In wearables, piezoelectric flexible films are more favourable than the use of an electromechanical system, pistons or flywheels, even if those components have high efficiency due to their straightforward integration into the textile. The working principle of body heat recovery is based on thermopiles, which are usually made of metal, and the Seebeck effect. [50] The Power Pocket by Vodafone is a device that is promoted for use in shorts and sleeping bags in a bid to harvest body heat and movement to boost the battery life of mobile devices. This device aims to provide a 24-hour source of power for people camping at outdoor music events. [70] Energy harvested from kinetic movement or by embedding solar cells in wearable technology, such as textiles, is expected to result in a favourable market outlook [13]. Ampy is a wearable device that converts kinetic energy to smart phone-charging energy; 8,000-10,000 steps provide 3 hours of battery life. [12]

Energy harvesting by wearable renewable sources cannot be viewed as a challenge or an obstacle for intelligent textile or garment commercial implementation. Nevertheless, in hospital and home monitoring applications, the patient in the hospital or at home stays inside inside rather than going out into the sunlight. In addition, such patients typically move very little. Thus, wearable energy-harvesting solutions are not appropriate. Inductive battery chargers can be viewed as a more reasonable solution for medical wearable systems. The inductive link is composed of two coils: the primary coil is integrated into the substrate and generates an alternating magnetic field, and the secondary conductive coil can be integrated into textile electronic system by using conventional textile technologies, stitching, embroidery, weaving, lamination, etc. [50]. The primary coil could be integrated into a bed or chair at home or in a hospital. In these cases, energy harvesting can be accomplished using solar panels, which are not wearable. The harvested solar energy should be transferred to the rechargeable batteries of the wearable system.

Students at Aalborg University have developed textiles that recharge mobile devices inductively (see Figure 8). These textiles are based on conductive yarns in the fabric [34]. The Powermat recharger works the same way, but the system is integrated into the table. [183]

Figure 8. The Powertex textile is an inductive recharger for mobile devices. [34]

It is predicted that the use of smart phones and tablets as displays, user interfaces and wireless data communicator in wearable and intelligent textile technology will dramatically increase during the next decade. If this prediction is true, the overall energy needs of the application will decrease, as the display does not need to be integrated with the wearable system. The display uses the most of the energy needed for the application; signal processing and transmitting need only a fraction of the energy needed by the display. Small conventional or flexible and even stretchable batteries could then be embedded into the garment. [41] Research in the field of textile batteries is continuous. The textile battery can be fabricated using poly(3,4-ethylene dioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) as an electro-active polymer and conductive yarns as the electrodes. The conductive yarns are sewn into a textile substrate and then coated systematically with PEDOT:PSS. Pure stainless steel has better performance than silver-coated filament yarn. [42] Energy-harvesting fabrics can be produced by using hollow lead zirconate titanate (PZT) fibres. [43] A group of researchers at the University of Illinois managed to develop a stretchable lithium-ion (Li-ion) battery that continues to work when stretched, folded and twisted [13]. This battery could be used in many applications in the future, including epidermal health and wellness monitoring, and could even provide power for implantable electronics for monitoring the activity of the heart and other organs or for wearable photovoltaics (PV). The stretchable battery itself enables true integration with stretchable electronics in a small package and could even be applied to some soft substrates with other components. Recharging can be accomplished wirelessly.

4 Wearable textile electronics in medical and health care

The medical and health care sector is an important and constantly evolving area of the technical textiles industry. The global population continues to increase, and life expectancy has also increased. According to the statistical forecast from the European Commission, the proportion of individuals aged 65 years or over in the total population will increase from 17.1% in 2008 to 30.0% in 2060 [57]. The interest in ubiquitous wearable health-monitoring systems is therefore both socially driven and technologically driven. The rising cost of medical assistance, the ageing of the population and the desire to live longer lead to the need for long-term follow up of patients and early illness detection; intervention must also be improved. [35, 58]

Advances in sensor technology and data communication and processing and greater self-monitoring by individuals signify a shift towards ‘well-being management,’ such as exercise and diet, for long-term health conditions. These parameters must be monitored using ubiquitous healthcare technologies [60]. Hospitals are critical places for ill individuals who need surgery or other acute actions to save their lives. As the patient status is balanced, returning home as soon as possible is an advantage for both the patient and the hospital. Inhabitants demand more healthcare services, which cannot be provided easily without significantly increasing operational costs; [57, 61] thus, a more accessible and less expensive healthcare solution and procedures are required. The monitoring of vital signs could be utilized during post-surgery monitoring and during rehabilitation after surgery or injury [60]. There are 300 million people in Europe and North America and 860 million people worldwide who have at least one chronic disease, and it is estimated that 25% of these individuals would benefit immediately from wireless home monitoring solutions. [9] The ideal monitoring system would be non-obtrusive and provide continuous and long-term monitoring of the patient’s vital signs, resulting in improved autonomy and quality of life for the wearer. [50]

The monitoring system, which is discussed in detail in Chapter 3, always consists of input and output interfaces, sensors, displays, a data storage and processing unit (CPU), a communication and energy source, and a battery or renewable energy source. To achieve the ideal working wearable system, all of the parts should have textile-like properties, such as comfort, vapour permeability, and flexibility, as well as garment-like requirements, such as being lightweight, having a good fit, mobility and washability. Thus, the system should not diminish any feature of the regular garment. Otherwise, non-acceptance of the monitoring system might occur. The patient's acceptance of the system is significant in a medical context in which direct intervention is required; thus, only a textile monitoring solution could provide a ubiquitous system to meet genuine needs and facilitate clinical interaction through enhanced comfort, mobility and convenience [35]. The main aim in developing successful health monitoring garments is to improve the wearers' quality of life rather than reduce it due to the use of uncomfortable or cumbersome clothing.

Researchers at Aalto University in Finland have stated that it is inefficient for elderly patients to be kept as long-term inpatients at health care centres. That research group proposes converting this kind of inpatient clinic to short-term hospitals, which concentrate on rehabilitating the patients for returning to their homes. [62] However, elderly patients might believe that lying in a health care centre is safer than being at home without nursing care. A remote-controlled wearable vital sign-monitoring system would be a great solution for this scenario. Home monitoring helps patients to gain confidence about being safe, as the system can send information to the hospital personnel and alarm the hospital personnel automatically when a change in condition is registered. [35, 60] The user can even observe his/her own status, or the system can help the wearer remotely in the rehabilitation process by informing, reminding, supporting and even encouraging him/her. If the patient needs to spend time in the hospital, the textile monitoring system should be disinfected or sterilized before discharge from the hospital. If the garment is not needed anymore, the next wearer would receive a perfectly cleaned and sterilized product for use. The third scenario for vital sign monitoring using textile electronics could be the preventative monitoring of risk groups. Due to unhealthy lifestyles, heart disease and heart attacks are growing problems, especially in Asia.

Textiles have many benefits in body monitoring. These materials provide an ideal platform for the integration of functions and components in medical systems. The materials are flexible and elastic and provide comfort and a good fit. In addition to garments, these materials can be applied to bedding. Thus, textiles are versatile in design, material and structure, and it is possible to adjust the properties according to the needs of the application and the user. Textile solutions enable mobility during monitoring, which makes them ideal solutions for long-term monitoring. [35] The wearable body-monitoring applications consist primarily of different sensor types; with the help of an accelerometer and ECG measurement, it can be determined whether a high heart rate results from a possible heart disorder or from physical exercise. [63] LifeVest, which is manufactured by the Zoll Medical Corporation, continuously monitors the patient’s heart, and if a life-threatening heart rhythm is detected, the device delivers a treatment shock to restore a normal heart rhythm. LifeVest is used for a wide range of indications, including for patients with newly diagnosed heart failure, patients with a recent myocardial infarction, patients who require coronary revascularization before or after bypass surgery or stent placement, and patients with cardiomyopathy or congestive heart failure that places them at particular risk. This device is also worn by patients who are at risk of heart attacks and provides protection during changes in condition and while permanent risk has not been established. LifeVest provides doctors with time to assess long-term risk and make appropriate plans. [64, 65, 66, 67] The caregivers are able to follow the whole monitored community remotely and react when needed. In addition to hospital and home monitoring wearable technology, another application area is pre-hospital emergency care. Time is a critical factor in sudden emergency situations, and all of the components of monitoring chains should be instantly applicable. [68]

In addition to monitoring vital signs, wearable technology could be used for chronic pain relief. It is estimated that 1.5 billion people worldwide suffer from chronic pain and take medication for pain relief. [66, 69] The real benefit of the system remains controversial. Philips presented their integration of blue light-emitting LEDs into soft, flexible and wearable devices for healthcare applications. Their back pain-relieving device is underpinned by a series of LEDs that are attached to a conductive fabric matrix and linked to a skin temperature sensor. [76] In medical and home care, one application scenario could be the stimulation of users, both mentally and physically. A motion-activated garment or textile solution with integrated user interfaces for games and music could help in rehabilitation and provide a general good feeling. Location technology, such as indoor textile-based RFID tags and outdoor GPS textile antennas, in textiles would help register the location of a patient at home or in the hospital for improved protection and safety. As movement and location are to be detected in combination with vital sign measurement, the solution could also be used in studies of mental behaviour.

Areas for the application of textile fibre-based electrodes can be found in the professional, protective and fashion wear sector, the medical and health care sector, the sports, fitness and well-being sector, and home interiors, as well as in the automotive, construction and gaming industries. In body monitoring, a textile electrode (in other words, a conductive textile) can be used to measure bio-signals, such as ECG, pulse, heart rate, stress level, sleep quality, physical pain, EMG of muscle rate and balance, body motion, EEG of brain function, vitality level, respiration rate and frequency, body composition, including fat content and fluid balance, which are obtained via bioimpedance, skin temperature, skin conductivity and blood oxygen saturation. In addition to electrodes, conductive fibres and textiles can be applied as power sources, for signal transfer, as heating elements, antennas, switchers, detectors and actuators, and for EMI-shielding and ESD control. In addition to conductive textiles, other technologies for wearable sensors can also be utilised. Accelerators and optical sensors cannot be fabricated using fibre technology, but pressure sensors and humidity sensors can also be produced by exploiting conductive textiles, rather than using conventional approaches. However, due to the small size of electronic components, embedding these components into textiles to produce textile sensors is possible.

4.1 Electrodes for body monitoring

Textile conductivity sensors (i.e., textile electrodes) are perceived as the most advanced components in the textile electronic component field. Textile electrodes are ideal for long-term body monitoring because they have the same features as conventional textiles. In comparison to conventional adhesive gel electrodes, textile electrodes are soft, flexible and even elastic. These electrodes are able to absorb and transfer moisture, which makes them comfortable to wear. Textile electrodes do not cause skin irritation, and their integration with the garment can be invisible without conventional wire technology, which increases product acceptance. From a technical perspective, one disadvantage is the inherently high skin electrode impedance, which may cause interference and add noise to the measurement. [50] This noise increases during movement, but it can be reduced by filtering and by shielding the sensors, as discussed in Chapter 4.4. One advantage of flexible textile electrodes is that they follow the body topology, thus improving the contact area. The required variation in the shape and size of such electrodes is relatively easy to accomplish. Measurements are reliable and repeatable due to the constant placement of electrodes in a wearable system. [63]

By adjusting the conductive textile properties, numerous measurements may be obtained. The variables are the textile materials, the electrode shape and the structure. The materials and structure primarily affect the surface resistance and overall resistance, as well as the tactile and endurance properties during use. Conductivity fluctuates based on the size and shape of the fibre, the yarn type, the textile structure and the finishing treatments. The shape, size, flexibility and elasticity of the textile have an effect on the signal quality of the measurement. [73] ECG heart rhythm measurement is based on the measurement of voltage differences on the skin surface. These differences result from heart muscle depolarization during each cycle in the heart. The ECG measures the heart rate (R-R interval), pulse and heart rate variation (HRV). By observing heart functions, many kinds of information can be obtained: the activity level, physical condition level, stress level, sleep quality and even physical pain. The measurement also detects myocardial infarction and cardiac arrhythmias. [68] EEG measures the brain's vitality level, whereas EMG measures the activity of body muscles other than the heart. Both measurements are based on the same measurement system as ECG. By measuring EMG, the muscle activity rate and balance can be determined. Body motion detectors and movement information can be utilized in physical therapy or rehabilitation. Body motion can also be detected using a conventional strain and bending sensor that is integrated into the garment or accessory or by using a textile strain sensor, which is based on resistance changes during movement. In addition, it is possible to integrate conventional accelerator sensors into textiles to measure motion. In addition to motion detection, textile fibrous strain sensors can be used to measure the respiration rate and frequency. Breathing causes changes in resistance, and the rate of breathing can therefore be determined. In theory, the topography of the sternum (breastbone) can be detected using a textile strain gauge sensor. [74] [75] Electro-impedance tomography (EIT) measures lung function. This approach can be used to measure the respiration rate of each lung, to detect fluid in the lungs, etc. Electrical voltage is measured through the upper body. Electrical bioimpedance (EBI) also enables the measurement of body content, fluid and fat, and respiration volume via textile electrodes. Fluid has a low resistance, whereas fat is an insulator. Body content is measured from ankle to wrist. During bioimpedance measurement, the material's ability to resist alternating current (AC) is measured, whereas resistance measures the material's ability to resist direct current (DC). By measuring the bioimpedance of the body from hand to foot or hand to hand, the fat or fluid content can be determined. Respiration frequency and volume are measured through the sternum. The same sensor can be used to measure different variables by changing the location and frequency of altering current (AC) during measurement. The simultaneous measurement of different signs enhances the information about the situation. For example, ECG measurement together with accelerometer data produces information concerning whether a high heart rate is a result of physical activity or a sudden seizure. Basically, similar electrode structures can be applied to bioimpedance and resistivity measurements. This similarity enables the use of the same electrode for multiple measurements simultaneously. [21, 22, 23, 63] Skin conductivity can be measured by using textile electrodes or by integrating humidity sensors into the textile structure. Skin conductivity measures the sweating rate, which can be an indicator of impending unconsciousness or coma.

4.2 Thermal electrodes

Conductive textiles can also be used as thermal electrodes. Heating areas are quite simple to form using conventional textile manufacturing processes. Conductive yarns can be applied to woven, knitted or non-woven textile materials, or heating areas can be embroidered onto the fabric surface. Sefar has developed conductive fabrics that are able to measure temperature or generate heat. [77, 78] In WarmX, which is a heated apparel from GmbH, the heating zones of the garment are formed by polyamide fibres coated with silver ions, which are knitted directly into the underwear. [79]. The heating fibre material consists of metal or carbon nanotube (CNT) fibres. [80] During longer hospital operations, a serious reduction in body temperature may occur as a result of the anaesthetic, which can lead to hypothermia. Patients also lose a lot of body heat in operating theatres because they are generally air-conditioned to 18-22°C**.** A heating blanket consisting of thermal and conductive fibres would benefit surgical patients. [81, 82]

4.3 Antennas

Conductive silver-coated yarns can be used to form fabric antennas. A group of researchers at Drexel University created knitted antennas that are to be used with a deformation sensor. While stretching the antenna, the size and properties vary; therefore, the loss of return signal from the antenna is affected. One potential application is to measure the contractions of pregnant women during labour. [66] Traditionally, GPS location only works outdoors because it is based on satellites in space and attenuation occurs within buildings. However, indoor positioning systems are in development. In medical care, indoor positioning systems could be used to locate patients in the hospital and at home. Wearable textile antennas can be produced directly within clothing by using conductive yarn or fibres [81] or by applying conductive ink on a textile substrate [84].

4.4 EMI-shielding and ESD control

Conductive textile structures are suitable for electromagnetic interference (EMI)-shielding and controlling electrostatic discharge (ESD). Depending on the application, some electronic devices, electrodes and components must be shielded from EMI caused by surrounding electrical devices. Shielding provides protection from incoming EMI for sensitive components and/or prevents excessive emissions of EMI to other susceptible equipment. Conductive textiles can also be applied for the mechanical filtering of particles in the air, thus preventing undesirable particles from reaching the body, which is especially important in the prevention of infections [90].

Due to the growing number of products that contain sensitive electronic components, interference disturbs signal transfer, and this noise can lead to device failure. The most common type of EMI occurs in the radio frequency (RF) range of the electromagnetic (EM) spectrum, from 10^4 to 10^{12} Hertz. This energy can be radiated by computer circuits, radio transmitters, fluorescent lamps, electric motors, overhead power lines, lightning, and many other sources. The smaller size and faster operating speeds of these components make it more difficult to manage the EM pollution they create. Placing a Faraday Cage around an electrical device is the fundamental principle that underlies the housing technique for shielding against EMI. [85] Shielding is achieved by protecting the textile electrode or component with a second conductive textile layer.

In addition to EMI, uncontrolled ESDs are also a challenge in textile electronic solutions as they might cause a functional failure. In particular, textile electrodes embedded in a garment or strap would require the controlled discharge of static electricity caused by other garment layers of wearer. Conductive textile fibres can provide ESD protection if required by the application. Shielding also improves signal strength, which leads to a higher quality of ECG. Thus, shielding improves the potential to measure weak signals from muscles (EMG). The undesirable noise caused by EMI or uncontrolled ESD can be filtered from the measurement, but this filtering slows the ability to observe changes during measurement; thus, shielding would improve this ability. Uncontrolled discharges reduce personal safety in the medical environment (e.g., the operating theatre). The static electricity of a person can be controlled with a conductive floor, by wearing conductive ESD footwear and garments, and with grounding bracelets. The best protection against static electricity can be gained by using conductive fibres. [86, 88, 89] Investigations indicate that metal fibres, such as copper and steel, in combination with cotton jersey knit are effective against electromagnetic waves. [90]

4.5 Wearable sensor applications

This section discusses the sensors to be used in wearable applications that are embedded within textile structures but are not based on conductive fibres. Accelerator sensors, optical sensors, humidity sensors and piezoelectric sensors can be embedded into garments or used in other wearable solutions to provide data from the user or his/her surroundings. [92].

SenseCore of Switzerland developed dry detachable electrodes, which are clipped onto a garment. These electrodes can measure the biometric data of the user (e.g., heart rate, respiration, post-exercise oxygen consumption (PEOC) and temperature), as well as information about the training session (e.g., distance, speed, and acceleration). The data are transmitted via Bluetooth to a computer device. [31] STBL Medical Research AG (STBL), Freinbach and EMPA, Switzerland have developed a device that can be worn comfortably on the wrist and records blood pressure continuously using piezoresistive fibres. [94] The Moticon insole is a wireless system that consists of 13 capacitive pressure sensors and can be used for sports and healthcare applications. This device can measure weight distribution and motion for use in rehabilitation and training. The system provides data for impact analysis after leg surgery and data concerning the correct activity for individuals with walking and posture problems. [31, 95] Optical fibre sensors are a competing technology for conductive fibres for measuring vital signs, such as heart rate, and other heart-related issues. [77, 96] This technology is inexpensive and simple, but it cannot be integrated into fabric like conductive fibres. Opto-Phone is a continuous and non-contact technique that uses laser beam illumination, an advanced camera and sensitive software to detect heart rate, blood pressure and blood glucose levels from up to 100 m away [45, 99]. Electromagnetic wave sensors can be woven into fabric and incorporated into garments to measure vital signs of the body. This technology supports patients with long-term health conditions, such as congestive heart failure, COPD and diabetes, and reduces the number of unplanned hospital admissions and emergency interventions. [56, 102]

Detachable, disposable electrodes are an alternative to washable textile electrodes. These disposable electrodes may incorporate multiple sensors, including ECG and an accelerometer, which will allow the measurement of heart rate, activity, sleep and other physiologic metrics. [100, 101] As disposable sensors cannot be integrated into a garment, the electrodes might be misplaced. The strength and security of the signal can be better than that of textile electrodes, but long-term monitoring can cause skin irritation. The low cost of disposables is an advantage when compared to textile electrodes. Another competing technology for textile electrodes that is in development is a thin adhesive film sensor, which is attached separately to the skin surface (Figure 9). [100, 101] However, separately set sensors are not the best choice for medical home monitoring systems because to obtain reliable and accurate data, the sensors must be placed by an experienced medical professional. Separate sensors might not be suitable for long-term monitoring of human vital sign because it might be difficult for the wearer to wash himself. Like conventional gel electrodes, adhesive sensors might not be breathable and can cause skin irritation or allergic reactions, which makes them more useful for short-term monitoring. Adhesive sensors achieve good skin contact, thereby improving signal quality, but body movement causes the stretching of the skin. This stretching might feel uncomfortable and might even prevent the full movement of the extremities.

Figure 9. Detachable, disposable electrodes are one competing technology for textile electrodes. The application uses a smartphone as a user interface. [100]

5 Decontamination in healthcare

Microorganisms are important symbionts of humans (e.g., during digestion), but some specific microorganisms, including viruses, cause diseases. Disinfection and sterilization are used to control microorganisms on surfaces or in liquids in the medical environment. A variety of physical and chemical control methods are available. The biocidal applications include skin washing, wound treatment, product preservation, food and water disinfection, surgical device decontamination, and product sterilization. The development of infection-control methods has reduced the incidence of infectious diseases, such as gastroenteritis and pneumonia; however, microorganisms remain a significant cause of morbidity, mortality, and economic loss, and we continue to be challenged by the identification of new or more resistant microorganisms, such as antibiotic-resistant bacteria, human immunodeficiency virus (HIV), Ebola virus, viroids, and prions [47]. The Freedonia Group published a study that demonstrated that the global demand for infection-prevention products is forecasted to increase 6.4% annually to US$130 billion in 2017. This estimate is based on two drivers (i.e., the upgrading and enforcement of patient and staff safety standards in healthcare facilities, and the expanding volume of hospital, surgical and outpatient procedures). [71]

The contribution of textiles to the spread of viral infections is remarkable. Most infection-induced respiratory problems are caused by viruses, which can cause infections of the upper respiratory tract in the form of colds, coughs, acute bronchitis or even pneumonia, particularly in small children. For ill people in hospitals, the respiratory problems caused by viruses or bacteria might be even fatal. Garments, hands and other surfaces are often involved in the spread of pathogens. Figure 10 illustrates the pathways by which pathogens spread. Previous studies demonstrated that textiles that are in regular contact with hands can contribute to the spread of viruses. Viruses do not have their own metabolism; thus, viruses cannot survive without the host, and unlike bacteria, viruses do not multiply on surfaces. According to one study, finished microfibre cloths absorbed 91% of the applied viruses. At the same time, the virus concentration in the cloth was reduced by approximately 90%. [77, 82, 83]

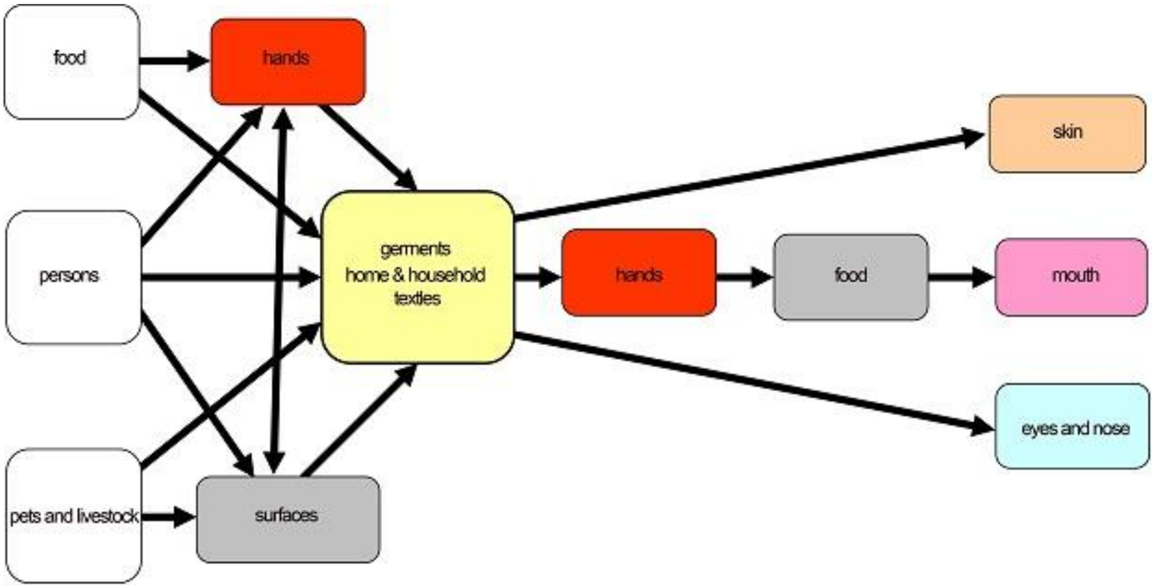

Figure 10. The pathways by which pathogens spread, with textiles at the centre. [83]

Many devices must be sterilized, either before distribution or before every use. Furthermore, the sterilization process must not compromise the performance of the devices. Examples of devices that require sterilization are examination and surgical gloves, clean room garments, specimen cups, wound care products, sutures, needles, syringes, catheters, drain bags, IV bags, fluid delivery systems, dialysis equipment, implants, surgical instruments, dental instruments, surgery supplies, and combination products. [93] Sterilized products are widely used in hospital inpatient departments, intensive care units and operating theatres. Products must be clean from stains before the sterilization treatment. The use of an antimicrobial treatment on textile surfaces prevents the spread of microbes by preventing bacterial growth. Together with material sterilization and disinfection, sterilization is beneficial for the prevention of nosocomial infections in hospital environments. [97] Some metals, such as silver, are naturally antimicrobial; thus, additional treatment is not necessary when the electrodes consist of these materials. Silver is capable of hampering the development of unpleasant odours, bacteria, mites and fungi. The micro-encapsulation of active materials into textiles has been long established; fibres coated with silver particles have been in medical use since the 1990s. The application areas for these materials are bandages, dressings and medical devices. In addition to silver, carbon fibre fabrics are also used to absorb odours. [35] The silver treatment can be applied to fibre or yarn or on a fabric surface. In addition, this treatment has a long durability and is resistant to laundering. In other words, as long as the surface conductivity has not changed, the antibacterial property remains.

Based on interviews with professionals, long-term textile body-monitoring systems used in hospitals should tolerate 20 cycles of sterilization [19].

The antimicrobial agent can be embedded within the fibre or yarn or applied to fabric or ready-made products. However, the antimicrobial treatment tends to leach during washing and abrasion. Textiles in the medical environment are expected to withstand hundreds of hot laundry cycles and must also endure sterilization in some applications. This challenge was the motivation for the development of permanent antimicrobial treatments. A US researcher at the University of Georgia invented an inexpensive technology that is said to render medical linens and clothing, face masks, paper towels, diapers, intimate apparel, athletic wear and socks permanently germ-free. [59] [98] The Kodak's antimicrobial agent can be embedded into synthetic fibres before spinning to ensure the antimicrobial effects. Fabric-based medical devices are uniform and constant throughout the life of the product. [103] Scientists at the Hohenstein Institute in Bönningheim, Germany developed a nanoparticle-based textile finish with both antiviral and antibacterial functions to be used in hospitals to interrupt the chain of infection. [77]

Ageing occurs as a result of physical and chemical reactions of plastic materials, which cause changes in properties as a function of time. The extent and type of ageing depends on environmental factors, such as temperature, humidity, UV light, the surrounding atmosphere and mechanical stress on the material. The sterilization process causes the same kinds of reactions as the natural ageing of materials. Sterilization fastens the molecule chains by cross-linking and/or degrading. Oxidation caused by oxygen in the air and hydrolysis caused by moisture, as well as crystallinity, can change with time. Irradiation multiplies mechanical, chemical and physical changes. [105] Conductive textile sterilization would open the possibility for new application areas. The textile sensors used in health care and hygienic products are typically disposable. Cost analysis is necessary to determine the unit costs for both cases. The sterilization of conductive non-disposable textile-electronic products may turn out to be more cost-effective and to have market potential due the competitive price and ecological aspects.

5.1 Terminology

The basic principle of decontamination is to remove or inactivate the infection-causing organisms that are in or adhering to the material. The decontamination process and method depends on the purpose of the product; thus, any process that reduces microbial numbers on a surface can contribute to the prevention of infection. This section defines the terminology of decontamination control.

Decontamination is a general term for the destruction of microbial contamination on items or surfaces in order to make the material safe to use or discard. Both chemical and physical inactivation methods are in use. Decontamination is generally a combination of cleaning and the disinfection or sterilization of an item. Non-microbial matter is also eliminated. [47,107] An antibiotic substance kills or inhibits the growth of bacteria. This term has also been applied to substances that affect other microorganisms, particularly fungi. In contrast, an anti-infective substance is capable of killing microorganisms or resisting the growth of microorganisms, particularly pathogenic microorganisms. This term is used to encompass drugs that act specifically on certain microbial types, including antibacterials (antibiotics), antifungals, antivirals, and antiprotozoal agents. The term ‘anti-infectives’ can be used for treatments for specific infections of animals, plants, and humans. Generally, antimicrobial products enable the use of physical or chemical methods for killing microorganisms. The efficiency and quality can be adjusted depending on the process or product and the target microorganism (e.g., antibacterial or antifungal). An antiseptic agent will destroy or inhibit microorganisms on or in living tissue, such as skin. [47] The bioburden is the microbial load (i.e., the number of microorganisms, such as pyrogens, viruses, moulds, and fungi, that are present in or on a material). [47, 93] A biocide is a chemical or physical agent that inactivates microorganisms. Biocides generally have a broad spectrum, in contrast to anti-infectives, which have a narrower range of antimicrobial activity. [47]

Sterilization can be defined as the inactivation or destruction of all living organisms, including resistant forms, such as bacterial or fungal spores. In the case of viruses, sterilization inactivates their ability to replicate. Therefore, this process therefore makes items sterile. [107, 109] Sterilization therefore includes disinfection but provides an increased level of safety. Sterility is measured by the Sterility Assurance Level (SAL) of the device or the material. The SAL, which is expressed as 10^{-N}, is the expected probability of surviving organisms. Typical SALs are 10^{-6}, indicating that the expected probability of any surviving microorganism after sterilization is 10^{-6}. Some less critical or low-risk devices might need SALs less stringent than 10^{-6}. The sterilization conditions must be selected to achieve the targeted SALs. [93] The probability of any surviving microorganisms after different sterilization treatments depends on the number of microbes and their resistance, as well as on the treating environment. [109] Bacterial spores are most resistant to destruction, and if the sterilization process effectively eliminates bacterial spores, it can generally be assumed that all other pathogenic and non-pathogenic organisms have been destroyed. [93]

Disinfection is any process whereby the potential of an item to cause infection is removed by reducing the number of viable microorganisms, or the bioburden, present. [107] This process destroys vegetative, sporeless microbes and viruses on inorganic surfaces using chemical or physical treatments. Disinfectants are often subdivided into high-level, intermediate-level, and low-level, depending on the product claims. [47] Disinfection is effective against most pathogens, with the exception of the most resistant bacterial spores. The cleaning process removes the ‘soil’ from a surface, including dust, soil, large numbers of microorganisms and organic matter (e.g., blood). The cleaning process is a prerequisite for textile disinfection and sterilization. [107]

5.2 Risk categories and levels

The decontamination method is chosen according to the object’s purpose of use in a certain environment or under certain conditions. The primary goal is to ensure the safety of the patient, the staff, the devices and the environment. Decontamination ensures that no toxic substances remain on the surface that could cause other negative reactions for the patient or staff. In addition, the decontamination process cannot damage the device. A growing concern is the impact of the decontamination process on the environment, as this process always requires energy, water and chemicals. Thus, the use of these resources should always be minimized without compromising the safety of the patient or the staff. [107]

During the 1950s, Dr. Earl Spaulding developed a classification system that classified medical devices according to their risk level, as illustrated in Table 1. The required use of the device and the associated infection risk dictate the recommended antimicrobial process.

Table 1. Risk categories and levels of decontamination required. [107]

Definition	Suitable decontamination methods	Examples
High-risk items/Critical devices are in close contact with a break in the skin or a mucous membrane, such as the blood or tissue, or are introduced into a normally sterile body area.	**Sterilization** is required. Alternatively, **high-level disinfection** can be used if sterilization is not possible or practicable.	Surgical instruments Syringes and needles Intrauterine devices and associated equipment Dressings Urinary and other catheters Arthroscopes and laparoscopes
Intermediate-risk items/**Semi-critical devices** are in contact with intact mucous membranes or non-intact (broken) skin.	**Disinfection** is required. To ensure efficacy, cleaning is a necessary first step, followed by disinfection. This process would include certain types of microorganisms that are considered much more difficult to inactivate.	Respiratory equipment Gastroscopes A variety of endoscopes Probes Re-usable thermometers
Low-risk items/Non-critical devices or surfaces are any surface that only contacts intact skin.	**Cleaning and drying** are usually adequate, meaning the physical removal of microorganisms and visual signs of soiling. In some cases, **disinfection** is needed to encompass viruses, such as influenza and HIV, most bacteria and some fungi.	Stethoscopes Blood-pressure monitoring cuffs Washing bowls Table tops Bedrails Chairs
Minimal risk items are not in close contact with patients.	**Cleaning and drying** at an adequate temperature is sufficient.	Floors Walls Ceilings Sinks

However, the device can change its classification depending on how it is used. For example, the same device may be critical when used for a surgical procedure or semi-critical when used for non-invasive diagnostic purposes. The exact requirements for ensuring the safety and effectiveness of cleaning, disinfection and sterilization vary among countries and among regions. In addition to product risk-level categorization, further classification can be based on whether the device is for single use or re-use. The emphasis is placed on ensuring safe handling and decontamination between patients. [110]

5.3 Decontamination process

The decontamination cycle describes this process (see Figure 11) as it is used in healthcare facilities today. The devices that enter the cycle can be either new or used. The handling of items after use and during transportation must be accomplished without damaging or losing the items or posing any safety risks to staff, visitors or subsequent patients. Single-use and re-useable products are separated. Cleaning removes the contamination from an item, including patient material, such as blood and tissue, microorganisms and even different chemicals used during a procedure. Cleaning may be the only decontamination step required, but this step is always the pre-treatment before any further decontamination, such as disinfection and sterilization. Cleaning and disinfection may sometimes be achieved in a one-step process, but these goals are most often achieved using a two-step process of cleaning followed by disinfection. The level of disinfection depends on the purpose of use. In some cases, sterilization may be directly applied at this stage as an alternative to disinfection and for immediate use with a patient. During the inspection process, the instruments or materials are checked for cleanliness and functionality. Defective devices are either repaired or discarded. Packaging is designed to protect a single device or a set of assembled devices during sterilization, storage and transport. After sterilization, the devices may be transported for direct patient use or stored until required for a specific procedure. The correct storage, distribution and waste handling of re-usable devices are essential steps in the decontamination cycle. [110]

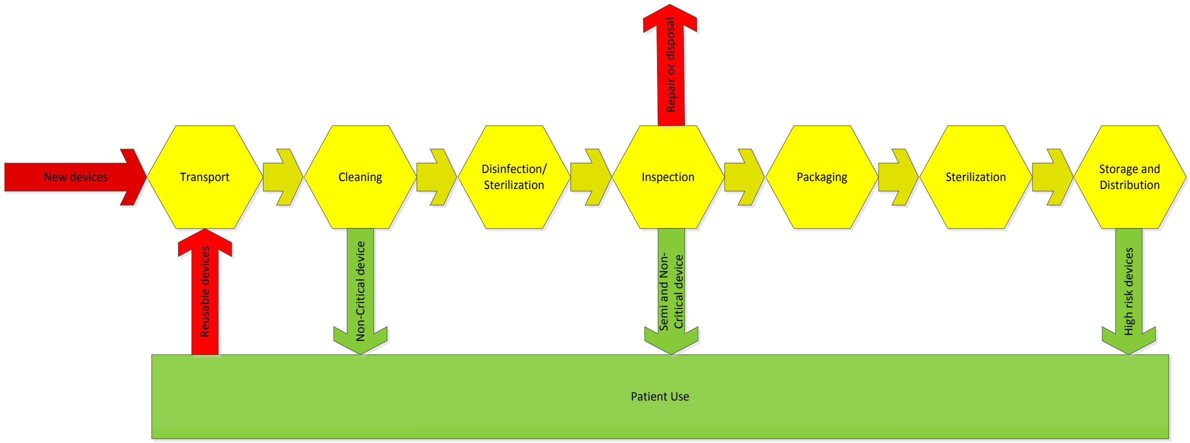

Figure 11. A summary of the decontamination process for patiend-used, instruments and materials [110]

5.4 Decontamination methods

Product sterility can be achieved using a variety of methods. The method to be used depends on the product type, size, and material. The main sterilization methods for medical devices can be divided to chemical and physical methods.

Autoclaving, hot steam, dry heat sterilization and irradiation methods, such as methods that use gamma and electron beams, are physical methods, whereas ethylene oxide and low-temperature plasma treatment are used for chemical sterilization. In addition to the material content and structure of the device, the packing material must be considered in order to achieve complete sterilization. The packing material must be permeable to moisture for steam sterilization, chemical gas or radiation and also allow the removal of moisture. All materials within a device should retain their integrity during and after the sterilization cycle or cycles. [93] After the treatment process, the sterility of the items is tested. The most common approach is to use minute organisms containing biological indicators. The indicators are placed in various locations in a sterilization chamber. The death of the organisms in the biological indicator confirms the effectiveness of the sterilization procedure. [93, 111] Steam is the most commonly used sterilization method for reusable devices in hospitals. Most sterilization methods, except for ethylene oxide sterilization, are ‘safe.’ Table 2 presents a comparison of the available methods. Some of these methods are described in more detail in Chapter 5.4

Table 2. Summary of features of different sterilization methods used for medical devices. [93]

Sterilization characteristics	Steam	Dry heat	Ethylene oxide	Gamma radiation	Electron beam (e-beam)
Process type	Batch	Batch	Batch	Batch	Continuous
Post-sterilization testing for SAL	Parametric release; biological indicators	Parametric release; biological indicators	Parametric release; biological indicators	Dosimetric release	Dosimetric release
Post-sterilization treatment	Need to dry the product	None	Need to aerate the product to remove residues	None	None
Penetration	Requires vapour-permeable packaging. Surface penetration	Good penetration	Requires gas-permeable packaging; high pressure, temperatures for improved penetration	Excellent penetration	Near complete penetration, need dosimeters; low penetration in high-density materials
Safety	Almost no safety concerns	Almost no safety concerns	Considered a mutagen/ carcinogen; need to remove residual absorbed EtO	Minimal concern; environmentally safe; nontoxic (need protection from radiation)	Almost no safety concerns
Reliability	Excellent	Good	Good	Excellent	Excellent
Turnaround time	Slow	Slow	Slow	Fast	Fast
Process parameter controls	Temperature, pressure, vacuum, relative humidity, time	Temperature, pressure, vacuum, time	Temperature, pressure, vacuum, relative humidity, gas conc., time	Time	Time
Material constraints	Heat-resistant and hydrolysis-resistant materials only	Heat-resistant materials only	Polymers that do not absorb or degrade with EtO	Radiation-stable polymers; complex parts and kits not effectively sterilized	Low-density materials only; e-beam stable polymers
Relative cost	Inexpensive	Relatively inexpensive	High capital investment	High capital investment	High capital investment

Sterilization characteristics	Steam	Dry heat	Ethylene oxide	Gamma radiation	Electron beam (e-beam)
Advantages	Simple process, widely used, excellent for reusable devices, excellent for heat-stable liquids	Relatively simple process	Well characterized, good for kits, combination products, parametric release	Simple, fast, excellent penetration, dose uniformity	Simple, fast, less material degradation
Disadvantages	Comparatively high temperatures, generally not appropriate for single-use devices and large lots	High temperatures, limited use	Relatively complex process, some limits to penetration, need to remove EtO residuals	Limited applicability to kits and complex designs/ products; no drug/ combination products; material degradation	Limited penetration, poor for high-density products, dosimetric release is not very uniform, affected by part configuration

The following table presents the sterilization method recommendations for the materials investigated in this study.

Table 3. Sterilization matrix of plastics, including the material groups investigated in this study. [93]

Polymer	**Steam**	**Dry Heat**	**Ethylene**	**Gamma**	**e-beam**
Polyurethanes	Poor	Poor	Good	Good	Good
Polyamides					
Nylon 6, Nylon 66	Fair	Fair	Good	Fair	Fair
Aromatic	Good	Good	Good	Good	Good
Nylon 12, 10,	Poor	Poor	Good	Fair	Fair
Polyesters					
PBT	Fair	Fair	Good	Good	Good
PET	Poor	Poor	Good	Good	Good
Co-polyesters	Poor	Poor	Good	Good	Good
Elastomers					
Silicones	Good	Good	Good	Good	Good
TPU	Poor	Fair	Good	Good	Good

Disinfection can be achieved using water treatment, which reduces the number of pathogens to an acceptable level. Disinfection is not the same as sterilization, which destroys all living organisms. According to a study performed by S. Nurmi, S. Salo and G. Wirtanen, aerobic microbes, yeasts, moulds and some *S. aureus* cells were found on textiles cleaned by laundering. The microbial contamination on different operating textiles appears to originate from the wearer, with additional microorganisms from other environmental surfaces and patients, from laundering and from logistical processes. [120] This finding indicates that clothing and textiles convey bacteria in hospitals and that laundering is not always a sufficient inactivating treatment for the bioburden on textiles. [121]

The cleaning process aims to remove contamination from an item. As mentioned previously, cleaning may be the only step required in the reprocessing cycle in the case of some non-critical devices. For other re-usable instruments, cleaning is normally a prerequisite for further reprocessing, such as disinfection and sterilization, as part of the decontamination cycle. The presence of organic and inorganic materials on devices can inhibit contact with the surfaces of the device and thus reduce disinfection or sterilization activity and effectiveness. In addition, the presence of soiling can cause toxicity and immune reactions in the patient and may even damage the device and affect functioning. Further, it is a prerequisite for staff working in the decontamination facility to protect themselves from any contact with contamination. In most healthcare situations, the product is described as being clean if the surface or device is visibly clean and is thus defined as being 'visibly free from dirt, stains, or impurities.' It is assumed that invisible soiling may not be a risk for the patient or affect any subsequent disinfection/sterilization step. However, some bodily fluids are invisible to the naked eye, including tears, pericardial fluid, synovial fluid, cerebrospinal fluid, etc. The evaluation of cleaning effectiveness is made by visual observation, but the protein level of the surface can also be observed. [110]

5.4.1 Autoclaving

The principal method for sterilization in hospitals is the steam and dry heat autoclave process, which is used for instruments, textiles and laboratory devices. Autoclaving is used frequently in hospitals for the sterilization of multiple-use articles. Autoclaving is not the predominant method for the commercial sterilization of medical devices due to the difficulties involved with the autoclaving of packaged products. [93]

The process variables are saturated and pressurised steam, temperature and time. Saturated steam conveys its evaporation heat to the material to be sterilized. High temperatures, along with moisture, destroy microorganisms completely. Steam should penetrate and reach all surfaces of the product for proper sterilization efficacy. Poor cleaning, improper moisture, impermeable packaging, or over-packing of the autoclave chamber can reduce the effectiveness of steam sterilization. Before the three-phase sterilization process, the autoclave is preheated. The product is inserted into the chamber, and the first step is the pre-treatment, in which the air is removed by a vacuum pump. It is important to remove all of the air from the autoclave because air reduces the steam concentration, which jeopardizes the effectiveness of sterilization. In the second step, increasing pressure causes resistance, which leads to increased steam temperature. High-pressure steam first condenses when it comes in contact with the part/material and then continues to heat the material. The appropriate time and temperature depend on the type of product, the material and the amount of load in the chamber. The typical conditions for steam sterilization are presented in Table 4. A prerequisite for sterilization is that the device has been in saturated steam at 121°C (250°F) for at least 15 min, or for 10 min at 126°C, or for 3 min at 134°C (273°F), at a pressure of 2.5 kg/cm^2. [109] The lower the temperature, the longer the exposure time that is required for sterilization. Multiple-use devices are exposed to several such sterilization cycles, as they are sterilized after each use. The materials used in such devices must be able to withstand the number of cycles specified for the device and maintain performance, safety, and effectiveness. The third and last step is the reduction of pressure and the evacuation of steam. As the pressure decreases, the water boiling point decreases, and humidity evaporates rapidly from the device. [93]

Table 4. Typical steam sterilization conditions. [93]

Temperature (°C)	Sterilization Time (min) for 1 Cycle
132–134	3–10
121	8–30
115	35–45
111	80–180

The material of the device dictates the sterilization temperature. Plastic materials to be sterilized should have a higher softening temperature than the sterilization temperature when considering steam sterilization. The consequences in plastics are plastic softening and deformation. The injurious effects are oxidation caused by air and hydrolysis caused by wet steam. [105] Materials with high heat-distortion temperatures, such as polycarbonate, polyesters, and polyamides, might be prone to hydrolysis. [93] Alterations of haptic and mechanical properties, such as elasticity and tear strength, may occur in textiles. A partially crystallized organic polymer’s crystallinity rate and glass transition temperature can increase due to the sterilization process, which further decreases elongation at break and increases impact strength. The sterilization of polyester increases the glass transition temperature and crystallinity rate, but there is no effect on strength properties. [105] Even if a device to be sterilized has a higher softening point than the autoclave operation temperature, warping, distortion or deformation can occur due to the release of moulded–in stress. Moulded-in stress is caused by the rapid cooling or improper design of the part, and heating the part relieves the moulded-in stress. Cumulative effects of multiple sterilization cycles are possible for plastics. [93] Most plastics will survive 1–5 cycles of steam sterilization. Polysulfones, polyether sulfones, polyetherimides, polyether ether ketone (PEEK), and liquid crystal polymers (LCPs) are the most suitable materials for reusable devices that need up to 100 sterilization cycles. Polyphenylsulfones, PEEK, and LCPs can be used for applications that require more than 100 cycles. Polyphenylene sulfones have the highest endurance; these materials can withstand up to 1,000 cycles of steam sterilization. [93] The most frequently used plastics in medical applications are classified in , and the materials investigated in this study are included as part of a wider material group. The specific materials investigated here are presented in red and yellow.

Table 5. Autoclaving capability and heat distortion temperatures (HDT) of plastics used in medical applications [93]. The plastics used in this study are marked in grey.

Polymer	**HDT (°C)**	**Steam at 121 °C**	**Dry Heat at 135 °C**	**Hydrolytic Stability**
Polyolefins				
HDPE	80–120	Fair	Poor	Good
LDPE	60–80	Poor	Poor	Good
UMHPE	60–80	Poor	Poor	Good
PP	100–120	Good	Fair	Good
PP copolymers	85–105	Good	Fair	Good
COC	170	Good	Good	Good
PVC				
PVC plasticized	60–80	Poor	Poor	Good
PVC unplasticized	90–115	Good	Good	Good
Polystyrene/Styrenics				
Polystyrene	70–90	Poor	Poor	Good
ABS	80–95	Poor	Poor	Good

Polymer	**HDT (°C)**	**Steam at 121 °C**	**Dry Heat at 135 °C**	**Hydrolytic Stability**
SAN	95–105	Poor	Poor	Good
Acrylics	75–100	Poor	Poor	Fair
Polycarbonates	135–140	Fair	Fair	Fair
Polyurethanes	50–13	Poor	Poor	Poor
Acetals	145–160	Good	Fair	Good
Polyamides				
Nylon 6, Nylon 66	170–220	Fair	Fair	Poor
Aromatic	250–300	Good	Good	Good
Nylon 12, 10, 6/12	70–150	Poor	Poor	Fair
Polyesters				
PET/PBT	75–140	Fair	Fair	Poor
Co-polyesters	60–80	Poor	Poor	Poor
High temperature thermoplastics				
Polysulfones	170–215	Good	Good	Good
PPS	195–215	Good	Good	Good
LCP	200–300	Good	Good	Good
PEI	200–210	Good	Good	Fair
PEEK	160	Good	Good	Good
Fluoropolymers				
PTFE	75–130	Fair	Fair	Good
FEP	70	Good	Good	Good
ECTFE/ETFE	115	Good	Good	Good
PVF/PVF2	140–150	Good	Good	Good
Biopolymers	25–80	Poor	Poor	Poor
Elastomers	20–40	Poor	Poor	Fair
Thermosets	150–300	Good	Good	Good

Small-scale autoclaves are defined by European standards (SFS-EN 13060:2004) as having a chamber volume under 60 litres. Small-scale autoclaves are classified into three categories: B-, N- and S-type. The B-type autoclave is a general autoclave with a three-phase process that is suitable for all materials, packed and unpacked, including textiles. The N-type autoclave can only be used for unpacked solid device sterilization. There is no vacuum pump in the system, so it is possible that air that remains in the chamber might jeopardize the success of sterilization. This possibility means that hollow or tube-like devices or textiles are not suitable for this type of autoclave. The S–type autoclave can be used for hollow, porous or packed products only if the autoclave has a suitable program for such materials. [112] Autoclave sterilization can be performed for fabric, cotton wool, wadding, metal instruments, glass and silicone devices. Rubber and other heat-sensitive devices can be sterilized with a rubber program, which requires sterilization at 121°C with a pressure of 1 kg/cm^2. The sterilization time is then longer. [26]

Autoclave validation is accomplished using physical, chemical and biological indicators. Physical indicators indicate the temperature and pressure during the process. Chemical indicators change colour during the process, and the result can be identified after the treatment. The Dick Bowie method uses a chemical indicator, which indicates the air evacuation capability of the pre-vacuum program, chamber sealing and the steam quality. Traditionally, the effectiveness of sterilization is indicated using a biological indicator, for which a paper sheet contains a large amount of highly resistant spores. The most widely used spore for wet-heat sterilization is *Bacillus stearothermophilus*. [93] After treatment, the paper sheet is examined, and any remaining viable spores are identified. The sterility of the paper sheet means that the process can destroy a wide range of bioburdens on materials. In addition, the autoclave must be calibrated regularly. [93,112]

Another autoclave-based method is dry heat sterilization, but this method is not as effective and efficient as wet-heat steam sterilization. The advantage of steam sterilization is better heat penetration of the material or part, which enables a shorter exposure time and a lower temperature. In addition, higher temperatures and longer times are generally required for dry heat sterilization. The temperatures range from 160°C to 170°C (320–338°F) for periods of 2–4 hours, depending on type of material and device. Higher temperatures and shorter times can be used for heat-resistant materials. Dry heat is not generally regarded as a suitable method for plastics due to their low thermal transmission properties and the difficulty of ensuring that all parts of the product have been exposed to the required temperature for an adequate time. Most plastics will either warp or deform during prolonged dry heat sterilization. However, dry heat sterilization is the most suitable for metal instruments, glass, powder, oil and fat. A dry heat sterilization autoclave uses electrical resistance as a heating element, and the system is based on the conduction of heat and air circulation in the chamber. Heated air rises and releases heat to the materials to be sterilized. The cooled air falls and starts to heat again due to an electrical resistance heating element located low in the chamber. The system is validated using a heat indicator, and heat calibration is also performed regularly. [93]

5.4.2 Ethylene oxide

Ethylene oxide (EtO) has been widely used as a low-temperature sterilizing agent since the 1950s [93]. This agent effectively destroys all microorganisms, including bacterial spores, without damaging or corroding the material being sterilized. The penetration capability is high, and the agent evaporates from the material relatively well. [116] Temperature-sensitive and moisture-sensitive materials and devices typically use ethylene oxide sterilization. EtO is supplied in three basic forms for sterilization: 100% EtO, 10% EtO with 90% hydrochlorofluorocarbon (HCFC), and 8.6% EtO diluted in 91.4% carbon dioxide (CO_2) [93]. Thus, gas sterilization is a choice only if the device cannot withstand the high temperatures used in primary methods (i.e., hot steam or dry heat sterilization) because the validation of sterilization effectiveness is challenging and the detection of ethylene oxide residues on the surface is problematic. [109, 116] Ethylene oxide must be evaporated completely before the device can be used due to its toxicology. Complete evaporation can be performed by the sterilization device during the program.

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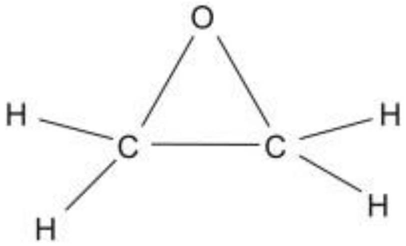

Figure 12. Chemical structure of ethylene oxide.

The packaging film must also be permeable to both water vapour (for bacterial growth) and air (for aeration and EtO removal) to be effective. [93] Sterilization is accomplished by mixing ethylene oxide with a propellant gas at a certain ratio. For small devices, pure ethylene oxide is used; for large devices, a mixed gas is used [116]. The process variables are humidity content, temperature and exposure time. For the destruction of spores, humidity is needed due to the resistance of spores to ethylene oxide in dry conditions.

The process consists of three phases: preconditioning, sterilization and post-treatment. Preconditioning is performed at a specified temperature and relative humidity. The sterilization device then performs the evacuation and heating of the chamber. Moisture and gas are inserted into the chamber for the required time. The gas concentration is typically

200-800 mg/l. [93] After a specified exposure time, the third phase is the rinsing of the ethylene oxide from the chamber and the load with the help of vacuum-sterile air-pulses. Every phase is performed in the same vacuum/pressure chamber. The temperature range is between 35-55°C, with a sterilization time of 2-6 hours. After the treatment, possible residues from the load must be removed by air ventilation in an appropriate place. [109] This method is preferable for materials that do not absorb ethylene oxide, such as polyamide. The identified damage can include surface opacity and cracking of the material. [105] An important negative aspect is that ethylene oxide is toxic, flammable and explosive, as well as environmentally toxic. Carbon dioxide (CO_2) should be used as a carrier gas instead of the environmentally damaging toxin freon (HCFC). [109]

The validation of sterilization is based on humidity and temperature indication for the chamber and load. In addition, a biological indicator is used, according to standards (SFS-EN 866-2). [109] The efficacy of EtO sterilization is measured using these biological indicators. More recently, parametric release methods have been developed to measure the effectiveness of EtO sterilization. Parametric release eliminates the need to send the biological indicators to a testing laboratory to evaluate sterilization levels by measuring the microorganisms in the biological indicators. [93]

Low-temperature plasma sterilization is based on low-temperature gas plasma in combination with hydrogen peroxide. The process temperature is below 50°C. The liquid 55% hydrogen peroxide transforms to a gas under vacuum; the gas then changes into plasma form (i.e., completely or partially ionized gas) with the help of an adequate amount of radio wave energy. [111] Argon gas has good ionising properties and is recommended for the sterilization process. In addition, other useful gases include oxygen, nitrogen, hydrogen, hydrogen peroxide, nitrogen oxides and halogens. [105] Only steam and oxygen remain after the process; thus, no injurious substances remain after treatment that could be a risk for department personnel, product users and the environment. For this reason, this method was developed to replace ethylene oxide sterilization. However, the method cannot be applied to textiles. [111]

5.4.3 Irradiation

Irradiation is commonly used for sterilization and can be generated by either gamma rays from a cobalt (^{60}Co) source or an electron beam (e-beam). Gamma rays are produced from a

^{60}Co source and have a penetrating power of up to 50 cm. [93] The ability of electrons in an e-beam to penetrate is much lower than that of gamma rays. For example, a 10 MeV e-beam will penetrate to only approximately 5 cm. [93]

The effectiveness of radiation depends on the properties of the material, such as density, production method, product size, coverage, velocity and dose of radiation. [105] The effect of radiation is cumulative, and for items that must be repeatedly sterilized, the total dosage can rise rapidly. To achieve the full sterilization of a product with packaging, the products at the outer edges of the packing are subjected to higher doses than products at the centre of the packing load. [93] Irradiation is very effective for fully packaged and sealed items, but this approach is even more suitable for single-use items for which only one radiation dose is required. Most plastic films are transparent to radiation. [93] As gamma radiation has a higher penetrating power, it allows for a high packing density of devices and products in the sterilization chamber. If an e-beam is used, the packing density of the load in the chamber must be low to ensure that the electrons reach the centre of the packing load. E-beam sterilization can be harmful to products that contain batteries or electronic components. [93] The destruction level relates exponentially to the dose rate. Irradiation sterilization is based on the process through which molecule ionization destroys organisms effectively. The dose needed in medical applications is at least 2.5.Mrad = 25 kGy. The product does not remain radioactive because the radiation does not cause any change in the nucleus of the atom. [105] Thus, the products are completely safe to handle and use immediately after sterilization. Dosimeters are used to track the dose received by the materials in the chamber. The dose that ensures acceptable microbiological reduction is described as the minimum dosage (DMin), and the maximum dosage (DMax) is the highest dose that maintains the quality, aesthetics, and performance of the material or device. [93]

In plastic devices, irradiation causes degradation and cross-linking, which will lead to changes in tensile strength, elongation at break and impact strength. The exact change depends both on the type of polymer and any additives used. The changes in mechanical properties are not necessarily observed immediately. Discoloration and yellowing of the material are also fairly common. Degradation and cross-linking can be prevented by using stabilizers, such as antioxidants and free radial scavengers. In general, polymers that contain aromatic ring structures are more resistant to the effects of radiation than aliphatic polymers. [93] Stabilizers, softeners, antioxidants, pigments and additives can have a significant effect on the radiation stability of a material; thus, the membrane tolerance can deviate significantly from the raw material tolerance. Generally, PTFE and polyamides tolerate gamma sterilization fairly well. [105] Table 6 shows the radiation stability of various plastics.

Table 6. Radiation stability of various plastics. [93]

Polymer	**Comment**
Polyolefins (PE, PP)	PE can cross-link; use the PP copolymer or stabilized to prevent discoloration and degradation
Polyvinyl chloride	Tint-based; stabilizers are used for the prevention of discoloration and degradation
Acrylics and Polycarbonates	Prevent degradation and colour change by stabilizing.
Polyurethanes	Some discoloration might appear.
Acetals	Not used with gamma radiation
Polyamides	Polyamides (aromatic ring and 10, 12, 6/10, and 6/12) are suitable.
Aromatic Polyesters	Stable
High-temperature thermoplastics	Good grades with PEK, PEEK, PEI, and polysulfones
Fluoropolymers	Teflon and FEP must be stabilized. All other fluoropolymers are stable.
Elastomers	Stable
Thermosets	Typically stable

5.4.4 Disinfection

Heat disinfection inactivates vegetative bacteria, including mycobacteria, enveloped and non-enveloped viruses and fungi, but this method is not capable of destroying most bacterial spores. Wet heat transfers thermal energy better than dry heat. Heat disinfection is one of the oldest and most widely used processes in microbiology. This method is also more reliable than most chemical disinfection processes. Temperatures between 65°C and 100°C are generally used. The higher the temperature, the shorter the time needed to achieve disinfection. The efficacy of thermal disinfection depends on several parameters, principally temperature and time. The parameters are usually monitored automatically during each disinfection cycle. In addition, microbiological monitoring is used to verify the accuracy of disinfection. [107]

Table 7. The times and temperatures that are currently accepted in the UK to achieve thermal disinfection for various applications. * 1 s would be sufficient, but in practice, the temperature measurement requires a minimum of 12 s. [107]

Temperature (°C)	65– 70	73– 78	80– 85	90– 95
Time	10 min	3 min	1 min	12 s*

In healthcare, thermal disinfection is used for linens, bedpans, white and green clothes and textiles. These materials are cleaned and disinfected in a one-step process by laundering them at 90-93°C. [27] A washer-disinfector is defined as a machine that cleans and disinfects devices and other articles in one step. Textiles are widely used in hospitals, and reusable clothing is regarded by surgeons as more comfortable and suitable for the operating theatre [122].

5.4.5 Cleaning

The cleaning process consists of three steps. First, detergent is needed to loosen and assist in the removal of the soil. Second, mechanical abrasion during the process improves soil removal. Third, water is essential for rinsing away the soil. All three components must always be present in an optimal ratio; otherwise, effective cleaning cannot occur. [110] A typical cycle consists of cleansing with detergent at <35°C, a main wash at 55°C, thermal disinfection at a defined temperature and time, and drying. [107]

The traditional textile disinfection process by laundering wears out textiles and weakens their properties. The high energy and water consumption of the laundering process led to a search for alternative solutions for textile disinfection. It has been claimed that by replacing water-based methods with liquid carbon dioxide (CO_2)-based cleaning methods, the operational costs, capital infrastructure, and sustainability impact of the process can all be significantly reduced. Nexus has researched and developed a system for textile disinfection and sterilization. As a primary cleaning solvent, liquid CO_2 is cheap, inexhaustible, and readily available worldwide. The extremely low viscosity of CO_2 is said to allow for very effective filtration without pressure losses. CO_2 is naturally lipophilic and thus bonds with fats, oils and other lipids (i.e., the main components of body oil and sebum). Because the CO_2 process does not require either heat drying or exposure to mechanical abrasion, the fabric will retain its mechanical and chemical properties longer. CO_2 processing is said to be able to lower the bioburden present on garments in comparison to traditional laundering, and lower doses of gamma radiation are required to achieve the required sterility assurance level. CO_2 cleaning also has a sustainable aspect when any water or hazardous chemicals are used in the cleaning process. The elimination of water from the process leads to energy savings due to the absence of secondary waste streams and the pre-treating, pre-filtering, heating, or recycling of water. In a CO_2 system, all of the waste removed from garments is captured on board. Depending on the contaminants present, the waste can be up-cycled into new products (e.g., in bio-diesel blends). [123, 124]

As a sensitive technology, dry cleaning could benefit wearable textile solutions in medical care. As mentioned above, mechanical abrasion in combination with chemicals is harmful for textiles. Before sterilization, the textiles must be cleaned. Thus, dry cleaning could be used as a pre-treatment for the sterilization of water-, abrasion- and impact-sensitive materials and components. Depending on the solution, disinfection with dry cleaning technology alone could be sufficient.

Research results appear to indicate that the conductivity of textile electrodes made by printing is not maintained after 60 dry cleaning treatments. However, by applying a protective polyurethane layer on top of the printed samples, the resistivity remained below 2.3 $\Omega\ cm^{-1}$ after 60 dry cleaning cycles. In that study, screen printing was used to print four kinds of silver-based conductive inks on flexible foam and non-woven substrates. After printing, the resistance was $< 0.05\ \Omega\ cm^{-1}$. [125]

6 Production of electro-conductive textiles

This study focuses on textile electrodes that are produced by making the textile or fibre electrically conductive. Conductive textiles can be used as electrodes for measuring and detecting vital functions of the body, as discussed in detail in Chapter 4. The electrode is defined as a passive sensor because it requires an external power source. In contrast, active sensors are able to convert input energy to voltage. [73] Depending on the end use, the electrical properties of conductive textiles can be modified. The properties and amount of conductive components in the material structure quantify the maximum conductivity of the textile electrode. However, the manufacturing technology and the textile, yarn and fibre structure have a great effect on the electrical properties of the electrode. The surface can be one-side conductive or double-side conductive without being conductive throughout the material. Naturally, conductivity can vary between the sides. The material can be produced to be fully and even equally conductive in each dimension. In addition, the conductivity of the electrode can change after exposure to an external stimulus (e.g., extension, pressure or temperature). When designing the textile electrode, the stress of the conventional textile manufacturing process, the mechanical features, the chemical finishing treatments and further processing technologies for the textile electrode must be taken into account. On the other hand, the electrical requirements of a material used for an electrode must be considered (e.g., for ECG electrodes, low AC impedance, a non-polarisable nature and electrochemical stability are important features). [127]

Textile sensors can be used as capacitive, inductive, resistive or galvanic sensors. Capacitive electrodes enable skin-contactless or contact-free measurement of ECG and EMG. [29, 128,130] The magnetic induction sensor assesses respiration and pulse. This sensor is also a skin-contactless measurement in which the impedance distribution within the thorax is measured. The beat-to-beat time is beneficial for apnoea detection. The measurement principle is that alternating current is driven to the conductive coil, forming an alternating magnetic field, B_1, which induces eddy currents within the thorax. The eddy currents form another alternating magnetic field, B_2. The variation of the B_2 field depends on the physiological activity of the person. Thus, the pulse and respiratory action can be assessed by monitoring the voltage of B_2. [131] Inductive textile-based coil sensors for measuring ECG have been produced. The correct positioning of these electrodes is essential for this measurement. [132] The resistive electrode measures the change in the resistance of the electrode. An example of such a sensor is shown in Figure 13. Thus, this type of sensor can be used as a strain sensor or a pressure and force sensor. A galvanic electrode is based on measuring the voltage difference between at least two electrodes that are always in skin contact, which is called the galvanic skin response (GRS). [29, 130]

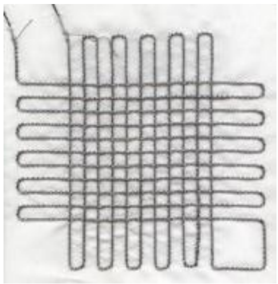

Figure 13. Resistive sensor for which the resistance changes when elongating. [130]

In addition to their electrical properties, these biomedical electrodes can be classified in many other ways (e.g., based on electrode material features, such as flexibility, based on the manner of use, such as wet or dry electrodes, [127] or based on whether the electrode is reusable or disposable).

Smart fabrics can be divided into sensors and actuators; both types of fabrics are varieties of transducers. As the transducer converts a variable, such as light, sound or temperature, into an electrical signal, it is a sensor. In contrast, the effectors work by converting electrical energy into physical expression. [133] The skin electrode system consists of the skin, the electrode and an electrolyte. Traditional resistive and capacitive electrodes use metals in a conductive layer on top of an insulating layer. The electrolyte, which is traditionally a wet-gel, is needed to improve the electrical skin contact and reduce the skin impedance of a resistive electrode. Stable electrical contact with the skin is paramount for resistive electrodes. The capacitive electrode measures the potential voltage change of the skin and requires a dielectric material in order to form the capacitive coupling. In this case, the charge accumulation causes disturbing noise for the measurement. Variations in skin impedance, which are called motion artefacts, are caused by body movement during measurement. One cause is the electrode itself, which moves and causes a disturbance of the electrode charge layer. Another cause is the stretching or deformation of the electrode. [127] Skin impedance is in the range of 200 Ω/cm^2 – 93 $k\Omega/cm^2$ at a frequency of 60 Hz. This parameter depends on the skin condition and the electrical source. For the majority of applications, the electrode resistance should always be lower than the skin impedance. [128] By reducing the skin impedance by short-circuiting the skin epidermis layer, the motion artefact can be minimized.

In practice, motion artefacts are avoided by using a hydrating gel or paste or sweat between the electrode and the skin and by choosing only slightly polarisable or non-polarisable electrode materials. Non-polarisable electrodes are used to measure biopotential, whereas polarisable electrodes are used for electrical stimulation. In those cases where hydration cannot be achieved, as with bed-bound patients, the solution for improving the signal quality could be skin puncture. In textile electrodes, the slippage of yarns during movement also causes extra noise for the measurement. This noise can be reduced by coating the material on the reverse side or by bonding the interlacing points [127]. Depending on the application, disturbing noise can be filtered efficiently from the measurement by the signal-processing unit of the system [134].

It may be necessary to use textile electrodes for continuous long-term monitoring, such as for cardiac risk patients, stress monitoring and any application in which the analysis of ECG and HRV is required, as conventional gel electrodes can cause skin irritation. Moisture management is an important factor for textile electrodes and conventional gel electrodes. [12, 66] A dry electrode has higher contact impedance than a wet electrode. In addition, a dry electrode is more sensitive to motion artefacts and radio waves from the surroundings. The simplest way to reduce the contact impedance is by increasing the pressure between the skin and the electrode. [128]

Textile electrodes should be moisturized before use. The drying of textile electrodes during measurement might weaken the signal quality. In sports applications, continuous moisturisation of the electrode is fulfilled by sweating. A challenge arises in some applications in which the natural sweating process does not exist, such as bed-bound patients in hospitals. Thus, during long-term ECG measurement without bodily activity, especially among the elderly, who typically have dry skin, adequate moisturization of the electrode must be ensured. Empa has solved this problem by building a moisturizing element within the textile electrode ECG belt. The element is manufactured from a waterproof membrane and a water vapour element, which continuously moistens the textile electrodes. Fresh water is supplied from a special reservoir that is integrated into the belt structure. The entire structure, including the reservoir and the moisturizing element, is produced using laser welding technologies to make the device watertight, robust and comfortable to wear. These textile electrodes are manufactured by the Swiss embroidery specialist Forster Rohner AG. [12, 66]

Figure 14. ECG belt with a continuous electrode-moisturizing element. [66]

The textile electrode must be attached to the garment or application, and signal transfer from the electrode must also be arranged. In addition to conventional textile processing and garment manufacturing techniques, lamination, welding and laser cutting are beneficial assembly techniques for textile electrodes. Laser cutting and attachment by lamination and welding are more precise than sewing, and the result is slimmer and smoother, with an electrode that is invisible and more comfortable during use.

6.1 Electrically conductive materials

Various metal materials have been demonstrated to be suitable for textile electrode fabrication. Gold (Au), silver (Ag), copper (Cu), titanium (Ti), [127] aluminium (Al), nickel (Ni), stainless steel, and brass can be used. As mentioned above, the end use of the product determines the metal to be used. Metals are widely available and have high conductivity with reliable electrical properties. Metals are durable and strong. The principal disadvantage of metals is that pure metal fibres are heavier than polymer-based conductive fibres. These fibres might even be five times heavier than textile fibres, which is undesirable in wearable solutions. In addition, metal fibres are not flexible, elastic or soft, which are the usual properties of conventional textile fibres. [135, 136] A homogeneous fibre blend is more difficult to produce due to the weight of the metal. Stainless steel is one option that is is widely used to produce conductive textiles. AISI 316L (Ni 10-14% and Cr 16-18%) is a ductile stainless steel that is suitable for textile applications. The most useful way to use steel fibres is to use them in filament form and mix them with conventional fibres. For example, 200 tex yarn with a mixture of 20% steel and polyester fibre generates an electric resistance in the range of $10^1 – 10^2$ Ω cm^{-1}. Nickel tends to cause allergic skin reactions for some people, which is a limiting factor for the application of this material in body-sensing systems.

Noble metals, copper, silver and gold have much higher conductivity than any steel. Silver is used in many applications due to its high conductivity and antibacterial nature. Silver also has a more reasonable price than gold. [136]

Carbon fibres are fabricated using heat treatment of carbon-based materials. The most suitable materials contain a large amount of carbon, such as polyacrylicnitrile (PAN) and viscose, which are used most frequently. Polyvinylalcohol (PVA), polyamides, phenols, PVC, coal and bitumen can also be used as raw materials for carbon fibres. After spinning, the fibres are carbonated via a pyrolysis process. The material-carbonating process must be performed without melting. Graphite is one allotrope of carbon that has even higher conductivity (10^3 S cm^{-1}) than carbon black (10^2 S cm^{-1}). [137] Carbon nanotubes (CNTs) are an allotrope of carbon in nanostructure. Teijin Aramid, The Netherlands and researchers at University of Houston have managed to make conductive fibres that have a flexibility and strength similar to those of textile fibres and a high thermal and electrical conductivity that are equivalent to those of metals. Textile-like features enable the processing of such fibres in a similar manner to conventional textile fibres. [115] Traditionally, the properties of CNTs are an extremely high mechanical strength, high thermal insulation and metal-like conductivity. [136] CNTs produce high conductivity because they contain a lower concentration of carbon in comparison to carbon with a larger particle size. The idea is based on the layered structure of the tubes; one tube consists of multiple stacked carbon nanotubes (MWCNTs). One tube structure CNT is typically 0.5-4.5 wt% of fibre, but MWCNTs require only 0.005 wt% to achieve a resistance of 103 Ω cm^{-1}. A conductive textile can be produced by coating the yarn or fabric with a MWCNT layer. [138]

Graphene is an emergent conductive material that is being studied by many investigators. Graphene has fascinating features; this material is a lightweight, thin, potent conductor that is chemically inert and has a high mechanical strength and a large surface area. Graphene is predicted to be the next revolutionary material for electrical and chemical engineering. The conductivity of this material is not as high as that of silver, but the price is lower, and graphene is not as volatile as silver. Haydale, UK has managed to use graphene-based inks for many substrates, including polyvinylchloride (PVC), polyester (PES) and ceramics, using screen printing, flexographic techniques and gravure printing technologies. The main applications for graphene in the wearable area could be plastic electronics, flexible and liquid-crystal displays (LCDs), printed circuit boards (PCBs), sensors, organic light-emitting diode (OLED) devices, thin-film photovoltaics, supercapacitors, electrochemical devices and even solar cells and energy storage devices. [31, 77, 106, 139]

The most well-known and commonly used conductive polymers are polypyrrole (PPy), polyaniline (PANI), and polytiophene (PT). PPy and PANI have the highest conductive properties and are also the most suitable materials for textile fibre manufacturing processes; however, these materials have a much higher resistance than metals, which naturally limits their application areas. [136] These intrinsically or inherently conductive polymers (ICP) have a long conjugated double-bonded chain structure, which makes them electrically conductive. The strong intermolecular interactions of these materials make them insoluble and infusible. Doping agents are used to form charge carriers, which are extra electrons, in the chain. ICPs are typically semiconductors with a resistance between 10^{-4} and 10^{10} Ω/m. In some cases, the conductivity level of copper (10^{7} S/m) can be achieved. [136, 140] The polymer is made conductive by oxidation; without oxidation, the material is an insulator. The conductivity can be modified by changing the concentration of dopant in the polymerization process. The conductive polymers cannot be melted for extrusion; thus, a conductive coating on a conventional polymer is a better choice for conductive polymers. [135] As an example, polyaniline (PANI) is an electrically conductive polymer that can be synthesized through either bulk chemical or electrochemical polymerization. This polymer is conventionally prepared by polymerizing an aniline monomer. The nitrogen atoms of the monomer units are bonded to the para-carbon in the benzene ring of the next monomer unit. In chemical preparation, bulk polymerization is the most common method for producing polyaniline. Conventional bulk chemical synthesis produces granular polyaniline. [141]

The degree of doping is easier to vary for these materials than for filled conductive plastics, especially when the material has a low conductivity. Polyacetylene (PA) exhibits high conductivity. After doping, this material can achieve a conductivity equal to that of copper, which leads to possibilities for applications in optoelectronics, in contrast to other ICPs, which are used primarily for antistatic purposes. The common feature of ICPs is that they have very poor mechanical properties and that they are non-melting and insoluble in most common organic solvents, which creates a challenge for fibre processing. The extrusion of polyamide or polyester blended with PANI is the most difficult, but polypropylene (PP) is workable. Solution coating is a method in which an ICP solution is first spread onto the surface of a substrate material, and the solvent is then evaporated. The solvents for doped PANI are toluene and water, under certain conditions. ICP coating can also be accomplished via chemical polymerisation or electrostatic spinning processes. [136]

Conductive polymers can be used to replace metal conductors and semiconductor materials in many applications. These applications include pathways of circuits and devices, displays, lighting, chemical biological, environmental and medical sensors, anticorrosive coating scaffolds for tissue growth, antistatic shielding (ESD), and electromagnetic shielding (EMI). [141] Quantum Tunnelling Composite (QTC) is a new class of electrically conductive materials that is under study. This composite can change from an electrical insulator to a metal-like conductor when exposed to pressure. This material was developed especially for medical applications, for which it could be used for blood pressure control, respiratory monitoring and sensing in prosthetic sockets. [142]

Low-conductive electrode materials are sensitive to electrical noise caused by skin impedance or electromagnetic interference from the surroundings; this noise disturbs the signal quality. [128] As pure raw materials, all conductive materials are basically inappropriate for textiles, as their properties are opposite to the preferred properties of textiles. Conductive materials are brittle, inflexible, hard, insoluble, etc. The principle of conductive textiles is that the more conductive is the material used in the structure, the more conductive the textile will be. However, for many materials, this outcome does not occur without causing changes in the physical properties of the textile. A compromise must be reached between conductivity and textile-like properties. Thus, the optimization of the material amount and the technology is essential and must be decided according to the end use.

6.2 Conductive fibre-based textile structures

The conductive fibre can be fabricated in various ways. First, the fibre can be made of a fully conductive material, such as metal fibres, or inherently conductive polymers (ICP). Second, the traditional textile fibres can be coated with a thin layer of conductive material, or the non-conductive polymer can work as an insulating cover for the conductive core. [136] The goal is to achieve a large capacity for conducting electricity and thus minimize the resistivity of the fibre. This outcome can be achieved by maximizing the surface volume value of the fibre. In practice, this goal is achieved by using fine fibres and/or by forming pores on the fibre surface. [127] Third, the conductive particles, or fillers, can be embedded within the conventional polymer matrix by blending the particles with an insulating polymer material before spinning. [135, 136] The conductive particles in dispersion include silver, nickel, stainless steel, aluminium, graphite and carbon black. A high concentration of charges and a homogeneous blend are essential for achieving highly and equally conductive fibres using this method. [140] The weight percent (e.g., in the carbon nanotube case, this value is approximately 20%) can impact the mechanical properties of the fibre; thus, a conductive coating is a more effective way to produce conductive fibres than the inclusion of conductive particles. The coating is cost-effective in comparison to pure metal fibre structures because the metal layer needed for this approach is thin. The coating method retains the textile-like features of the fibre. [135] After the fibre production process, yarn and textile manufacturing can be performed using conventional methods. Materials based on filament fibres have better conductivity than materials based on stable fibres, which have additional fibre contact resistance. In addition, filament fibres are more beneficial for avoiding electrode noise caused by increased stable fibre contacts. [127]

Conductive yarns can be fabricated by coating the spun yarn, as in the case of fibres, or by wrapping a helix of conductive ribbon or foil around the non-conductive core. A helical structure enables a certain degree of flexibility and extensibility for the yarn. [135] In addition to coating, conductive yarns can be formed by blending conductive and non-conductive fibres or by twisting conductive yarns and non-conductive yarns. Again, as in the case of fibres, the yarn should maximize its conductivity; a compacted structure provides less resistivity than a textured structure. The optimal cross-section of the yarn is elliptical or flat. [128]

Dense fabric increases the conductivity and electrical stability and creates less noise (i.e., electromagnetic interference (EMI)); this topic is discussed in detail in Chapter 4.4. A knitted structure causes more noise than a woven structure due to the intrinsically looser and elastic structure. Further, in a woven structure, conductive yarns might even conduct without resistive fibre-fibre contact; in contrast, in a weft-knitted material, the conductivity is based only on fibre-fibre contact. [127] Warp knitted fabrics are similar to woven fabrics, as warp direction resistance is observed. Thus, the conductive yarns are continuous, and the conductivity of the fabric is not based on fibre-fibre contacts.

The most important property of a textile electrode is conductivity, which is modified by the conductive material, the yarn and the textile structure. As conductive materials add extra costs, it is essential to use these materials only in adequate amounts for the application. To optimize the electro-mechanical properties of textile sensors, textile resistance models have been developed. One model was developed for plain knitted structures, which is based on the relationship between loop contact resistance and load, and the contacting force, in biaxial extension. The program provides the equivalent resistance of the designed fabric. [143, 144]

Non-woven materials made of conductive fibres provide the weakest electrical properties due to their high, randomly distributed fibre-fibre contacts. This property leads to increased resistivity and the disturbance of measurements. [127] The embroidering method can be used to make the textile electro-conductive and enable the textile to be used for ECG biosignal measurement [155]. The advantage of the embroidery technique is that conductive threads can be arranged in any direction; thus, nearly any shape and size is possible for generating conductive areas. [133] In addition, the machine adjustment between the style changes is relatively easy and fast in comparison to woven structures. The textile ground material and conductive threads are not very limited because they are not integrated together in the same process, which is the case during the knitting and weaving of conductive structures. The ground material can be woven, non-woven or knitted. [133] The disadvantage of this technique are that the abrasion resistance of the conductive material might be poor, as the structure does not protect the conductive yarns, which form a separate layer on top of the fabric. In body contact applications, it might be challenging to achieve an adequately soft material surface for the skin. During sensor design, it must be noted that if one side of conductive material is needed, the reverse side should possibly be insulated by laminating or coating. The embroidering method is beneficial for PCB fabrication. Metal-coated yarns are more appropriate for embroidering than metal fibres because they are softer and more flexible. [128]

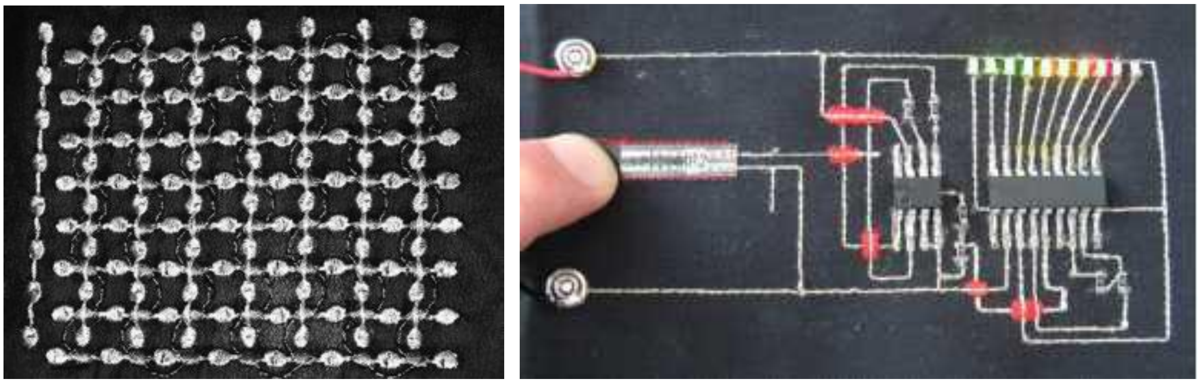

Figure 15. On the left, an embroidered conductive textile [128]; on the right, textile-integrated electronics, with a commercially available microsensor on the textile. [130]

6.3 Textile conductive coating

The use of a conductive coating on the fibre, yarn or textile is one method for making the material conductive. The conductive layer can be based on metal, a conductive polymer, or carbon. There are various methods of achieving the metallisation of a textile (e.g., vacuum deposition, ion plating, electroplating and electroless plating). In the vacuum deposition and ion plating methods, the evaporated metal particles are deposited onto the material, fibre or textile surface. The difference between these methods is that the vacuum method allows the deposition of metals in any solid form and with any purity level, while in ion plating, the ionised metal particles are accelerated onto the material surface after the evaporation of molecules from the metal material into an inert gas. The latter method achieves a higher density and a stronger adhesion of the coating. In the electroplating process, which is also called electro-deposition, an electrical current is used to add a metal coating to the substrate. The electrolytic cell consists of an electrolyte and two electrodes: an anode, as a positive electrolyte, works as a metal source, and a negative cathode electrolyte works as a material to be coated. The low-voltage current causes the movement of metal ions from the anode to the cathode. By the means of the electrochemical process, ions are converted into metal form and brought onto the textile surface. Electroless plating, which is also referred to as chemical or autocatalytic coating, is based on several chemical reactions that occur at the same time in an aqueous solution, leading to the removal of metal ions from the material to the substrate to be coated. [135] Conductive polymers can be used to coat fibres and textiles. This outcome can be achieved during the dyeing process, in which certain dye molecules are used as dopant anions to improve the electrical conductivity. Another method is chemical vapour deposition (CVD). This approach consists of two steps. In the first step, the textile material is impregnated with a conductive agent solution containing an oxidant and a doping agent and then dried. In the second step, the conductive polymer is evaporated and deposited onto the pre-treated substrate. Both methods are suitable for coating materials with polypyrrole (PPy) because this material has a good affinity for both natural and man-made fibres. The advantage of conductive coatings is the ability to modify the conductivity depending on the end use. [135]

Conductive inks are made by adding conductive fillers to printing ink or paste. Conductive inks are applicable for use with the conventional printing, lamination and coating methods to generate a conductive surface on the textile. Problems can occur, especially with knitted substrates, because the thin print is prone to crack during bending or stretching. This cracking causes discontinuities in conductivity at certain points. [133] Carbon black and metal nanoparticles in powder form can be used. [128] Non-elastic materials, such as woven and non-woven structures, are easier to implement because only cracking during bending must be avoided. The abrasion resistance is another essential mechanical property that must be addressed in body sensor applications.

The conventional textile printing methods, such as screen printing, transfer printing and digital printing, can also be used to apply conductive ink to textiles. The required properties for conductive inks are flexibility, abrasion and laundry resistance and elasticity; these properties ensure that ink cracking will not occur. All of these properties affect the durability of the conductivity. [128] The simplest method (i.e., screen printing) is an attractive technology for conductive printing, as this method enables a versatile layout of conductive areas. This method is also well-known and cost-effective. Depending on the textile electronic application, the printing of a layer structure produces the best results. The first layer works as an insulator between the textile and the print and makes the surface smooth for the conductive ink. The second layer is conductive, and if needed, a third layer provides electrical insulation and mechanical protection against weathering, abrasion and laundry chemicals. [147] The advantages of the digital printing method are that this approach is a dry process with minimal water consumption, that there is little waste of ink materials, and that accurate and fine lines with multi-colour patterns are possible. The setup costs are low because this method employs a computer-programmed system. For the same reason, the modification of the pattern style is rapid. Each colour is made using the same process, in contrast to traditional screen printing, for which separate stencils are always needed for every colour. The current disadvantage is the slow speed of the printing process; however, when more colours are used in the pattern, the difference in production speed is smaller.

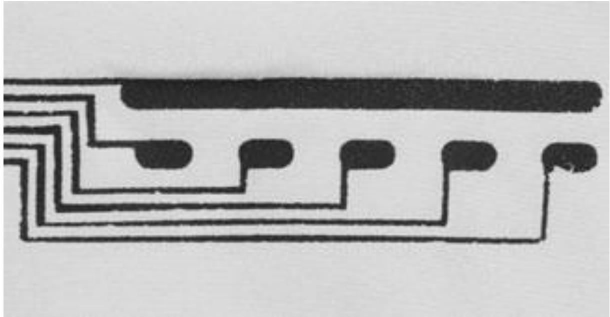

Figure 16. Conductive ink applied on a substrate. [128]

The conductive polymeric film is applied to the textile surface using photolithography and subsequent chemical etching. [133] Researchers at ETH Zurich are developing thin-film adhesive sensors that are extremely thin and flexible. The component can be wrapped around various materials, even organic materials, such as a single hair, without damaging the electronics. These kinds of components can be incorporated into textiles by weaving. [77]

Figure 17. Thin-film adhesive sensor. [77]

7 Repellence of materials

Repellent finishes are used to resist the attachment and adherence of water and soiling particles to the textile surface. Water repellence also contributes to the functionality of reverse-side coated fabric. The coating vapour permeability decreases if the fabric is wet. These so-called self-cleaning or easy-to-clean treatments of textile products reduce electricity and water consumption, as the need for frequent laundering is thereby decreased. In addition, lower washing temperatures can be used, and fewer washing chemicals are needed. [148]

Nanotechnology is the key for creating highly repellent, super-hydrophobic textile surfaces. The definition of nanotechnology is that at least one dimension of the material is in nano-scale (e.g., the molecule size of the liquid is in the 0.1-100 nm (1 nm = 10^{-9} m) range). Nanotechnology involves imaging, measuring, modelling and manipulating matter at the nano-scale in order to improve the physical, chemical and/or biological properties of a material, system or device. [149,150] Polymer nano-materials are classified into nanostructured and nanoparticle materials. The bulk material is nanostructured, as it is composed of nanoscale grains, whereas nanoparticles are usually dispersible. In the case of a nano-composite, the inorganic component is used as a filler in the polymer mass. Nanofibres, polymer nanocomposites (PNs) and nanostructured surfaces are exploited in textile structures, coatings and finishes. [150] Textile nanocoating implies the coating of a less than 100 nm thin film on the substrate. The film surface is formed by molecular or atomistic deposition.

Various methods are used to apply nanocoatings: physical or chemical vapour deposition, electro or electroless plating, laser vaporization or plasma-enhanced chemical vapour deposition. Textile nanofinishing forms a functional molecular layer on the fibre surface. In electrostatic self-assembly used for polymers, the functional molecules attach covalently to the substrate. This process forms a self-cleaning hydrophobic layer for individual fibres that is similar to that of a lotus leaf. [150] Textile finishes that are based on nanotechnology and aim to achieve dirt and water repellence are widely used in sports and outdoor wear. The small size of the particles improves the desired properties without weakening the other important and necessary properties of the material. In the case of textiles, a nano-scale repellent finishing forms a thin layer around the individual fibres without inter-fibre adhesion, which enables the textile to maintain its original surface drape, hand characteristics and vapour permeability. Due to their small size and high surface area to volume ratio, nanoparticles have a high affinity for the textile structure, which makes the treatment durable against physical stress. [149, 150, 151]

A textile with a self-cleaning property is a value-adding factor for wearable technology, especially in the medical sector. Textiles are widely used in hospitals and appear to be a friendly environment for the growth and spreading of unwanted bacteria; textiles are also effective transporters for bacteria. Antibacterial treatments, cleaning, disinfection and sterilization are methods used to eliminate bacteria and viruses from surfaces. Repellent treatment contributes to the cleaning of textiles, as dirt and water do not readily attach to the treated textile surface and can be easily cleaned or rinsed away. The textile must always be visually clean before disinfection or sterilization; thus, a repellent finish would also reduce time and energy consumption in hospitals, as discussed in detail in Chapter 5.3.

Repellent treatments mimic the characteristics and physical shapes of the surfaces of natural organisms. For example, the hydrophobic plant surface is not smooth but micro-structured, like the lotus plant leaf (see Figure 20). This surface is composed of numerous hundred-nm hydrophobic wax crystals. As the droplet contact angle (θ) to the surface is greater than 150°, the material surface is called self-cleaning and has a super-hydrophobic nature (see Figure 18) This phenomenon is also termed the Lotus Effect®. In addition to textiles, these self-cleaning surfaces are used in paints and class coatings. [152]

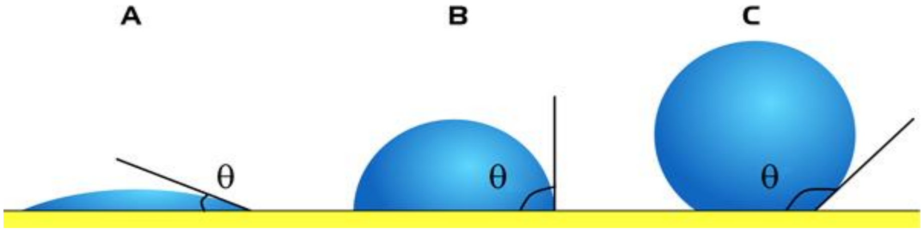

Figure 18. Water droplet contact angles on different substrates. a) Hydrophilic material with a contact angle (θ) < 90. b) Hydrophobic material with a contact angle (θ) of 90-150, and c) super-hydrophobic material, for which θ > 150°. [153]

In addition to the contact angle, the roll-off angle of the material is also used to describe the repellence of the material. For super-hydrophobic materials, the roll-off angle is typically 10-20° (see Figure 19).

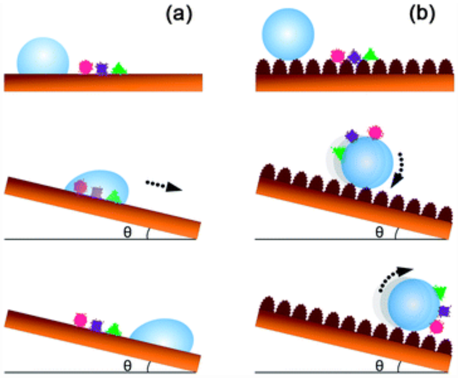

Figure 19. The self-cleaning effect is based on the rolling of droplets on the surface. The roll-off angle can be measured. The super-hydrophobic material on the right (b) is repelling dirt based on the rolling effect, in contrast to the picture on the left (a), where the surface is not super-hydrophobic and enables neither the rolling nor picking of dirt. [154]

Washing wears out the textile to some degree during every laundry cycle. The need for laundry washing could be reduced by using a self-cleaning finish on the textile surface. A lower washing temperature, a shorter washing time and a smaller amount of chemicals reduce the water and mechanical stress applied to the textile. Therefore, there are real advantages of soiling-repellent treated textiles. The emissions generated by using the product would decrease, and the product lifetime would increase in comparison to that of an untreated product. The reduced need for washing has positive environmental impacts, as water and energy consumption during product use will decrease. The repellent finish thus provides ecological and economic benefits to the user.

7.1 Repellent processing methods

There are three main techniques for achieving water or soiling repellence properties for textiles. The originating surface mimics the lotus leaf surface, as it is hydrophobic and structured. The water droplets roll on the surface and simultaneously pick up small dirt particles, making the surface both water- and soil-repellent.

First, nano-whiskers can be applied to the textile surface. These materials are hydrocarbons that generate an appropriate ‘pile’ surface effect on textile. The space between the whisker piles is smaller than the liquid drop but larger than its molecules; the liquid therefore stays on top of the whiskers, with a very low adhesion strength to the textile structure. [149, 151]

Second, a three-dimensional surface structure can be achieved by using gel-forming additives. [151, 156] These liquid repellent finishes can be applied to textiles using conventional coating methods. Producers recommend the use of Foulard, spray or dip coating, followed by heat drying and curing in an oven at 130-170°C for 3-10 min. [126, 149, 157] The third method is to use plasma coating to treat the textile surface. The low-pressure plasma process modifies the fibre surface structure by grafting and polymerizing the monomers on the surface of the substrate. [151]

Alexium has developed a reactive surface treatment (RST) based on sol-gel plasma coating for modifying the surface structure. The result is a nano-coating that repels water and stains. The initial goal was to protect the wearer from chemical and biological threats and to use the treatment for infection control. In addition to textiles, this technique can be used for rubber, paintings, glass and moulded plastic products. This system uses microwaves to achieve the encapsulation of an individual fibre, which maintains the textile material's vapour permeability and protects the fibre from environmental stress. The original coating is based on silane and is independent of the fibre surface chemistry; thus, this coating can be applied to almost any material. This technique enables us to produce multifunctional surfaces (e.g., antimicrobial/biocidal and water- and soil-repellent surfaces). Fluorochemicals usually require aqueous surfactants and emulsifiers for repellent surface formation. These elements are not needed in the RST process; thus, washing contaminants from the material is also not necessary. [158, 159] Plasma treatment using an atmospheric pressure plasma jet (APPJ) improves the detergency performance of polyester textile materials against serious dirt, such as carbon black, oleic acid and stearic acid. [160] TWD Fibres GmbH in combination with researchers from Textile Technology and process engineering (ITV) and the Institute of Textile Chemistry and Chemical fibres (ITCF) have managed to develop a super-hydrophobic filament PES yarn with permanent self-cleaning properties by imitating the lotus leaf effect. [51, 161]

7.2 Repellent finishes

The goal of all processing techniques is to achieve a small contact area for droplets on the surface and imitate the lotus leaf effect. Therefore, droplets have a low adhesion level. This property enables the cleaning of the surface by simply rinsing dirt away. [162] The repellent surface can be achieved using several different chemicals and materials. Here, these materials are divided into fluorocarbon-based, fluorocarbon-free or inorganic materials. Despite the chemical structures and formation processes of these materials, the connective factor for all of the materials is that they aim to mimic the lotus leaf effect (see Chapter 7.1). The principle of repellent materials is based on surface tension. If the solid material has a lower surface tension than the liquid droplet, repellence can be achieved. The surface tension must be approximately 10 dyne/cm. [159] The three-dimensional structure of the repellent surface has peaks or piles by which the droplets are supported.

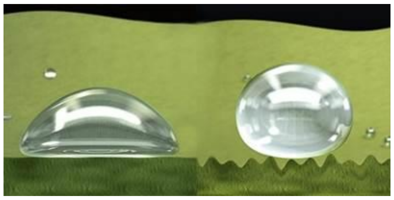

Figure 20. On the left, the droplet is lying on an untreated surface. On the right, the surface has been treated with a repellent. [149]

7.2.1 Fluorocarbon technology

The most widely used fluorocarbons are based on C6 technology, meaning that the chain contains six perfluorinated carbon atoms. [159] C6 fluorocarbon technology avoids the formation of perfluorooctaboic acid (PFOA), which is persistent in the environment and will enter the body. Most C6 treatment producers state that their products do not contain environmentally harmful PFOS and PFOA. [149, 163] The REACH legislation’s limit for PFOA is 1 µg/m^2 of material, meaning that residues of PFOA can still be included. PFOS and PFOA traditionally originate as by-products in the manufacturing process of water/oil-repellent fluorocarbon-based finishes. The repellent finish does not contain such chemicals. [164] PFOA dissolves in water and tends to accumulate in the blood, liver and kidneys. Animal studies indicate that this material is not metabolized from the body. PFOS is also persistent, bioaccumulative and toxic. Perfluorocarbons (PFCs) are persistent in the environment, with a slow elimination time; thus, these molecules can accumulate in people. However, a clear correlation between the PFC concentration in the population and illnesses has not been detected. However, risks during pregnancy and an effect on cholesterol level have been recorded. Tests with rats concerning PFOA and its salts indicate that these molecules cause cancer; therefore, PFOA is considered a probable human carcinogen. [165]

The Rucostar EEE6 water- and oil-repellent effect also uses C6 technology, but this approach is based on hyper-branched star-like polymers, which enable the reduction of the fluorocarbon resin content of the finish. This structure is a crystal structure with high wash and abrasion resistance. The crystallization of dendrimers occurs after the textile application process. [164] Schoeller's NanoSphere C6 nanotechnology has Bluesign certification, which means that environmental risks are minimised during the material manufacturing process. [166]

Fluorocarbons are traditionally applied to textiles in a liquid form by impregnation, but research and development of dry, environmentally friendly processes, such as ultrasonic (US) spraying, are on-going. It is possible to use US spraying for the formation of a hydrophobic surface on a textile. This approach is a dry process, which reduces water, energy and chemical consumption. The steps of the process are as follows: chemical plasma pre-treatment (N_2/Ar) of the surface, followed by US spraying of the active agent and infra-red (IR) curing to achieve washing resistance. In addition to hydrophobicity, the same processes are suitable for antimicrobial and flame retardant effects. [167]

7.2.2 Fluorocarbon-free technology

The current trend is to develop fluorocarbon-free technologies, but to date, the washing endurance of these approaches is not as good as that of fluorocarbons. Fluorocarbon-free repellent chemicals are not oleophobic; thus, these chemicals do not repel oils. Fluorocarbons are currently the most effective and durable chemicals for achieving a repellent surface. Nanotex Aquapel is based on the modification of the fabric molecular surface by hydrophobic whiskers, but this approach uses hydrocarbon polymers to generate a fluorocarbon-free repellent surface. [149]

The OrganoTex® system uses plant-based catalysts and biodegradable organic polymers to achieve repellence. The organic polymer forms a 3D shape on the surface. The polymer consists of two ends: the repellent end and the reactive end, which is strongly bonded to the fabric fibres. The unbound reactive end is biodegradable. By using plant-based catalysts, the reactive binding ends are rendered non-degradable. This approach leads to environmentally friendly but durable water-repellent properties. [169]

®Ruco Dry Eco is a fluorocarbon-free alternative from Rudolf Chemie. This treatment is biodegradable, but the treated product should be called eliminable rather than biodegradable, as the polymeric components remain and are effective beyond the life cycle of the textile, which can be recyclable. The finish is not resistant to oil or solvents, and dry cleaning cannot be performed. The solvent is usually used on the reverse side during the coating and lamination processes; thus, the dissolving of the finish must be assessed. As mentioned earlier, oil repellence can only be achieved using perfluorinated carbons. [170]

7.2.3 Inorganic technologies

Inorganic material technology can also be used to achieve a repellent surface. The principle is similar to that of organic technologies; the surface imitates the lotus leaf, as in the case of carbon nanotubes, or the dirt particles break down on the substrate surface due to a photoelectric process.

Carbon nanotubes (CNTs) and surface-modified carbon nanotubes (PBA- g- CNTs) can be used to form the lotus leaf-mimicking surface. This method enables even originally absorbing fibres, such as cotton, to achieve a hydrophobic surface with a contact angle greater than 150°. The advantage of CNTs is their electrical conductivity, which provides potential for textile electronic applications. [159] A nano-layer of titanium dioxide (TiO_2) is coated to produce self-cleaning properties. In that case, the photocatalytic properties of TiO_2 are used for partially or totally discolouring organic stains. Under illumination, the semi-conductive TiO_2 generates reactive substances, oxidative radical species ($HO_2 \cdot$ - $HO\cdot$) and oxidants (H_2O_2) with the help of oxygen and water vapour. The reactions cause the degradation of organic compounds, dirt, pollutants and microorganisms into substances such as carbon dioxide (CO_2) and water (H_2O). As titanium dioxide works as a catalyst in the process, self-cleaning is a constant and continuing property. Zinc oxide is an alternative to TiO_2 that employs the same photocatalysis mechanism. [151, 159] TiO_2 is not very effective in using solar energy, which leads to a fairly slow stain breakdown process. In the photoelectric process, titanium dioxide has a high conduction band gap energy. The photons' energy must be equal to or higher than the band gap energy in order to excite electrons in TiO_2. Only blue and UV light photons, which make up 3% of the solar spectrum, have enough energy to accomplish this goal. Thus, only a small portion of the available solar energy will degrade the stain particles from the fabric, making the process slow. After excitation, the electrons must react with oxygen atoms, which then react with the stains. These reactions require a large amount of light energy to achieve complete stain breakdown. [159] The application of titanium dioxide to the textile using a low-temperature sol-gel plasma process has been studied. At least with polyester fabric, the plasma process appears to improve the adhesion between TiO_2 and polyester. The coating also promoted the high UV protection of polyester fibres. A self-cleaning surface has also been produced for keratin fibres and cotton using sol gel plasma. [151] In addition to the self-cleaning property, TiO_2 has been proven to have an antimicrobial nature [171]. Researchers managed to improve the decomposition rate of stains by adding CNTs to the TiO_2 coating agent. This treatment also appears to mitigate the tensile degradation caused by photocatalytic reactions; thus, CNTs have the ability to protect substrate fibres from degradation by UV radiation and also improve the decomposition rate of stains. [172] Silicone-based repellent materials consist of polydimethylenesiloxane or silanol and silane, with tin octoate as a catalyst. The ecological challenges of these materials are process residuals, which cause water pollution and are toxic for aquatic organisms, such as fish. [165]

8 Specimen materials and treatments

The aim of the material selection process was to choose materials that are approved as suitable for body measuring purposes, meaning that the selected materials are commercially available via mass production or that the electrical suitability of the selected materials has been proved through laboratory testing. In addition, we also considered previous studies concerning the requirements for textile body-monitoring electrodes, as presented in Chapters 1-7. The textile electrode materials that are suitable for sports and well-being applications have properties and requirements similar to those required for healthcare applications for long-term body monitoring; thus, these materials are an obvious starting point for our study and the selection of textile electrodes. During the selection of water- and stain-repellent finishing treatments, the emphasis was on commercially available products that do not contain PFOA or PFOS and on the sensitivity of applying the technology to textile fibres. The selection of the sterilization method was based on the frequency with which the process is used in the health care sector, as well as on the process reliability, simplicity, durability and safety. This chapter presents the fundamentals and specifications for the textile electrode materials and treatments investigated in this study.

8.1 Selection of electrically conductive fibres

This study concentrates on textile electrodes made of metal and metal-based fibres due to their high conductivity and presumably good resistance to heat, mechanical abrasion, moisture and chemicals. In practice, the commercial application of silver-plated textile yarn is expected to withstand up to one hundred cycles of laundering. The melting point of metal is much higher than that of conductive polymers; thus, the steam sterilization treatment should not influence the electrical features of metal materials. The electrical resistance of conductive polymers is much higher, which limits those materials to certain application areas. In addition, the endurance of these materials against mechanical abrasion and treatments is unstable. [136] The material features are discussed in detail in Chapter 6.

Stainless steel metal fibres have potential due to their low cost in comparison to silver-plated fibres. However, the most frequently used stainless steel (AISI 316) contains 10-14% nickel, which can cause allergic reactions during skin contact. The hand-feel of textiles that contain steel fibres might be harder, and these textiles are prone to break easier than silver-plated polymers. In contrast, silver is non-allergic and has useful antibacterial characteristics. [136] Pure carbon has a low resistance, even as low as 10^2 Ω cm^{-1}. However, when combined in a sandwiched fibre structure, polymers such as nylon-carbon and polyester-carbon exhibit a remarkable increase in fibre resistance (10^{10}- 10^{16} Ω cm^{-1}). Carbon does not possess high chemical wear resistance and releases its black colour easily, resulting in the discolouration of the surrounding materials. However, the thermal insulation of carbon is better than that of metal. The electrical resistance of carbon fibre is 10^5-10^0 Ω cm^{-1}, but due to its lack of textile-like properties, carbon cannot be applied alone. A mixture with textile fibres is required, which significantly reduces the conductivity. Thus, the main application area is ESD textile products. [136]

Based on a literature search of material properties and user experiences with commercial electrodes, as well as a study of sterilization methods, silver and steel were chosen for making the textile conductive. Silver is even more suitable for the health care environment because this material provides a wide range of applications due to its durability, high electrical conductivity and antibacterial properties. Steel was chosen as a reference, as this material is the second best option for the conductive element in the structure. [136] Thus, other metals, conductive polymers and carbon fibres were excluded.

8.2 Selection of textile structures

Softness, elasticity and moisture management are desired features for textile materials used for body-monitoring sensors that are in contact with the skin. These features add comfort during long-term use. Depending on the textile structure, elastic electrode materials are suitable for respiration sensors. [136] Researchers have managed to use electrodes 1 C and 3 C to measure the bioimpedance of the body [176]. A description of all of the materials investigated in this study is shown in Table 8.

Table 8. The material content of the textile electrodes under study. Codes: C = Conductive textile, NK = Non-Conductive knit, NB = Non-Conductive elastic band, S = Heart rate-monitoring strap

Material Code	Description	Weight (g/m^2)	Structure	Material content
1 C	Conductive knitting	158	Warp knitting, conductive fibre	71% polyamide, 18% elastane, 11% silver-plated polyamide
2 C	Conductive knitting	156	Warp knitting, conductive coating	62% PA, 17% elastane, 21% silver coating made by electroless/chemical vapour deposition
3 C	Conductive Band	-	Woven band, conductive fibre	87% polyester, 13% silver-plated PA
4 C	Conductive Band	-	Woven band, conductive fibre	polyester, stainless steel
5 NK	Functional, coolmax knitting	110	Weft knitting	100% polyester
6 NK	PU-coated Knitting	220	Weft knitting, coated face surface	60% polyurethane, 40% polyester
7 NK	Knitting	130	Warp knitting	53.6% polyamide, 46.4% elastane/spandex
8 NB	Elastic band	-	Woven	47% polyamide, 40% polyester, 13% elastane
9 NB	Elastic band	-	Woven	89% polyamide, 11% elastane
10 S	Polar Wearlink 1+	-	Woven electrode, 3 C	45% polyamide, 28% polyurethane, 27% polyester
11 S	Suunto Comfort Belt	-	TPU moulded electrode	PA, EA, TPU, SS, ABS

The knit can be made conductive by using conductive fibres or by applying a conductive coating on the knit textile surface. The most reliable electrode function can be achieved if the surface is equally conductive in every direction. The coating of the textile is the most effective way to produce such an electrode. The coating was chosen to be applied to a knitted textile rather than a woven structure because maintaining the conductive feature is more challenging when the material is elastic. Therefore, silver-based knits with both technologies were chosen for this study. The warp knit electrode 1 C has silver-plated PA fibres in its structure, whereas electrode 2 C has a silver coating on a weft knit surface. The silver coating on fibre 1 C is made by electrochemical impregnation. Textile 2 C is coated using the chemical vapour deposition technique. Water- and stain-repellent finishes are traditionally applied to the reverse side of laminated or coated woven fabrics; thus, from this perspective, the applications of a repellent finish to non-coated knitted fabrics is relevant to this study.

Figure 21. Material 1 C: Silver-plated PA fibre in a warp knitted structure.

Figure 22. Material 2 C: Silver coating on a knitted structure.

The conductive textile bands (3 C and 4 C, see Table 8 have similar woven structures. One textile uses a silver-plated polyamide as a conductive yarn, and the other textile uses pure stainless steel fibre in its structure.

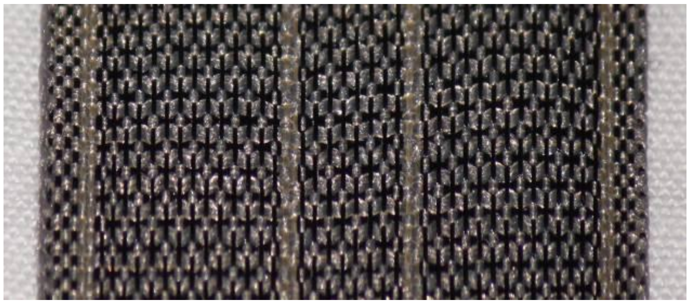

Figure 23. Material 3 C: Silver-plated PA fibre in the woven band structure.

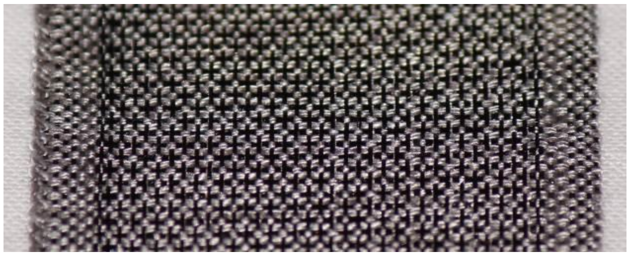

Figure 24. Material 4 C: Steel fibre in the woven band structure.

As the sterilization treatment is performed on a ready-made product, each component must withstand the process. Thus, the non-conductive textile components used in textile heart rate monitoring are included in this study. Textile specimens 5 NK, 6 NK and 7 NK are different kinds of functional knits. All of the conventional materials under study are man-made fibres that are used in sports apparel, as well as wearable body-monitoring applications, garments and belts. These types of fibres are more functional for long-term measuring than natural fibres (e.g., because moisture management, abrasion resistance and colour fastness and drying speed after laundering are lower in natural fibres).

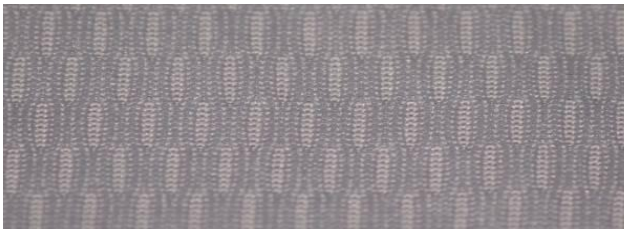

Figure 25. Material 5 NK: Coolmax polyester knit.

Figure 26. Material 6 NK: TPU-coated interlock knit.

Figure 27. Material 7 NK: Warp knit.

Woven elastic bands are common components of heart-monitoring systems. Materials 8 NB and 9 NB are non-conductive elastic bands that have different material contents but the same woven structure.

Figure 28. Material 8 NB: Woven elastic band.

Figure 29. Material 9 NB: Elastic band.

The commercial heart rate-monitoring straps Polar WearLink 1+ and Suunto Comfort Belt consist of the materials shown below. The basic difference between these straps is the electrode material. Polar uses a woven conductive textile as the electrode, whereas the Suunto strap uses a conductive moulded TPU electrode doped with carbon.

Figure 30. On the left, the Wearlink+ heart rate-monitoring strap; on the right, the Suunto Comfortbelt [3].

8.3 Selection of repellent finishes

Both repellent finishes investigated in this study (i.e., Nano-tex and Nano-X), are based on fluorocarbon nanotechnology, which can be exploited to achieve advanced repellent properties on textile surfaces. Nanoparticles have a high affinity for the textile fibre, which makes the repellent property durable to abrasion and machine washing. These finishes coat individual fibres, keeping the original visual appearance and hand-feel. [149] This topic is discussed in detail in Chapter 7. Inorganic, UV degradation-based self-cleaning treatment technologies are excluded (see Chapter 7.2.3). In the sensor applications used for body monitoring, the natural exposure to UV light that is used for the degradation of dirt does not exist. These inorganic self-cleaning methods are much more appropriate for outdoor products.

Nanotex is based on PFOA- and PFOS-free fluorocarbon (FC) C6 chemistry. The by-product of this technology generates perfluorohexanoic acid (PFHA), which is biodegradable, in contrast to PFOA and PHOS. In accordance with our materials and end use in the medical sector, Nanotex recommended that we use their product Nanotex Resists Spills (RS) in this study. Based on their test results, the Nanotex treatment was non-irritating and non-allergic for the skin. The curing treatment after application was performed at 140°C. [177]

Nano-X is a fluorine-based inorganic-organic polymer with a flame retardant agent and a natural biopolymer, which also has an antimicrobial property. Nano-X claims to reduce the growth of fungi and bacteria, as demonstrated by testing. The product VP BF 50025 is an aqueous impregnation solution for textile impregnation (PES, cotton, PA and mixtures), which also has hydrophobic and oleophobic properties. Nano-X is supplied in liquid form and can be applied by Foulard, spray or dip coating, followed by a curing process at 130-160°C. [126] The materials were applied by dip coating, followed by curing for 10 min at 150°C. Several variant formulas of VP EC 50025 were used in this study.

Fluorocarbons were chosen for this study because they are the most effective chemicals for achieving a soil-repellent surface and cleaning effectiveness during laundering. These chemicals are also commonly available. The most used frequently method of application is liquid impregnation, which is also suitable for fluorocarbon-free technologies. In addition, oil repellence can only be obtained using fluorinated carbon compounds [170].

8.4 Selection of decontamination methods

Depending on the end use of textile materials in the hospital environment, the materials must be either disinfected or sterilized before and after use (see Chapter 5). In the hospital, white and green garments (i.e., operating theatre garments) that do not need to be sterilized are disinfected by washing or treatment at 92°C. [27] Thus, the disinfection treatments that were applied to all of the materials under study are shown in Table 8.

During the selection of the decontamination method, the emphasis was on using the most common system in hospitals and the medical sector. This choice contributes to the implementation of wearable body-monitoring systems, as large investments will not need to be made in this sector.

The autoclave hot steam sterilization method is used frequently in the medical environment for the decontamination of textile products. This method is simple but effective, and the process is fairly fast and safe. The cycle time is 15-30 min, depending on the program or the product mass in the device chamber. This method uses only hot (121-134°C) water steam in the process, increasing safety for the product wearer, sterilization personnel and the environment. The disadvantage is the high process temperature, which can damage the material. The device cost is low in comparison to gamma irradiation. The device size can be chosen according to the products to be sterilized (see Chapter 5.4). [26] The gamma irradiation system is a dry and low-temperature system that is non-damaging to the material, but the device is a room-sized conveyor belt or chamber system that is expensive to purchase. This system is used primarily for single-use products for which sterilization before use is performed by the producer. Thus, the use of gamma sterilization in hospitals is infrequent. Hot air sterilization is also a dry process, but the temperature is even higher than the temperature used for autoclave sterilization, and the processing time is long (2 h at 160°C). If the process time is reduced to 0.5 h, the temperature must be 180°C. Based on the literature study presented in Chapter 5 and interviews with professionals [179] and device producers [26], autoclave hot steam sterilization was chosen as the best method for the sterilization of textile-based electrodes.

Figure 31. On the left, **the** autoclaving device used for textile sterilization from **the** outside. On the right**,** the textile products to be sterilized are in the autoclave chamber.

9 Testing methods, results and analysis

This chapter focuses on testing methods and results with analysis. Three different types of treatments (i.e., sterilization, disinfection and repellent finishes) were applied to the conductive woven and knitted fabrics. All of the selected treatments are wet and high-temperature processes. During sterilization and disinfection, high temperatures are used to kill bacteria, and during the repellent treatment, a high temperature is used for drying and curing. The repellent finish is a chemical treatment. The original electrical, physical and mechanical properties of a material might be changed by these treatments. Maintaining the thermal stability and abrasion resistance of the electrode after the treatments is the main aim of this study.

The properties to be tested were chosen according to the end use of the electrode. As the user environment is medical and health care and the application is wearable, the properties to be measured provide essential information for researchers, designers and producers of wearable textile technology. Standard testing methods were used whenever appropriate. The principle of testing is that the method correlates with the actual use of the material or product. Thus, in cases where the standard test is not the most appropriate test, an alternative testing method was used.

9.1 Decontamination of materials

The materials were sterilized using a hot steam autoclave sterilization device (see Figure 31). The Getinge HS22 (serial number 03050217) device is validated and calibrated by a third party regularly. This B-type device is commonly used in hospitals for textile sterilization. [26] As mentioned previously, high temperatures may damage the material. The exposure of polymers to external stresses, such as heat, abrasion, UV light, chemical or pressure, ages the material, and the impacts are cumulative. This topic is discussed in detail in Chapter 5.4. Based on interviews with health care professionals, textile materials should withstand sterilization up to 20 times [19]. This means that the sterilized garment could be worn by 20 different people. The garment would be washed regularly by the wearer between sterilization cycles. The impacts of the sterilization process on the textile material’s electrical and mechanical properties were observed during 20 sterilization cycles.

The effects of textile disinfection on resistance and dimensions were also studied. With respect to temperature, this process is a milder treatment, but chemicals and mechanical abrasion during laundering will stress the textile. In addition, the rate of decontamination is also lower. However, depending on the application, textile disinfection could be an adequate decontamination treatment in the hospital environment.

9.1.1 Surface resistance after sterilization

Electrochemical stability is crucial for the service life of an electro-driven application. Depending on the application, the increase in resistance alters effectiveness and affects the signal quality and thus the reliability of the measurement. In previous studies, abrasion and laundry washing were demonstrated to remove or destroy conductive components of textiles due to a weak bond between the fibre and the conductive component. [135]

The resistance (R) indicates the material's ability to resist electrical current (I, ampere). The unit of this parameter is the ohm (Ω). The lower the resistivity, the more the material conducts current. [137] A material's suitability for a textile electronic application depends primarily on the material's resistance and its ability to endure the external stress caused by heat, water, chemicals, pressure and abrasion. Heat leads to the thermal expansion of the metal material, which may cause the cracking and delamination of the metal coating of the fibre or textile. [135]

The electrical resistance of the textile material surface was measured according to AATCC Test Method 76-1995. The resistance is expressed as ohm/square (Ω/□). Two rectangular gold-plated electrodes (size: 20 x 10mm) were placed between the measuring heads and the specimen. The distance between the points to be measured was 100 mm. The resistance between the electrodes was recorded. [135]

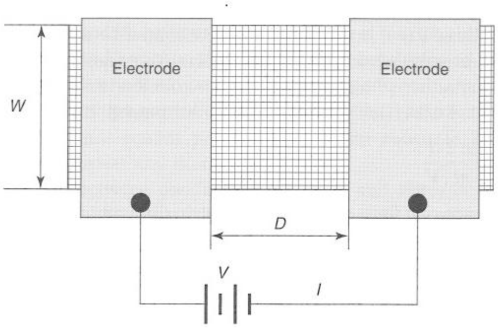

Figure 32. Surface resistance measurement; D is the distance between the electrodes. [135]

All of the resistance measurements were made in comparison to a dry electrode under the same conditions of room temperature and humidity. The testing was not performed under standard test room conditions because the absolute resistance of the material was not substantial, but the resistance change caused by additional treatments applied to the material were of interest. The fabric material measurement was made in both the warp and weft directions. The narrow woven band materials were measured only in the warp direction.

Conductive fibres, yarns and textiles have an anisotropic character, that is, these materials have different electrical properties when measured along different axes. The conductivity may change based on the thickness of the conductive coating. In addition, the fibre-fibre inter-connections in the textile structure have a great effect on the surface resistance. [135]

Textile electrodes perform most accurately for heart rate monitoring if the surface resistance is less than 100 Ω/□. Based on the experience of the electrode manufacturer, past that threshold, the quality of measurement starts to decrease. Generally, 1,000 Ω/□ is used as an absolute limit for the resistance of textile electrode surfaces to be used in ECG measurement. The operation range for the moulded TPU sensor is between 1,000 and 3,000 Ω/□. The existence of an equal surface resistance in all directions improves the measurement accuracy. Thus, high and unequal surface resistance negatively affects the signal quality, which limits the suitable application areas of textile electrodes. [134]

An autoclave steam sterilization device provides two programs that are suitable for textiles. One program is hot steam treatment at 121°C with a running time of 35-45 min per cycle. Another program is called the fast program, in which the running time is reduced to 15-20 min by increasing the treatment temperature to 134°C. The selection of the treatment program depends on the textile material to be treated and the expected product life cycle time, as the possible negative effects on the mechanical and electrical properties of the material that are caused by the treatment are cumulative.

The following results represent the surface resistances of four different electrode materials after sterilization. Two of the materials were knitted materials (1 C and 2 C) and two of the materials were woven bands (3 C and 4 C). The conductivity of specimen 1 C was achieved by using silver-plated PA fibre as the conductive element. Specimen 2 C was instead made conductive by silver-plating of the textile. The difference between the woven bands is that specimen 3 C has the same silver-plated PA fibre as specimen 1 C, and specimen 4 C has stainless steel fibre in its structure. The woven textile structure and the conventional fibre materials are the same in both woven structures. The surface resistance was measured after 1, 3, 5, 10 and 20 cycles. Three (3) parallel measurements were made at three different randomly chosen points of the material, and the average value of the three points is presented in the tables. The knitted materials were measured in both the row and wale directions. Visual observations of each material were made after the same cycle in which the resistance was measured. The graphs of all materials are summarized in Figure 35 and Figure 36.

Table 9. Surface resistance **(Ω/□)** of silver-plated PA fibre**s** in warp knitted material 1 C as a function of sterilization cycles **at** 121°C.

Specimen	**1 C**	**Warp knitting with silver plated Polyamide fiber**										
Sterilization cycles (121°C)	**0**		**1**		**3**		**5**		**10**		**20**	
Measurement direction	row	wale	row	wale	row	wale	row	wale	row	wale	row	wale
Surface resistance 1	6.36	15.69	7.21	18.75	10.47	12.99	21.8	39.9	20M	175	10.44	24.74
Surface resistance 2	6.3	17.11	6.76	15.3	9.56	16.19	23	46.84	2,5M	121	14.00	26.52
Surface resistance 3	6.43	17.75	8.08	16.42	8.34	17.03	21.9	31.26	50	48	16.60	26.56
Average	**6.4**	**16.9**	**7.4**	**16.8**	**9.5**	**15.4**	**22.2**	**39.3**		**114.7**	**13.7**	**25.9**
	Surface resistance (Ω)											

We observed that the specimen that was made using conductive fibres does not produce equal conductivity for the textile. This property is highly challenging due to the bond structure and the fibre–fibre interconnections, as discussed above. However, the variation between directions is not critical for galvanic heart rate monitoring, as demonstrated by the commercial application of electrode and bioimpedance measurement [177].

The results indicate that sterilization does not have a strong negative effect on the conductivity of knitted fabric 1 C (Table 9), as the bonding of the silver and PA is sufficiently strong. Even after 20 treatments, this kind of electrode can be used for body monitoring, although some cumulative changes can be seen. After 10 cycles, the surface resistance is extremely high, and after 20 cycles, the surface resistance returns to a reasonable level. Because the same samples are measured after 10 and 20 cycles, it appears that some kind of measurement error occurred.

Visual inspections indicated that after five cycles, the silver yarn becomes brighter and the bleeding of the black base material occurs (Figure 33). As the textile was dyed after weaving, this finding indicates that the dye migrates to the hot steam during the treatment. However, silver cannot be dyed but only absorbs the dye on its surface. No changes in material hand-feel could be observed.

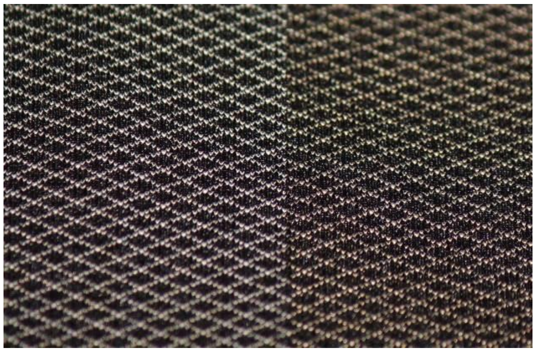

Figure 33. On the left, material 1 C after 20 cycles of sterilization; on the right, material 1 C before sterilization.

Table 10. Surface resistance (Ω/□) of silver-coated weft knitted material 2 C as a function of sterilization cycles at 121°C.

Specimen	**2 C**	**Silver coated weft knitting**						
Sterilization cycles (121°C)	**0 (ref.)**		**1**		**3**		**5**	
Measurement direction	row	wale	row	wale	row	wale	row	**wale**
Surface resistance 1	1.49	1.7	1.34	1.91	11.44	14.08	No cond.	No cond.
Surface resistance 2	1.5	2.05	1.39	1.88	34.45	19.25	No cond.	No cond.
Surface resistance 3	1.59	1.81	1.35	2.17	39.67	7.08	No cond.	No cond.
Average	**1.53**	**1.85**	**1.36**	**1.99**	**28.52**	**13.47**		
	Surface resistance (Ω)							

When comparing specimen 2 C to specimen 1 C, the equal resistance in both directions that is generated by the textile coating process technology can be observed. However, the endurance of the coating is low. The results indicate that the conductive coating disappeared after only five cycles of sterilization (see Figure 34). The hot steam caused the delamination of the silver coating of the textile that was applied by chemical vapour deposition. A remarkable increase can be seen between the first and third treatments.

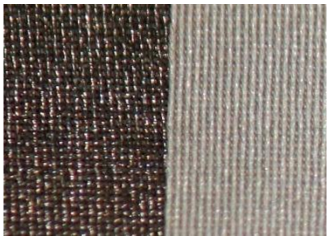

Figure 34. The conductive-coated specimen 2 C before hot steam sterilization treatment on the left, and the delaminated specimen after 5 cycles of sterilization on the right.

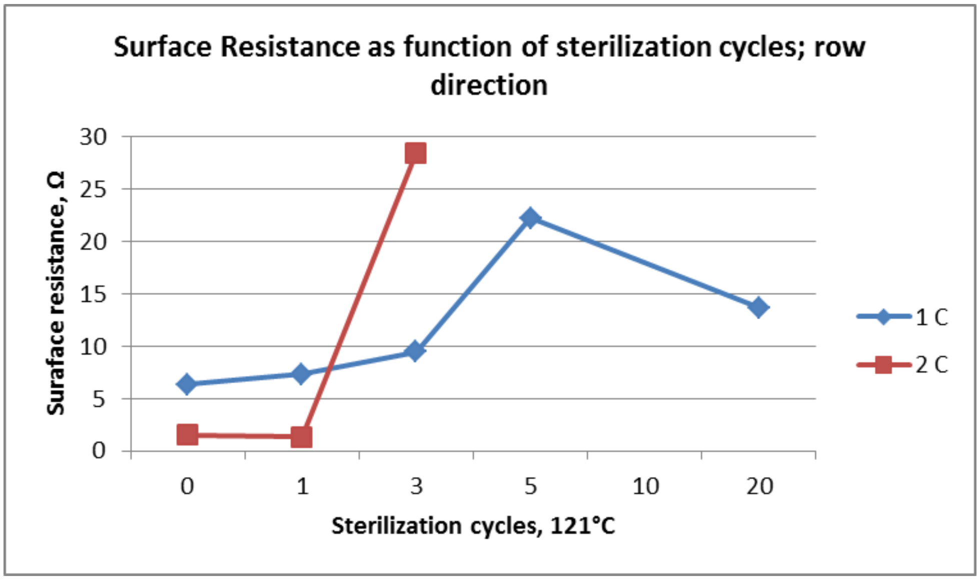

Figure 35. Surface resistance (Ω/□) of knitted materials after sterilization cycles at 121°C. The silver-coated PA textile lost its conductivity after 3 cycles. The average resistance value of three parallel materials is used.

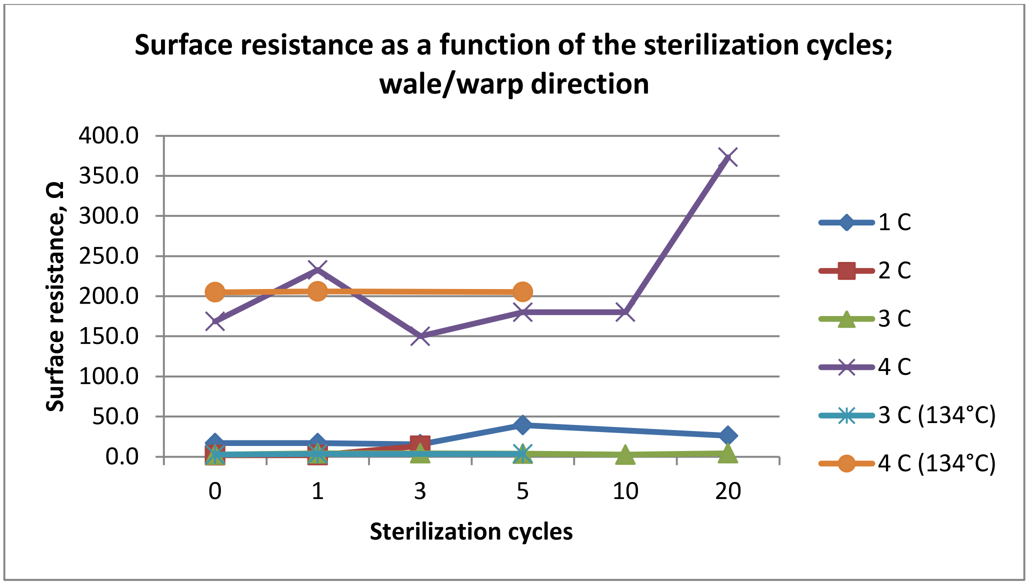

Figure 36. Surface resistance (Ω/□) after sterilization cycles at 121°C and 134°C. The average resistance value of three parallel materials is used.

Upon visual inspection, the yellowing of material 2 C after the first treatment cycle was observed. The intensity of yellowing increased after three and five treatment cycles. The material hand-feel became harder as a function of continued treatments.

The surface resistance of the woven bands (3 C and 4 C) was measured only in the warp direction because the width was only 34-36 mm, as the measuring electrode size was 10x20 mm (see Table 11 and Table 12).

Table 11. The surface resistance (Ω/□) of woven band 3 C as a function of sterilization cycles at 121°C.

Specimen	3 C	Woven band with silver plated polyamide fiber				
Sterilization cycles (121°C)	**0**	**1**	**3**	**5**	**10**	**20**
Surface resistance 1	2.25	2.56	5.14	4.05	2.22	6.51
Surface resistance 2	2.36	5.36	4.77	2.55	3.37	2.5
Surface resistance 3	2.64	4.45	3.04	4.6	2.06	4.14
Average	**2.42**	**4.12**	**4.32**	**3.73**	**2.55**	**4.38**
		Surface resistance (Ω) in warp direction				

Table 12. The surface resistance (Ω/□) of woven band 4 C as a function of sterilization cycles at 121°C

Specimen	4 C	Woven band with stainless steel fiber				
Sterilization cycles (121°C)	**0 (Ref.)**	**1**	**3**	**5**	**10**	**20**
Surface resistance 1	165	170	123	185	170	450
Surface resistance 2	157	220	137	160	235	250
Surface resistance 3	184	308	190	195	136	420
Average	**169**	**233**	**150**	**180**	**180**	**373**
		Surface resistance (Ω) in warp direction				

The results reveal an increase in resistance after the sterilization treatments, especially with two samples of material 4 C, for which the surface resistance tripled. This finding indicates that the absolute resistance is much higher than that of silver and is not consistent between the samples (see Figure 36). Material 3 C also doubled its surface resistance after 20 cycles of sterilization. However, the conductivity remained high, and this change does not limit the application areas of the electrode. In comparison to the conductive properties of the original steel and silver fibres, it can be stated that the resistance difference between these metals is the limiting factor for the suitable application areas. Sterilization did not cause any visual effects on the woven bands (3 C and 4 C), and the hand-feel of the material remained unchanged after the treatments.

The sterilization program with a higher temperature (134°C) was also applied to the woven bands (see Figure 36). The conductive fibres in structures of materials 3 C and 1 C are the same; thus, it was not necessary to treat material 1 C. The sterilization treatments were stopped after five cycles because the results indicated that the higher temperature does not change the surface resistance.

Table 13. The surface resistance (Ω/□) of woven band 3 C as a function of sterilization cycles at 134°C.

Specimen	**3 C (134°C)**	**Woven band with silver-plated polyamide fibre**	
Sterilization cycles (134°C)	**0 (Ref.)**	**1**	**5**
Surface resistance 1	2.25	3.64	4.39
Surface resistance 2	2.36	3.36	2.78
Surface resistance 3	2.64	3.41	3.28
Average	**2.42**	**3.47**	**3.48**
	Surface resistance (Ω)		

Table 14. The surface resistance (Ω/□) of woven band 4 C as a function of sterilization cycles at 134°C

Specimen	**4 C**	**Woven band with stainless steel fibre**	
Sterilization cycles (134°C)	**0 (Ref.)**	**1**	**5**
Surface resistance 1	176	230	154
Surface resistance 2	326	202	198
Surface resistance 3	113	186	264
Average	**205**	**206**	**205**
	Surface resistance (Ω)		

9.1.2 Surface resistance after disinfection

The visibly clean conductive specimens (1 C, 2 C, 3 C, and 4 C) were disinfected at 95°C according to standard EN ISO 6330 using a standard laundry machine (Electrolux W465H). The ordinary washing detergent OMO colour was used. The disinfection program (991) with washing requires 22 min, including three rinses. Specimens 1 C and 2 C were also treated with the Nanotex repellent finish before disinfection. The conductivity of three parallel samples was recorded (see Table 15 and Table 16).

Table 15. Surface resistance (Ω/□) of conductive knits 1 C and 2 C after disinfection, and Nanotex repellent-treated specimens 1 C and 2 C after disinfection.

			Row				Wale			
Treatment	Code	**Knitting Material Description**	**1.**	**2.**	**3.**	Average	**1.**	**2.**	**3.**	Average
REF	1 C	Warp Knitting, Silver plated PA	5.9	5.2	5.86	5.65	6.71	6.47	7.23	6.80
Disinf.	1 C	Warp Knitting, Silver plated PA	5.3	5.2	5.91	5.47	6.76	7.4	7.69	7.28
Nanotex+ disinf.	1 C	Warp Knitting, Silver plated PA	6.42	7.12	7.04	6.86	9.42	8.64	8.79	8.95
REF	2 C	Weft knitting, conductive coating	1.37	1.12	1.25	1.25	1.35	1.34	1.59	1.43
Disinf.	2 C	Weft knitting, conductive coating	6.29	7.59	5.82	6.57	5.57	5.27	4.96	5.27
Nanotex+ disinf.	2 C	Weft knitting, conductive coating	2.44	2.6	2.36	2.47	2.42	2.51	2.52	2.48
			Surface Resistance (Ω)							

Table 15 shows that one cycle of the disinfection process does not cause a significant change in surface resistance. The Nanotex-treated and disinfected specimen is not absolutely comparable to the reference because the samples are not the same piece of fabric. The measurements were made during the same day for all specimens in the table. The reference and disinfected specimens are the same sample; thus, the comparison is valid and reliable. In specimen 1 C, there appears to be a slight increase after treatment, whereas specimen 2 C exhibits a clear increase in surface resistance after one cycle of disinfection. This finding supports the results obtained using autoclave sterilization, where after five cycles, the conductivity had disappeared, indicating that the silver-coated textile is not durable during hot treatments. The repellent finish improves the resistance and may improve the durability of the silver coating adhesion. The effect of repellent treatments on the material conductivity is presented and analysed in Chapter 9.2.1.

Table 16. Surface resistance (Ω/□) of specimens 3 C and 4 C after one cycle of disinfection.

			Surface resistance (Ω) Warp		
Treatment	**Code**	**Woven Band Description**	**1.**	**2.**	**3.**
Reference	3 C	Band with silver-plated PA fibre	4.09	3.85	5.48
Disinfected	3 C	Band with silver-plated PA fibre	3.88	3.58	3.4
Reference	4 C	Band with stainless steel fibre	243	243	172
Disinfected	4 C	Band with stainless steel fibre	4.3 k	1.4 k	488

In the case of woven structures, specimen 3 C, which consists of silver-plated PA, appears to survive the disinfection process well in comparison to specimen 4 C (see Table 16). This result indicates that even after one cycle of disinfection, the resistance of the textile electrode containing stainless steel fibre increased to 10^3 ohm. This resistance level limits the electrode's application areas. This finding also indicates the existence of unequal resistance on the surface. This result appears to indicate that the mechanical stress of the disinfection process causes the brittle steel fibres to break. Microscopic examination could be used to identify the causes of the high and unequal resistance of steel-based specimen 4 C after the disinfection process.

9.1.3 Surface resistance after cleaning

The conductive samples 1 C, 2 C, 3 C and 4 C were treated with the Nanotex repellent finish, followed by 20 cycles of washing at 40°C using an ordinary home laundry machine. There were three parallel specimens, and measurements were collected at three points; the average for certain specimens is presented in Table 17.

Table 17. Surface resistance (Ω/□) of conductive materials 1 C, 2 C, 3 C and 4 C after 20 cycles of machine washing at 40°C.

Nanotex Finish		Unwashed			Washed 20 times at 40°C		
Code	**Material Description**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**
1 C	Warp Knitting with silver plated PA fiber	5.22	5	6.13	49.64	59.42	54.42
2 C	Silver coated weft knitting	1.11	1.23	1.09	7.2	6.96	5.87
		Row resistance (Ω), B					
Code	**Material Description**	Measuring distance 30 mm					
3 C	Woven band with conductive plated PA fiber	7.05	4.84	5.11	7.89	5.63	6.3
4 C	Conductive band with stainless steel fiber	324.24	330.4	1.8k	3300	6M	3M
		Warp resistance (Ω), A					

Resistance was examined in the row direction for knitted fabrics and in the warp direction for woven bands. A clear increase in resistance can be observed in every parallel sample of material 1 C. Specimen 2 C exhibited a pattern of growth similar to specimen 1 C. In comparison to sterilization and disinfection, for specimen 2 C, the high temperature (> 95°C) but not the mechanical stress caused by the washing machine causes the delamination of silver from the substrate.

The measuring distance in cases 3 C and 4 C was only 30 mm instead of 100 mm. The resistance of the woven bands supports earlier results obtained after sterilization and disinfection. Specimen 3 C, which contains silver-plated PA fibres, maintains its resistance level during washing, as observed after sterilization and disinfection. The results also demonstrate that mechanical stress destroys the conductive structure of specimen 4 C; however, this specimen can resist high temperatures as long as mechanical stress is not involved. Thus, a stainless steel textile electrode can be sterilized but not disinfected or washed. Therefore, steel fibres cannot be used in applications for which disinfection or sterilization is required because before sterilization, the product must always be washed. In addition, the visual appearance after 20 cycles of machine washing was fairly poor (Figure 37), with numerous steel fibres pointing upwards, which collected other fibres. The hand-feel also became rough. The thin steel fibres are difficult to see using the naked eye but can be identified by sliding the fingers along the surface. It is obvious that those fibres are the steel fibres rather than ordinary PES fibres because the yarns and the woven structure are the same in specimens 3 C and 4 C. Specimen 4 C still feels soft after washing.

Figure 37. Materials 4 C (above) and 3 C (below) machine-washed 20 times at 40°C.

9.1.4 Surface resistance as a function of abrasion

The surface resistance as a function of abrasion was determined using a Martindale abrasion resistance device, in accordance with standard SFS EN ISO 12947-2 [188]. The woven materials and testing method were chosen based on the test results after sterilization. The silver-coated textile 2 C could not be successfully sterilized, and as mentioned above, materials 1 C (warp knit) and 3 C (the woven band) contain the same conductive fibre in their structures.

Due to its size, the woven band sample (width 34-36 mm) was set to the abrading head (Figure 39), which was abraded with wool fabric. The resistance of the material was measured after 1,000, 2,000, 4,000, 6000 and 10,000 abrasion cycles (Table 18 Figure 38). The measuring distance was 30 mm with point heads due to the size of the specimen in the abrading head (34-36 x 40 mm). Based on previous research, it was known that the material abrasion resistance would not be more than 10,000, which determined the examination frequency for the material resistance.

The specimens were first treated with the repellent Nanotex finish or Nano-X finish. Abrasion was also performed for sterilized specimens. Nano-X had three different recipes; thus, these treatments are not totally comparable. Nano-X 1474 was chosen for abrasion after sterilization testing because this treatment achieved the best results with respect to the durability of repellence testing among the Nano-X finishes. Detailed results are presented in Chapter 9.2.

Table 18. The surface resistance (Ω/□) of specimen 3 C, which contains silver-plated PA fibres, as a function of abrasion cycles.

	Abrasion cycles, ISO EN 12947-2											
3 C, Finish	**0**	**1000**	**2000**	**4000**	**6000**	**10000**	**0**	**1000**	**2000**	**4000**	**6000**	**10000**
Nano-X 1474	2.30	3.46	4.23	4.49	4.75	1.67	0.98	1.09	1.25	1.18	1.20	1.14
Nano-X 1462	2.40	3.50	4.50	5.46	4.11	3.27	0.98	1.10	1.11	1.34	1.33	1.46
Nano-X 1460	1.80	2.13	2.95	3.30	3.32	3.25	0.95	1.07	1.00	1.11	1.25	1.43
Nanotex RS	2.42	4.00	3.12	4.00	7.00	4.70	0.80	1.20	1.00	1.16	1.20	1.20
	Warp Resistance (Ω)						Warp Resistance (Ω) on top of conductive warp					

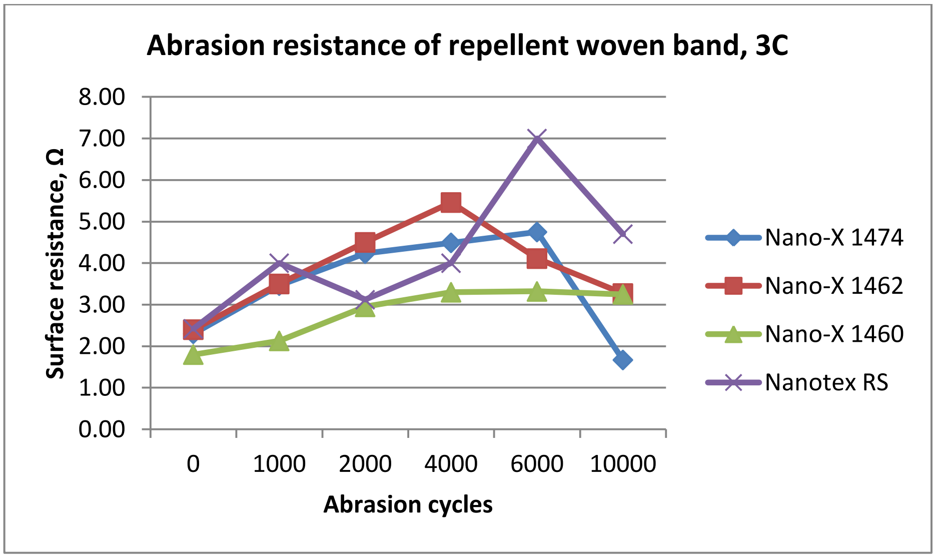

Figure 38. Abrasion resistance **(Ω/□)** of conductivity for specimen 3 C**.**

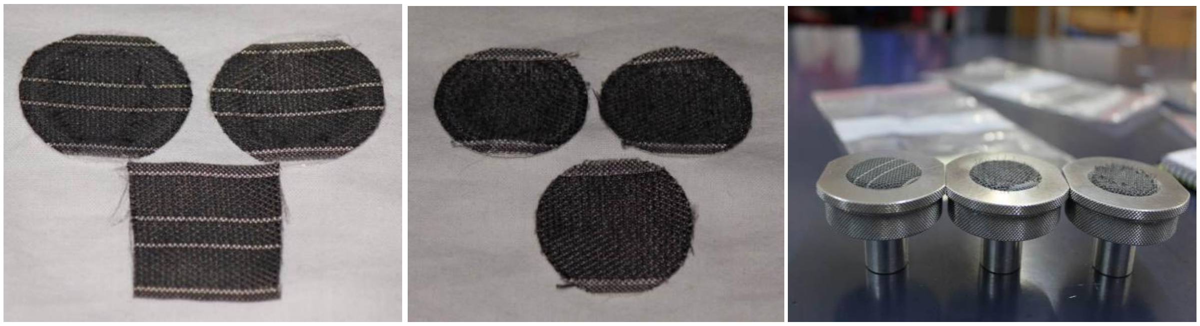

Figure 39. On the left, specimen 3 C; the above two samples were abraded for 10,000 cycles, and the reference is below. In the middle, specimen 4 C; the above two samples were abraded for 6,000 cycles, and the reference is below. On the right, the specimens in abrading heads. On the left is specimen 3 C, non-abraded. In the middle and on the right are specimens of 4 C after 1,000 abrasion cycles.

After 10,000 cycles, the material is broken but remains highly conductive, with a smooth appearance and soft hand-feel (see Table 18, **Figure 38** and Figure 39). The surface resistance of specimen 3 C appears to decrease after 10,000 cycles. A close investigation shows that because the non-conductive warp yarns are broken and thus disappear from the surface, the conductive yarns, primarily the weft yarn, rise up, reducing the surface resistance. In addition, Figure 39 shows that conductive silver fibres still exist in the warp and can be seen as horizontal stripes. It can be stated that the decrease in surface resistance is caused by the woven structure of the electrode. The repellent finish has no negative impact on the surface resistance of the material; these results are analysed and detailed in Chapter 9.2.1. In a comparison of specimens 3 C and 4 C, the surface electrical resistance of specimen 3 C as a function of abrasion cycles is much higher. The results for specimen 4 C are presented in Table 19 and Figure 40. The resistance increases as a function of abrasion cycles. The abrasion resistance of all 4 C specimens was 4,000 cycles. After 6,000 cycles, the material was broken, according to the standard. In addition, the material was not conductive. The appearance was poor, and the hand-feel was hard (Figure 39). This finding supports our earlier observation that the endurance of steel fibres against mechanical stress is rather low.

Table 19. The surface resistance (Ω/□, distance 3 cm) of specimen 4 C, which contains stainless steel fibres, as a function of abrasion cycles and sterilization cycles.

		Abrasion cycles, ISO EN 12947-2							
4 C, Finish	**Sterilization cycles**	**0**	**1000**	**2000**	**4000**	**0**	**1000**	**2000**	**4000**
No	1	17	70	70	200	75	140	180	600
No	20	23	200	160	326	60	120	300	232
Nanotex RS	0	40	200	370	400	60	160	250	1300
NANO-X, 1462	0	27	85	130	180	120	245	300	380
NANO-X, 1460	0	23	163	252	460	96	250	280	450
NANO-X, 1474	1	80	200	100	200	220	300	270	300
NANO-X, 1474	3	27	68	175	150	100	200	350	305
NANO-X, 1474	5	25	70	75	121	58	280	270	500
NANO-X, 1474	10	15	96	130	130	36	200	160	260
		Weft Resistance (Ω)				**Warp Resistance (Ω)**			

Figure 41 (based on Table 19) shows that sterilization or repellent finish treatment does not have a significant impact on the surface electrical resistance. Thus, a cumulative change in the material resistance property cannot be observed. However, a slight reduction of the resistance can be observed as a function of sterilization cycles. In addition, sterilization does not appear to have any effect on the abrasion resistance of specimen 4 C.

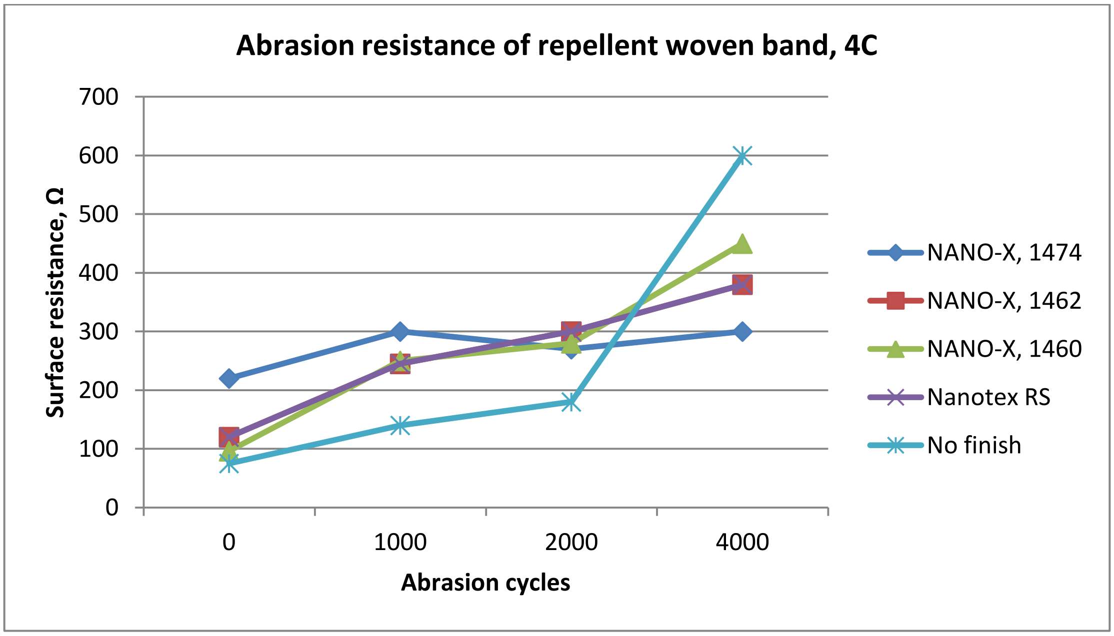

Figure 40. Abrasion resistance (Ω/□, distance 3 cm) of conductivity for specimen 4 C.

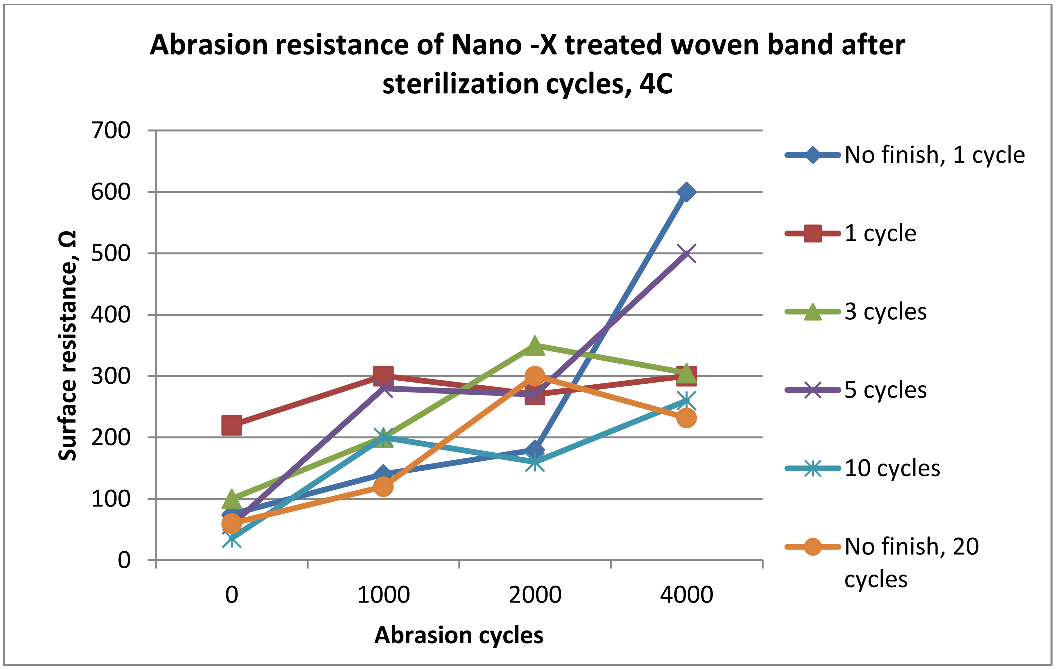

Figure 41. The impact of sterilization cycles on conductivity and abrasion resistance (Ω/□, distance 3 cm) of conductivity.

Upon visual inspection, the hairy effect and hard hand-feel can be seen and felt after only 1,000 abrasion cycles. The hard surface is obviously caused by broken steel fibres, which are turned upwards (see Figure 39).

9.1.5 Dimensional change after sterilization

The dimensional change of the materials was measured as a function of sterilization cycles and disinfection. When designing and developing devices, it is important to understand how the different materials react during the sterilization and disinfection processes, as it is a whole product comprised of different materials that is treated, rather than a single electrode. In addition to conductive materials, some commonly used knitted non-conductive textiles and a heart rate-monitoring strap consisting of 3 C electrodes were chosen for dimensional change testing. The product's visual appearance is impacted when the dimensional change occurs. The dimensional change also changes the placement of the electrodes. These changes must be observed because the electrode shape, size and placement are essential for achieving reliable measurements from the body.

The testing was performed by applying standards SFS EN ISO 5077:1994: Textiles. Determination of dimensional change in washing and drying [129] and SFS 2607: Textiles. Determination of dimensional changes in woven and knitted fabrics subjected to steam [187]. Measurements were obtained from 2-5 parallel specimens of each material under study. The average change in the material according to sterilization cycle and the maximum dimensional change in percent between cycles are presented in Table 20 and Table 21.

Table 20. Dimensional change of knitted materials in the row direction as a function of sterilization cycles at 121°C.

		Sterlization cycles (121°C)					
Code	**Knitting Material description**	**0**	**1**	**3**	**5**	**10**	**Change %**
1 C	Warp knitting with silver plated Polyamide fiber	200	181	182	181	181	**-9.5**
2 C	Silver coated weft knitting	200	192	-	-	-	**-4.0**
5 NK	Weft knitting	200	191	191	190	192	**-4.0**
6 NK	PU coated weft knitting	200	197	-		-	**-1.5**
7 NK	Warp knitting	200	192	191	190	190	**-5.0**
		Row direction (mm)					

Table 21. Dimensional change of knitted materials in the wale direction as a function of sterilization cycles at 121°C.

		Sterlization cycles (121°C)					
Code	**Knitting Materials Description**	**0**	**1**	**3**	**5**	**10**	**Change %**
1 C	Warp knitting with silver plated Polyamide fiber	200	195	197	197	197	**-1.5**
2 C	Silver coated weft knitting	200	193	-	-	-	**-3.5**
5 NK	Weft knitting	200	194	193	193	192	**-4**
6 NK	PU coated weft knitting	200	192	-	-	.	**-4**
7 NK	Warp knitting	200	200	200	200	199	**-0.5**
		Wale direction (mm)					

A negative dimensional change (i.e., shrinkage) of all knitted materials can be clearly observed. On average, the shrinkage in the row direction was even higher than the shrinkage in the wale direction. For specimen 2 C, the changes were measured after only one cycle of sterilization because the material cannot maintain its electrical resistance after further cycles. Generally, the negative dimensional change was within the commonly acceptable level (in the range of 0.5-4%), but the conductive specimen 1 C exhibits an exceptionally high shrinkage percentage of 9.5% in the row direction. Shrinkage does not appear to be cumulative, and the largest change occurred after one treatment cycle. Therefore, sterilization was performed for 10 cycles rather than for 20 cycles.

Weft knits 2 C and 5 NK have equal shrinkage percentages in both directions, in contrast to the warp knits. The warp knits appear to be much more stable in the wale direction, as the shrinkage is only 0.5-1.5% in the wale direction and is in the range of 5.0-9.5% in the row direction. The results for specimen PU 6 NK after 3, 5, and 10 cycles are missing because the measuring marks disappeared after 3 sterilization cycles. A clear and cumulative yellowing was easily observed for materials 2 C and 5 NK after the first cycle.

Table 22. Dimensional change of woven band materials in the weft direction as a function of sterilization cycles at 121°C.

		Sterlization cycles (121°C)					
Code	**Woven Material description**	**0**	**1**	**3**	**5**	**10**	**Change %**
3 C	Woven band with silver plated polyamide fiber	34	34	33	36	34	**0.0**
4 C	Woven band with stainless steel fiber	36	36	36	36	36	**0.0**
8 NB	Elastic woven band	30	30	30	30	30	**0.0**
9 NB	Elastic woven band	49	49	48	48	48	**-2.0**
		Weft direction (mm)					

Table 23. Dimensional change of woven band materials in the warp direction as a function of sterilization cycles at 121°C.

		Sterlization cycles (121°C)					
Code	**Woven Material description**	**0**	**1**	**3**	**5**	**10**	**Change %**
3 C	Woven band with silver plated polyamide fiber	200	192	191	190	187	**-6.5**
4 C	Woven band with stainless steel fiber	200	195	194	191	190	**-5.0**
8 NB	Elastic woven band	200	175	187	189	188	**-6.0**
9 NB	Elastic woven band	200	194	196	197	197	**-1.5**
		Warp direction (mm)					

The woven elastic and inelastic band structures are stable in the weft direction. The measuring distance is rather short, which might affect the results. In the warp direction, the negative dimensional change varies from 1.5% to 6.5%. On average, the negative dimensional change was smaller for the woven bands than for the knits; thus, the higher temperature sterilization treatment was applied only to the woven structures. For this experiment, only 5 cycles were applied because the results indicated that most of the dimensional change occurs during the first treatment.

Table 24. Dimensional change of woven band materials in the weft direction as a function of sterilization cycles at 134°C.

		Sterlization cycles (134°C)				
Code	**Woven Material description**	**0**	**1**	**3**	**5**	**Change %**
3 C	Woven band with silver plated polyamide fiber	200	190	187	187	**-6.5**
8 NB	Elastic woven band	200	190	188	190	**-5**
9 NB	Elastic woven band	200	197	198	200	**0**
		Warp direction (mm)				

Table 25. Dimensional change of woven materials in the warp direction as a function of sterilization cycles at 134°C.

		Sterlization cycles (134°C)				
Code	**Woven Material description**	**0**	**1**	**3**	**5**	**Change %**
3 C	Woven band with silver plated polyamide fiber	34	33	32	33	**-2.9**
8 NB	Elastic woven band	30	30	30	30	**0.0**
9 NB	Elastic woven band	49	48	47	48	**-2.0**
		Weft direction (mm)				

The results are similar after sterilization at a lower temperature for a longer time. Specimen 3 C is the only specimen that exhibits a slightly higher negative change in the weft dimension. It is noteworthy that the elastic bands 8NB and 9NB recover as function of sterilization cycles. This effect might indicate the loosening of the elastane fibres in the structure.

In addition, specimens 1 C, 2 C, 4 C, and 7 NK were washed at 40°C and then sterilized with a program at 121°C. No dimensional change was observed after sterilization, as the washed samples were the reference. Thus, the pre-shrinking of textiles during the manufacturing process can be used to stabilize the material prior to use in medical applications. This finding is independent of the manufacturing structure (i.e., knitting or weaving).

The dimensional change of the material is individual and dependent on the fibre materials, the textile structure and the production technology of the fibres, textiles and added finishing treatments. The dimensional change of the final textile material is difficult to predict. Thus, material stability during the sterilization process and the disinfection process can be achieved with heat treatment at the sterilization temperature before product assembly.

Conductive materials exhibit similar dimensional behaviour under heat as non-conductive materials. It can be stated the conductive element itself does not impact the dimensional stability of the textile material.

The dimensional change of the commercial heart rate-monitoring strap Wearlink + was measured as a function of sterilization cycles. The electrode of the product is specimen 3 C. In addition, sterilization was performed for another commercial heart rate strap. The difference between this strap and Wearlink+ is that this strap consists of moulded conductive TPU electrodes. This construction is widely used for heart rate monitoring. After one sterilization cycle, the dimensional changes were large. Based on a visual inspection, this structure is not suitable for sterilization because the treatment visually destroys the moulded electrodes of the product. The electrodes are melted during the process, and their shape is changed.

The dimensional changes were measured at three points on the strap (see Figure 42): the electrode size (a), the distance between (b) the two electrodes and the overall dimensions of the strap (c).

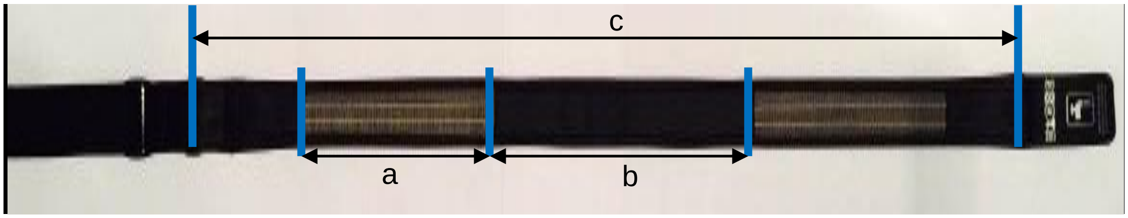

Figure 42. The measuring points in the dimensional change test.

Table 26. The dimensional change of materials 3 C and 6 NK in the Wearlink 1+ heart rate-monitoring strap as a function of sterilization cycles using the 121°C program.

		Electrode size (mm), a		Distance of electrodes (mm), b		Strap size (mm), c	
Sterilization cycle, 121°C	WearLink 1+ strap	warp /length	weft / height	wale / length	row / height	length	width
0 (ref.)	S2242-6	78	20	108	20	330	31
0 (ref.)	S2242-13	79	20	108	20	336	31
0 (ref.)	S2242-31	79	20	108	20	333	31
1	S2242-6	75	18.5	105	19	317	29
1	S2242-13	76	19	106	19	323	29
1	S2242-31	76	19	105	19	323	29
3	S2242-6	75	19	105	19	315	29
3	S2242-13	76	19	105	19	322	29
3	S2242-31	75	19	105	19	320	29
5	S2242-6	74	19	105	19	315	29
5	S2242-13	75	19	105	19	317	29
5	S2242-31	75	19	105	19	317	29
10	S2242-6	74	19	104	19	313	29
10	S2242-13	75	19	105	19	317	29
10	S2242-31	74	19	104	19	317	29
Shrinking max %		**6.3**	**5.0**	**3.7**	**5.0**	**5.7**	**6.5**

Material 6 NK, which is a surface-coated PU knit, is used in the Wearlink 1+ strap. In Table 26, the column distance between electrodes in the wale direction shows the dimensional change of material 6 NK (3.7%), which is consistent with the results presented in Table 21, as the dimensional change in the wale direction for material 6 NK is 4%. This distance is shorter (108 mm) than the standard measurement (200 mm); this difference can be explained by measurement inaccuracy or by the possibility that the product structure prevents the material from shrinking.

The percentage of shrinkage is similar at all measuring points, which allows these materials to fit together. In addition, the visual inspection reveals that the dimensional changes are rarely symmetrical. The overall shrinkage (in the range of 3.7-6.5%) is so significant that it must be considered in research and development, as this level of shrinkage may impact the body measurement quality.

Two more WearLink 1+ straps were sterilized at a higher temperature of 134°C, which is used in a faster sterilization program. The treatment was performed three times. The negative dimensional change (i.e., shrinkage) is consistent with the change observed after three cycles of lower temperature sterilization at 121°C (see Table 26 and Table 27).

Table 27. The dimensional change of materials 3 C and 6 NK in the Wearlink 1+ heart rate-monitoring strap as a function of sterilization cycles with a 134°C program.

		Electrode size (mm), a		Distance of electrodes (mm), b		Strap size (mm), c	
Sterilization cycle, 134°	**WearLink 1+ strap**	warp	weft	warp	weft	length	width
0 (ref.)	S2242-2	80	20	110	20	336	30
0 (ref.)	S2242-25	79	20	108	20	335	30
1	S2242-2	77	20	107	20	326	30
1	S2242-25	75	20	105	20	326	29
3	S2242-2	76	19	105	19	322	29
3	S2242-25	75	19	104	19	320	29
Shrinking max %		**5.0**	**5.0**	**4.5**	**5.0**	**4.5**	**3.3**

9.1.6 Dimensional change after disinfection

The dimensional change after disinfection was measured. Based on the results obtained concerning the impact of sterilization on the dimensional change, a single cycle of disinfection was determined to be reliable enough to evaluate the dimensional behaviour of the disinfected material.

The overall dimensional stability appears to be much better after the disinfection process than after sterilization (see Table 28). Specimen 1 C, the conductive warp knit, behaved in an unexpected manner, as the material exhibited a positive dimensional change in the row direction. This material also had the largest shrinkage (3%) in the wale direction. During sterilization, material 1 C is the most unstable, with a 9.5% shrinkage in the row direction and a 1.5% shrinkage in the wale direction. Another material with low success after disinfection was specimen 5 NK, which is a non-conductive weft knit. The shrinkage was 2.5% in the row direction and 3% in the wale direction. During sterilization, the shrinkage of specimen 5 NK was 4% in both directions. The rest of the materials exhibited shrinkage percentages in the 0-0.5% range.

The results indicate that larger dimensional changes occur when the temperature increases from the disinfection temperature of 95°C to the sterilization temperature of 121°C. After one cycle of sterilization, the shrinkage of the conductive weft knit 2 C was 4% in the row direction; after disinfection, this shrinkage was 0%. The corresponding shrinkage values in the wale direction were 3.5% after sterilization and 0.5% after disinfection. The non-conductive warp knit 7 NK had a 5.0% shrinkage in the row direction and a 0.5% shrinkage in the wale direction after sterilization. In contrast, after disinfection, the corresponding values were 0% in the row direction and 0.5% in the wale direction.

Table 28. Dimensional change after one cycle of disinfection. Three replicate specimens were measured.

		Specimen, mm				
		Reference	1.	2.	3.	Dimensional Change %
Code	**Description**	**Row**				
1 C	Warp Knitting, Silver plated PA fiber	200	203	202	-	**1.5**
2 C	Weft knitting, conductive coating	200	200	-	-	**0**
5 NK	Weft knitting	200	195	196	-	**-2.5**
7 NK	Warp Knitting	200	200	200	-	**0**
9 NB	Woven elastic band	49	49	49	49	**0**
Code	**Description**	**Wale**				
1 C	Warp Knitting, Silver plated PA fiber	200	194	197	-	**-3**
2 C	Weft knitting, conductive coating	200	199	-	-	**-0.5**
5 NK	Weft knitting	200	194	194	-	**-3**
7 NK	Warp Knitting	200	199	199	-	**-0.5**
9 NB	Woven elastic band	200	199	200	200	**-0.5**
Code	**Description**	**Weft**				
3 C	Band with silver plated PA fiber	34	34	34	34	**0**
4 C	Band with stainless steel fiber	36	36	36	36	**0**
Code	**Description**	**Warp**				
3 C	Band with silver plated PA fiber	200	200	199	199	**-0.5**
4 C	Band with stainless steel fiber	200	199	200	200	**-0.5**

Two warp knits (1 C and 7 NK) and two weft knits (2 C and 6 NK) were repellent-treated before disinfection, and the dimensional change was measured. The results indicate that the most stable materials are materials 2 C and 6 NK. The PU-coated weft knit 6 NK had a row shrinkage of 1.5% and a wale shrinkage of 4% after sterilization, whereas after repellent finishing and disinfection, the shrinkage was 0.75% in both directions.

Table 29. Knitting samples were disinfected after repellent finishing, and the dimensional change was measured.

		Specimen, mm		
	NANOTEX	**Reference**	**Disinfected**	**Dimensional Change %**
Material	**Knittings Description**	**row**		
1 C	Warp Knitting, Silver plated PA fiber	200	250	**25**
2 C	Weft knitting, conductive coating	200	200	**0**
6 NK	Weft Knitting, PU -coating	200	198.5	**-0.75**
7 NK	Warp Knitting	200	200	**0**
Material	**Knittings Description**	**wale**		
1 C	Warp Knitting, Silver plated PA fiber	200	194	**-3**
2 C	Weft knitting, conductive coating	200	199	**-0.5**
6 NK	Weft Knitting, PU -coating	200	198.5	**-0.75**
7 NK	Warp Knitting	200	220	**10**

Generally, the negative dimensional change is smaller after the finishing treatment. The most obvious reason for this difference is that the repellent finish acts as a stabilizing heat treatment for the material. The Nanotex repellent finish is cured at 140°C. However, for the warp knit specimens 1 C and 7 NK, a significant positive dimensional change was observed. Specimen 1 C exhibited a 25% elongation in the row direction, and specimen 7 NK exhibited a 10% elongation in the wale direction. The common factor is that both materials contain a large amount of elastane in their structures. The elastane content of material 1 C is 18%, and for material 7 NK, this value is 46.4%. Elastane is sensitive to heat, which weakens the elasticity. The effect of sterilization on the material elasticity is presented next, in Chapter 9.1.7.

9.1.7 Elasticity of fabrics as a function of sterilization

The elasticity of the fabric was measured using standard EN 14704; 2005, *Determination of the elasticity of fabrics. Part 1: Strip tests* [53]. This test is a strip test with a fixed load of 50 N. Five different elastic materials were chosen for the study: the conductive knits 1 C and 2 C, the non-conductive knits 5 NK and 7 NK and the elastic woven band 9 NB. Five parallel measurements were obtained for each knitted fabric material in both directions after sterilization cycles 1, 3, 5, 10, and 20. The elastic woven band 9 NB was measured only in the warp direction. The maximum elongation, the unrecovered elongation, and the range of the parallel measurements were recorded. For all specimens to be tested except material 5 NK, the elastic property was enhanced by the use of elastane (EL) fibres in the structure.

Table 30. Elongation percentage of the conductive knits 1 C, which contains a silver-plated PA fibre, and 2 C, which is a silver-coated textile, as a function of sterilization, with a fixed load of 50 N.

Load: 50 N	Max. elongation (%)				Unrecovered elongation (%)			
1 C	**Row**		**Wale**		**Row**		**Wale**	
Ster. Cycle	Median	Range	Median	Range	Median	Range	Median	Range
0	132.8	14	237	5	6	3	20	5
1	126	8.9	241	7	6	6	30	13
3	130.1	3.9	236	7	10	5	38	8
5	137	3	237	7	11	3	35	7
10	133.1	14.1	237	8	12	8	38	7
20	130.1	3.9	233	11	11	3	42	8
2 C	**Row**		**Wale**		**Row**		**Wale**	
Ster. Cycle	Median	Range	Median	Range	Median	Range	Median	Range
0	129	3	174.5	9	20	2	32	9
1	135	15	326.6	13.6	21	4	65.5	12
3	139.1	7.9	330	6.8	22	5	64	5

The warp knit 1 C (see Table 30), which contains a silver-plated PA yarn, exhibits a reduction of the maximum elongation as a function of sterilization cycles (Figure 43 and Figure 44). The decrease is 2.0% in the row direction and 1.7% in the wale direction. In contrast, the unrecovered elongation (Table 30, Figure 45 and Figure 46) increased from cycle to cycle, reaching +83% in the row direction and +110% in the wale direction after 20 sterilization cycles. A +50% increase in unrecovered elongation in the wale direction can be seen after only one cycle of sterilization, whereas in the row direction, this parameter appears to be stable. The weft knit 2 C, which has a silver-plated surface, exhibits a significantly increased maximum elongation (Figure 43 and Figure 44) and unrecovered elongation after three cycles. The maximum elongation is 7.8% in the row direction and 89% in the wale direction. The unrecovered elongation in the row direction is 10%, whereas this value is 100% in the wale direction after three cycles of sterilization. The sterilization of this material was stopped after five cycles because the material had lost its conductivity. For both specimens, the range of five parallel measurements was fairly high, and irregularity of the knit could be observed even in the reference samples. The range changes randomly as a function of sterilization cycles; thus, no linearity could be seen.

Table 31. Elongation percentage of two non-conductive knits: the weft knit 5 NK and the warp knit 7 NK.

Load: 50 N	Max. elongation (%)				Unrecovered elongation %			
5 NK	**Row**		**Wale**		**Row**		**Wale**	
Ster. Cycles	Median	Range	Median	Range	Median	Range	Median	Range
0	166	6	51.7	4.4	29	8	2	2
1	-	-	-	-	-	-	-	-
3	175	9	54.7	4.9	25	10	3	2
5	188	15	53.8	1.6	30	10	4	2
10	182	8	54.9	2.9	30	10	3	3
20	179	11	55	4.8	30	6	4	3
7 NK	**Row**		**Wale**		**Row**		**Wale**	
Ster. cycles	Median	Range	Median	Range	Median	Range	Median	Range
0	139.1	7	235	4	5	2	16	3
1	-	-	-	-	-	-	-	-
3	132	6	210	8	6	2	18	3
5	128	1.9	211	7	5	2	19	2
10	136.1	4	216	4	7	2	19	4
20	138	7.9	221	12	8	1	20	4

The weft knit 5NK (see **Table** 31, Figure 45 and Figure 46) appears to tolerate sterilization better than the other specimens, as the unrecovered elongation after 20 cycles in the row direction increased by only 3.4%, and the maximum elongation increased by 7.8% (Figure 43 and Figure 44). However, the unrecovered elongation in the row direction is quite high in the reference sample, at 29%. In the wale direction, the unrecovered elongation increased by 100%, but the absolute unrecovered elongation remains only 4% after 20 cycles. The maximum elongation increased slightly to 6.4% in the wale direction as a function of sterilization cycles. The material does not contain elastane, which explains the low original recovery (29% in the row direction) and good tolerance to sterilization.

The specimen 7 NK is a warp knit with a high elastane content of 46%. The maximum elongation in both directions decreases as a function of sterilization cycles. In the row direction, this parameter is 0.8% lower than the reference; in the wale direction, this parameter is 6% lower. The original unrecovered elongation is 5% in the row direction, but the increase after 20 cycles is 60% in the row direction and 16% in the wale direction. In addition, the growth is 25%.

In specimen 9 NB (elastic woven band) (see Table 32), there is no impact on maximum elongation as a function of sterilization cycles. In addition, the unrecovered elongation is fairly low (3%) in comparison to the other materials in the study (see Figure 45 and Figure 46), despite the increase of 300% after 20 sterilization cycles. However, the range of the maximum elongation is consistent with the results obtained for conductive knits 1 C and 2 C, with mostly large and variable ranges as a function of sterilization cycles.

Table 32. Elongation percentage of non-conductive elastic band 9 NB.

Load: 50 N	Max elongation %		Unrecovered elongation %	
9 NB	**Wale**		**Wale**	
Ster. Cycles	Median	Range	Median	Range
0	149	1.9	3	3
1	151	5	6	2
3	149	7	6	2
5	150	2	7	2
10	-	-	-	-
20	146	5	9	1

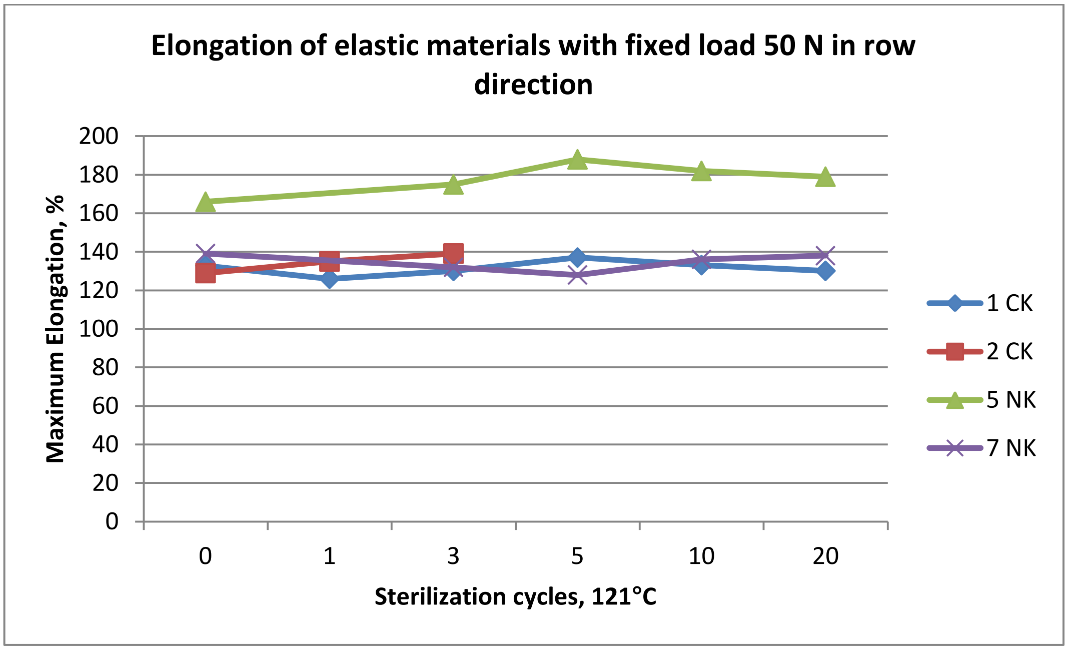

Figure 43. Maximum elongation with a fixed load of 50 N as a function of sterilization cycles; row direction.

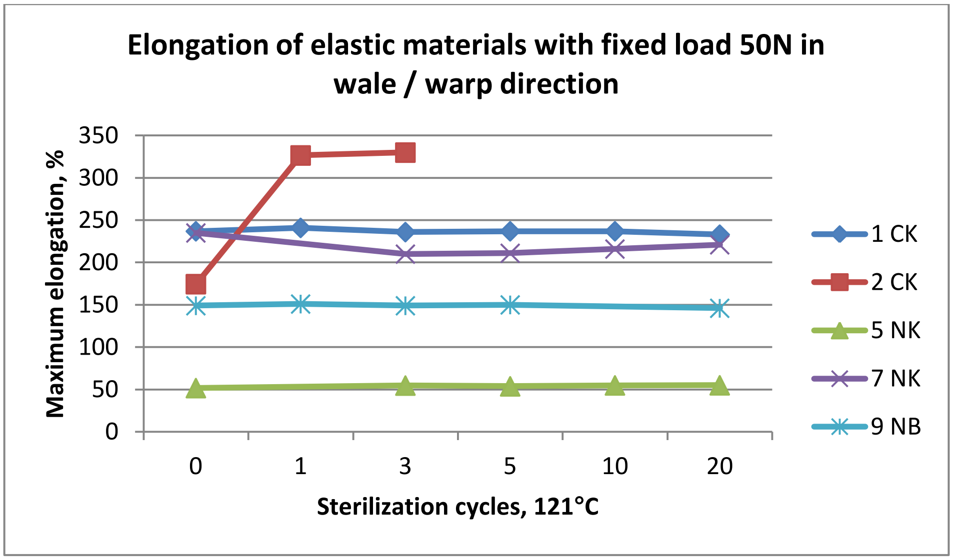

Figure 44. Maximum elongation with a fixed load of 50 N as a function of sterilization cycles; wale/warp direction.

In comparison to warp knits 7 NK and 1 C (see Table 30, Table 31, Figure 45 and Figure 46) the maximum elongation and unrecovered elongation of the references (see Table 33) are fairly similar, as is the maximum elongation after 20 cycles. However, an enormous difference can be seen after 20 sterilization cycles, as the unrecovered elongation and its growth are much greater for material 1 C than for material 7 NK (Figure 45 and Figure 46, Table 33). For specimen 5 NK in the wale direction and specimen 7 NK in both directions, the smallest ranges were observed for the parallel samples; thus, the material quality is most stable. Sample 5 NK, which is made of 100% polyester, has the highest elongation of all of the samples in the row direction but the lowest elongation of all of the samples in the wale direction.

Table 33. The growth percentage of the unrecovered elongation after 20 cycles of autoclave sterilization. *The growth is measured after three sterilization cycles.

Specimen code	Growth (%) of unrecovered elongation (row)	Growth (%) of unrecovered elongation (wale/warp)	Original unrecovered elongation % (row)	Original unrecovered elongation % (wale / warp)
1 C	83	110	6	20
2 C	10*	100*	20	32
5 NK	3,4	100	29	2
7 NK	60	25	5	16
9 NB	-	300	-	3

The maximum elongation varies significantly depending on the material, but the sterilization cycles do not have a significant effect on the maximum elongation of the materials (Figure 43 and Figure 44). However, when the growth of the unrecovered elongation after 20 cycles was evaluated (see Table 33), a high growth percentage was observed. Every elastane material exhibits cumulative growth after multiple cycles in both material directions (see Figure 45 and Figure 46).

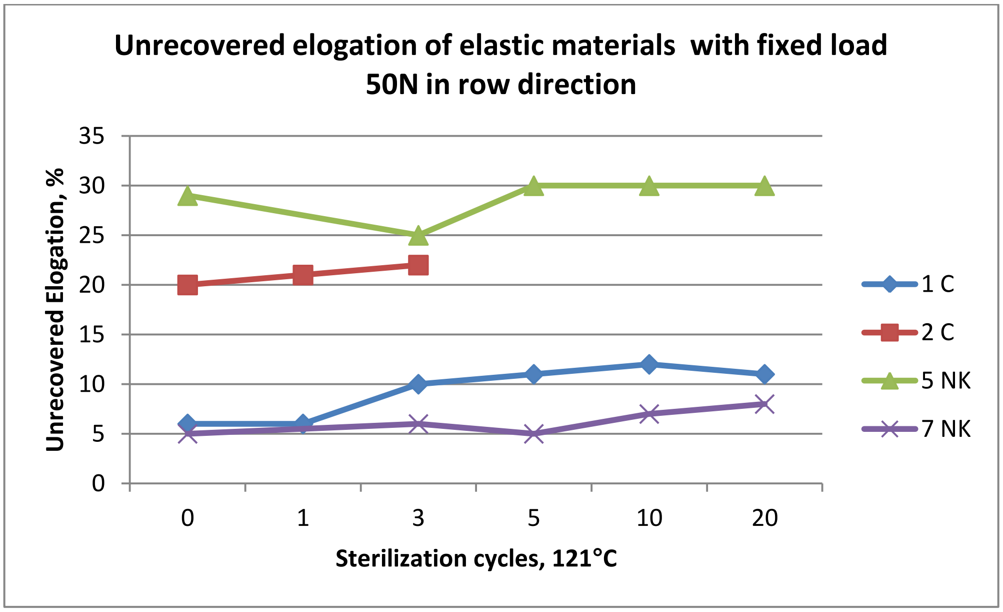

Figure 45. Unrecovered elongation as a function of sterilization cycles; row direction.

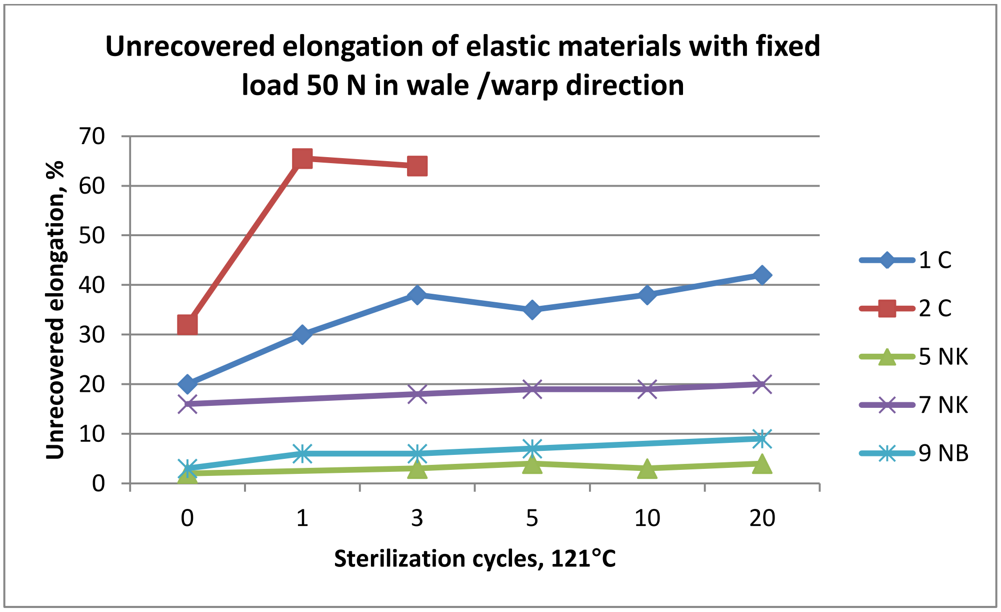

Figure 46. Unrecovered elongation as a function of sterilization cycles; wale/warp direction.

Based on theory, elastane does not tolerate heat well and loses its elasticity due to exposure. The effects of sterilization on the material can be seen more clearly when observing the unrecovered elongation of the material (Figure 46 and Figure 46). The higher the percentage, the greater is the final transformation of the material. The test results follow theory; sterilization reduces the elasticity of the fabric by negatively impacting the elastane fibre in the structure. Sample 5 NK does not contain elastane fibres in its structure, which explains the good resistance of this sample to sterilization in terms of both maximum elongation and unrecovered elongation. In the row direction, the unrecovered elongation before treatment is fairly high in comparison to other elastane-containing materials, but there is no a variation as a function of sterilization cycles.

Unrecovered elongation is the most important mechanical property of textile electronics, as this parameter indicates that the size and placement of the electrode may have changed, which might affect the measurement quality. Every material in this study exhibited a clear cumulative growth in unrecovered elongation after sterilization. This effect also weakens the visual appearance of the product, particularly in cases for which the materials in the product have different elongation behaviour. The range of the unrecovered elongation for all of the materials after 20 cycles was 4 to 64% in the wale direction and 8 to 30% in the row direction. However, elastane provides high elasticity in all directions, which is a desirable property in wearable technology. The results demonstrate that the elasticity of each material must be verified after treatment and that by choosing the correct material and structure, elastic “fast-dry sport” materials could be used for wearable technology in the medical and health care sector. In addition to the amount of elastane in the structure, the quality and number of elastane fibres and the textile construction can influence the sterilization durability of elasticity. Roughly, the smaller the original unrecovered elongation, the higher the acceptable growth percentage. Materials 7 NK and 9 NB had the lowest original unrecovered elongation, indicating that although the growth of the unrecovered elongation as a function of sterilization cycles is high, the absolute growth is not necessarily significant (see Table 33).

9.2 Repellence of the materials

Conductive knitted and woven materials (i.e., an elastic knit and an inelastic knit) were treated with two commercial repellent finishing agents: Nanotex and Nano-X. A repellent effect would be desirable for a textile electrode because such a property would contribute to the cleaning of the fabric. In hospitals, the materials must always be clean after washing, even though they do not go through the sterilization process. Two important aspects must be considered for textile electrodes: the conductivity must be maintained, and the repellent property must endure several washing cycles.

9.2.1 Surface resistance

Both finishing agents were applied to the materials, and the surface resistance was measured. The method for measuring surface resistance was performed according to AATCC Test Method 76-1995, as described in Chapter 9.1.1.

Table 34. The surface resistance of unfinished reference specimens. A and B describe the dates of measurement.

	Untreated, reference	Weft / Row			Warp / Wale			Weft / Row			Warp / Wale		
Code	**Description**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**
1 C	Warp Knitting with silver plated PA fiber	7.32	5.94	6.19	10.44	14	16.6	5.53	5.42	5.88	24.74	26.52	26.56
2 C	Silver coated weft knitting	1.49	1.5	1.59	1.25	1.16	1.09	1.39	1.07	1.19	1.7	2.05	1.81
3 C	Woven band with conductive plated PA fiber	-	-	-	3.39	3.23	3.12	-	-	-	4.05	3.77	3.72
4 C	Conductive band with stainless steel fiber	-	-	-	160	153	135	-	-	-	164.7	156.7	184.4
		Surface resistance (Ω), A						Surface resistance (Ω), B					

Nano-X chemical derivation formulations 1474, 1460, 1449, and 1452 are hydrophilic fluorine-based compounds. The surface resistance was measured using five different compounds. Formulation 1462 is a fluorine-free compound.

Table 35. The surface resistance of Nano-X-finished specimens with five different chemical recipes. The recipe frs 1462 is a unique fluorine-free compound.

	Nano-X Treated, unwashed	frs 1462			frs 1474			frs 1449			frs 1452			frs 1460		
		Row			Row			Row			Row			Row		
Code	**Material Description**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**
1 C	Warp Knitting with silver plated PA fiber	3.76	3.48	4.82	3.94	5.23	4.42	4.46	4.12	4.37	4.41	4.87	4	4.46	4.38	4.09
2 C	Silver coated weft knitting	0.64	0.77	0.7	0.54	0.78	0.94	0.78	0.85	0.87	0.89	1	1.01	0.74	0.75	0.93
		Wale			**Wale**			**Wale**			**Wale**			**Wale**		
Code	**Material Description**	**1**	**2.**	**3.**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**
1 C	Warp Knitting with silver plated PA fiber	6.32	6.47	5.54	6.14	6.75	7.06	7.04	8.47	6.66	6.42	6.44	6.42	6.38	6.66	6.11
2 C	Silver coated weft knitting	0.73	0.82	0.98	0.72	0.98	0.89	1.03	0.87	1.04	0.78	0.77	0.89	0.99	0.86	0.87
		Warp			**Warp**			**Warp**			**Warp**			**Warp**		
Code	**Material Description**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**
3 C	Woven band with conductive plated PA fiber	2.22	2.81	2.46	2.6	3.53	3.05	4.84	5.02	3.28	4.16	3.01	3.72	3	3.06	2.77
4 C	Conductive band with stainless steel fiber	1440	1530	1460	3300	2060	2600	20 000	1300	2000	3500	2100	5300	10600	26400	8600
		Surface resistance (Ω), A						**Surface resistance (Ω), B**								

No negative impact was observed after repellent Nano-X finishing for specimens 1 C, 2 C and 3 C. Specimens 1 C and 3 C contain the same conductive silver-plated fibre. Specimens

1 C, 2 C, and 3 C have an improved surface resistance in comparison to the unfinished specimen. In addition, specimen 2 C exhibits more equivalent resistance in both directions than the untreated sample. In conclusion, the Nano-X repellent finish has a positive impact on the material by decreasing the surface resistance of all silver-based conductive materials.

Specimen 4 C is the only material that cannot maintain its resistance after the repellent treatment. The surface resistance is in the range of 1.3-20.0 kΩ. The most probable cause is that the treatment technology somehow breaks the brittle steel fibres in the structure. A comparison of material 4 C before and after sterilization (see Figure 36) revealed that heat alone does not increase the resistance of specimen 4 C. However, if the mechanical stress of the treatment process is also involved, the conductivity increases and eventually breaks the conductive connections, eliminating the conductivity. However, as the finish forms a repellent layer around a single fibre, the finish might isolate the conductive fibres, increasing the electrical resistance, which could be another reason for the high resistance.

Visual inspection revealed that specimen 2 C with finish 1460 has a brownish appearance, whereas this effect cannot be detected with finishes 1462 and 1474. The appearance and hand-feel of Nano-X-treated materials are suitable for body monitoring. Nano-X does not appear to have any effect on the visual appearance or hand-feel of materials 1 C, 3 C, and 4 C.

Table 36. The surface resistance of Nanotex repellent-finished materials.

Nanotex Finish		Row resistance (Ω) B			Wale resistance (Ω), B		
Code	**Material Description**	**1.**	**2.**	**3.**	**1.**	**2.**	**3.**
1 C	Warp Knitting with silver plated PA fiber	5.22	5	6.13	17.95	18.02	20.12
2 C	Silver coated weft knitting	1.11	1.23	1.09	2.18	2.14	2.23
Code	**Material Description**	Warp resistance (Ω), A, distance 30 mm					
3 C	Woven band with conductive plated PA fiber	7.05	4.84	5.11	7.89	5.63	6.3
4 C	Conductive band with stainless steel fiber	324.24	330.4	1800	3300	6M	3M

The conductive materials were treated with the Nanotex repellent finish, and their surface resistance was measured (see Table 36). In comparison to the reference samples (Table 34), like Nano-X, Nanotex does not negatively affect the surface resistance of the knitted materials 1 C and 2 C. In contrast, the resistance might be lower than the resistance observed before the treatment. For Nanotex-treated specimens 1 C and 2 C, the silver turned slightly brown (Figure 47), and the hand-feel is as soft as before treatment. The reason for the brownish effect of the silver is unknown, but this effect has no negative impact on surface resistance, as mentioned above.

Figure 47. Slight brownish effect after Nanotex treatment for materials 1 C (left) and 2 C (right).

The repellent treatment of knitted silver-based materials (1C, 2C) has a positive effect on resistance. The clearest improvement can be seen in the wale direction of material 1 C; the same trend is also seen in the row direction. Nanotex generates a higher resistance than Nano-X, but in general, repellent treatments do not have any negative effects on the resistance of silver-based textile materials, especially because the resistance level is already very low in non-treated materials.

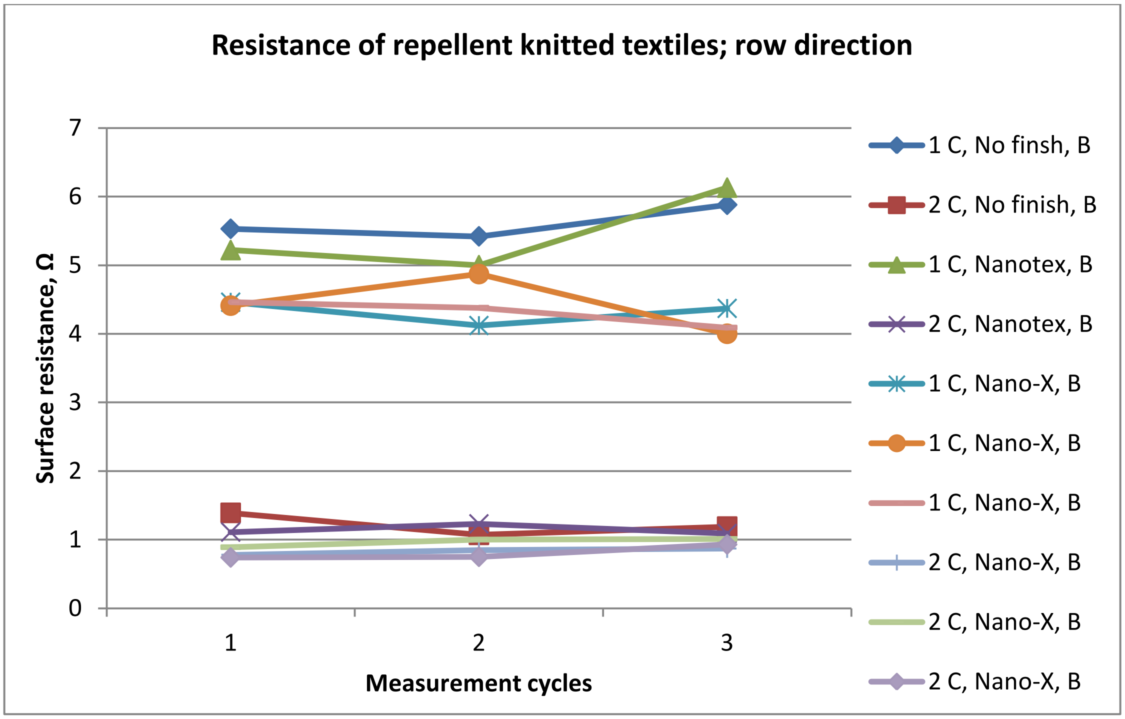

Figure 48. Surface resistance of repellent-treated and untreated knitted textiles; row direction.

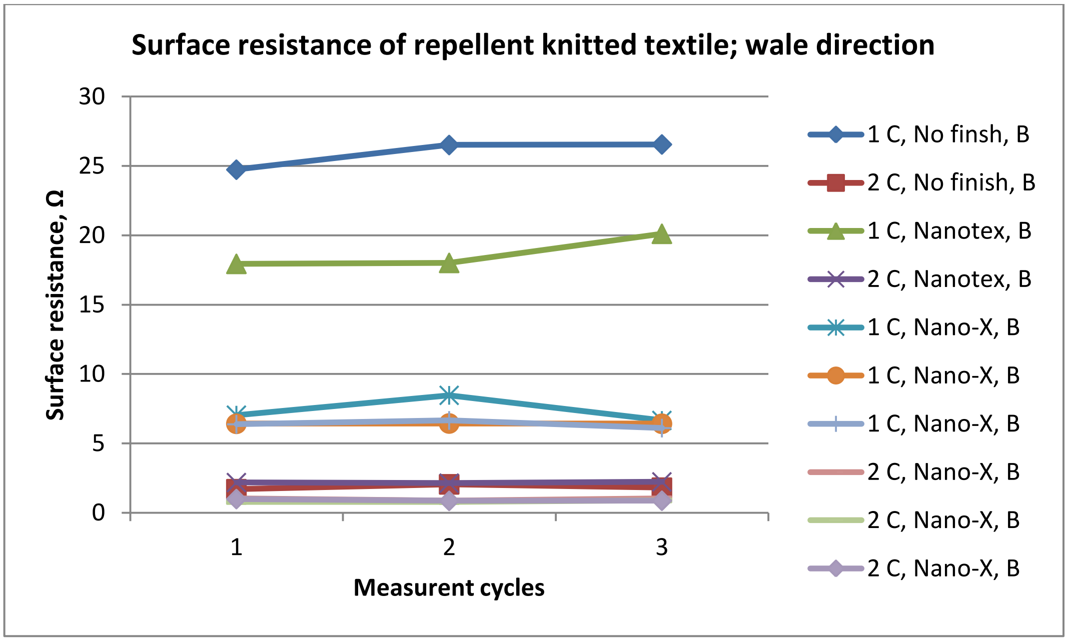

Figure 49. Surface resistance of repellent-treated and untreated knitted textiles; wale direction.

In the case of specimen 3 C, the measuring distance is only 30 mm rather than 100 mm; nevertheless, the results for specimen 3 C indicate (see Figure 50) that the conductivity increased due to the Nano-X repellent and that Nanotex has the opposite effect on conductivity. A slight increase in resistance was observed after Nanotex cycles. However, the differences in resistance are marginal due to the high conductivity of the original material. The highest resistance is still only approximately 8 Ω, indicating that the repellent treatments have no effect on the electrode application areas.

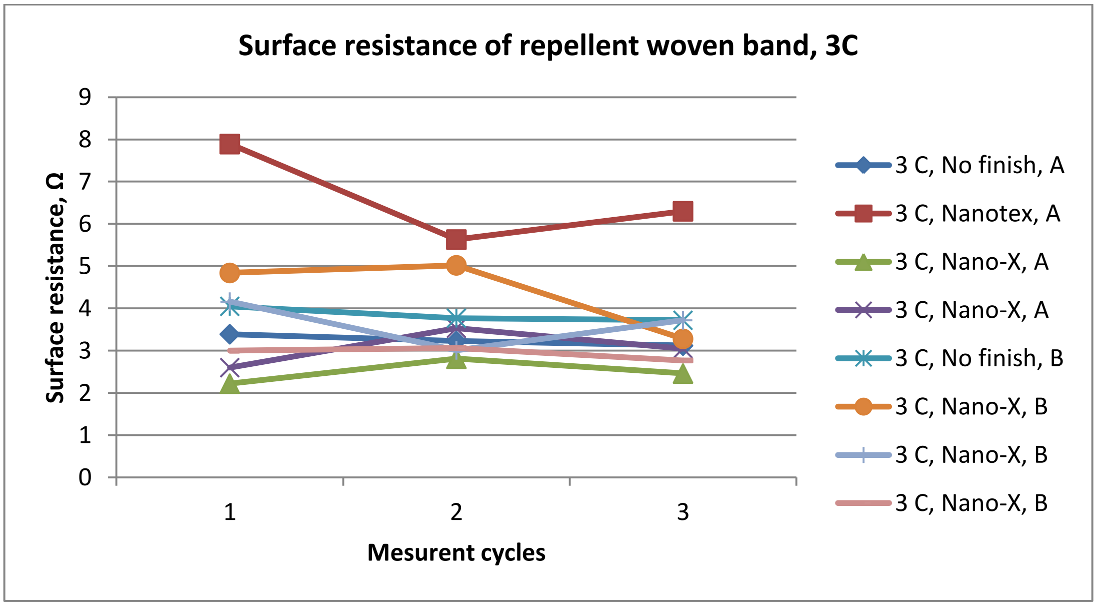

Figure 50. Surface resistance of repellent woven band 3 C.

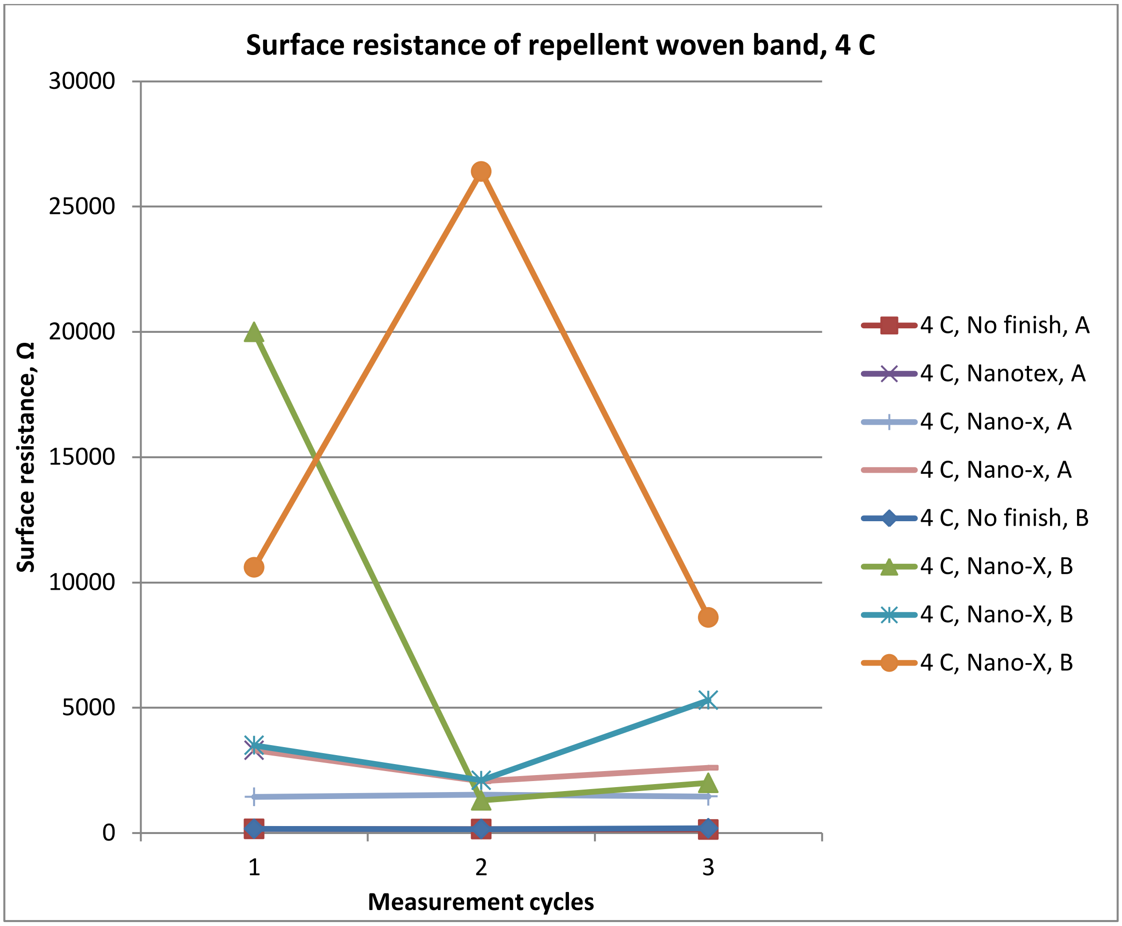

Figure 51. Surface resistance of repellent woven band 4 C.

The inconsistency of the graph (Figure 51) for material 4 C reveals the unequal conductive property of the material after the repellent treatment, as the resistance values vary remarkably between the parallel samples. The resistance is high and unequal. Specimen 4 C cannot maintain its resistance level after treatment, but the resistance increases and reaches 6 MΩ. Before treatment, the surface resistance is equal, which is an important feature for a body electrode. In general, the treatment increases the resistance so much that this treatment would not be suitable for steel fibre textile sensors to be used for body monitoring. However, understanding this behaviour in the context of steel fibres requires more testing and investigation.

9.2.2 Surface repellence after decontamination

The three most common stains in the hospital environment are sweat, blood and body lotion (see chemical content in Figure 52). The stain repellence was tested by staining the material with artificial sweat, body lotion and pork blood; after 1 h and 24 h exposure times, the material was machine-washed at 40°C. The durability of the repellence was tested by first washing the materials 20 times at 40°C and then repeating the repellent test with the same stains and exposure times. This test method attempts to imitate the reality of the hospital environment; thus, standard tests were not used in this study. The cleaning effect was only evaluated visually because this process provides an adequate inspection level for cleaned textile materials in hospitals. For those materials for which total decontamination is required, the sterilization process occurs after the cleaning process (as discussed in Chapter 5.3). The surface water repellence was tested after 20 cycles of washing, 20 cycles of sterilization and 1 cycle of disinfection by visual inspection of the water droplet shape and the rolling effect on the surface. This study concentrates on conductive electrode materials, but as a reference, two non-conductive and potential textile materials (6 NK and 7 NK) for textile electronic products for medical and health care were also chosen (Table 37).

Allergi- och Astmaförbundet – innehåller varken parfym, färgämnen eller parabener. Ingredienserna är rena, pålitliga och kontrollerade. Återställer fuktbalansen. För ansiktet och hela kroppen. pH värdet 5,5 – hudens eget.

B5 provitamin har en lång fuktgivande verkan.

INGREDIENTS: AQUA (WATER), PETROLATUM, PARAFFINUM LIQUIDUM (MINERAL OIL), CETEARYL ALCOHOL, GLYCERIN, CETEARETH-25, PANTHENOL, DISODIUM EDTA, ETHYLHEXYLGLYCERIN, PHENOXYETHANOL

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INGREDIENTS: AQUA (WATER), HYDROXYETHYL UREA, PETROLATUM, HYDROGENATED POLYDECENE, CAPRYLIC/CAPRIC TRIGLYCERIDE, PEG-100 STEARATE, GLYCERYL STEARATE, CETEARYL ALCOHOL, CHOLESTEROL, CERAMIDE NP, CERAMIDE NS, CERAMIDE EOS, CERAMIDE EOP, CERAMIDE AP, HEXANOYL PHYTOSPHINGOSINE, HEXANOYL SPHINGOSINE, BEHENIC ACID, GLYCERIN, ACRYLATES /C10-30 ALKYL ACRYLATE CROSSPOLYMER, SODIUM HYDROXIDE, CETEARETH-25, CETYL ALCOHOL, DISODIUM EDTA, ETHYLHEXYLGLYCERIN, PHENOXYETHANOL

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Figure 52. Producer and content of the body lotions used in testing.

Table 37. Table of materials used for repellence testing.

Material Code	Description	Structure	Material content
1 C	Conductive knit	Warp knit, conductive fibre	71% polyamide, 18% elastane, 11% silver-plated polyamide
2 C	Conductive knit	Weft knit, conductive coating	62% PA, 17% elastane, 21% silver coating
3 C	Conductive Band	Woven band, conductive fibre	87% polyester, 13% silver-plated PA
4 C	Conductive Band	Woven band, conductive fibre	polyester, stainless steel
6 NK	PU-coated Knit	Weft knit, coated face surface	60% polyurethane, 40% polyester
7 NK	Knit	Warp knit	53.6% polyamide, 46.4% elastane/spandex

The visual evaluation of repellence was performed by applying a water droplet to the substrate. The rolling effect was then tested by angling the material 10-20 degrees. In the case of material 1 C (Figure 53 and Figure 54), both treatments appear to have a repellent effect after 20 cycles of washing and 20 cycles of sterilization. The same good results were also achieved with specimen 2 C, although specimen 2 C did not retain any conductive property after 20 cycles of sterilization (see Figure 55).

Figure 53. Specimen 1 C with untreated, Nanotex-treated and unwashed, 20 x washed, and 20 x sterilized surfaces.

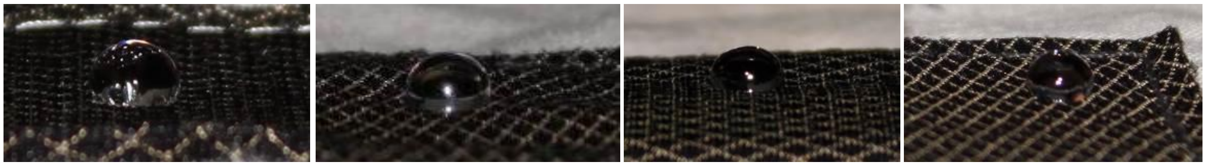

Figure 54. Specimen 1 C with untreated, 20 x washed 1474, 20 x sterilized 1474, and 1 x disinfected 1474 surfaces.

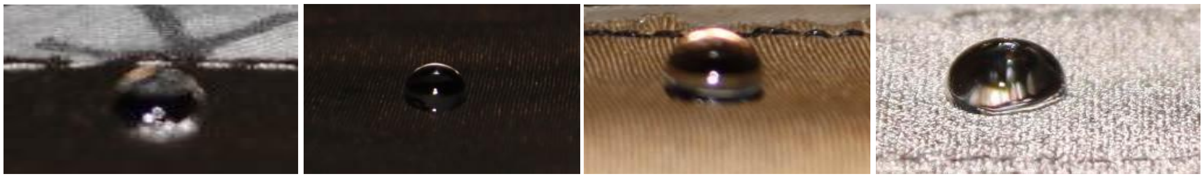

Figure 55. Specimen 2 C with untreated, Nanotex-treated and unwashed, 20 cycles washed, and 20 cycles sterilized surfaces.

The repellent effect can be easily recognized from woven bands 3 C and 4 C. Poor surface tension of the droplet on the untreated substrate is apparent (Figure 56, Figure 57, Figure 58 and Figure 59). The repellence treatment provides a durable effect, especially for specimen 3 C. The results obtained for specimen 4C show the impact of the substrate structure on the repellent property. As specimen 4 C does not tolerate washing and the steel fibres break during that process, washing also weakens the repellence effect.

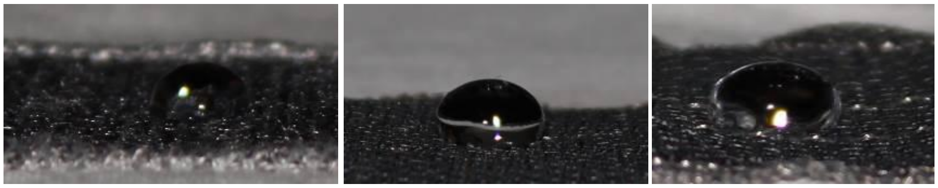

Figure 56. Specimen 3 C with untreated, Nano-X treated and unwashed, and 20 x washed surfaces.

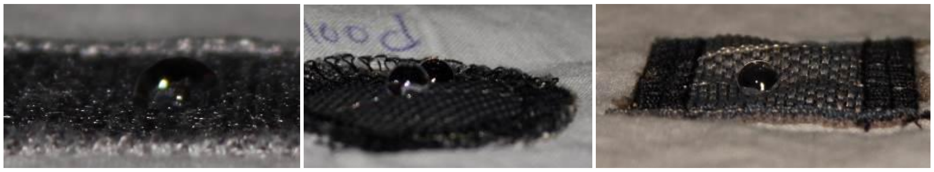

Figure 57. Specimen 3 C with untreated, Nanotex 20 x washed, and 20 x sterilized surfaces.

Figure 58. Specimen 4 C with untreated, Nano-X-treated and unwashed, 20 cycles washed, and 1 x disinfected surfaces.

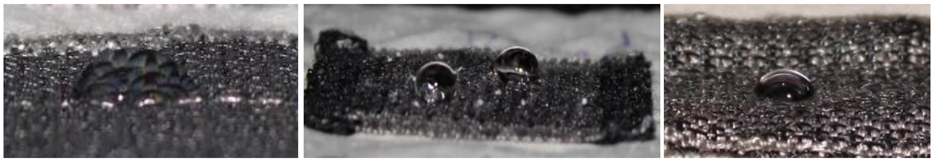

Figure 59. Specimen 4 C with untreated, Nanotex 20 x washed, and 20 x sterilized surfaces.

The PU-coated textile did not show any repellent effect after Nanotex or Nano-X treatment, indicating that this textile is not a suitable substrate for the treatment. PU is naturally resistant to water but does not have a strong enough repellent effect to cause the droplet to roll away when the material is inclined. The contact degree of the droplet is always small (see Figure 60)

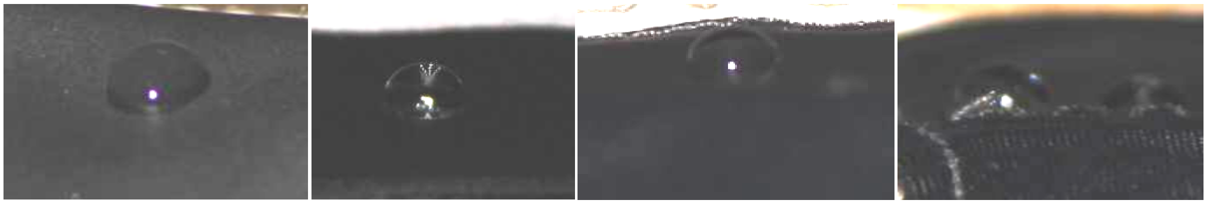

Figure 60. Specimen 6 NK with untreated, Nanotex-treated, 20 x washed, and 20 x sterilized surfaces.

Specimen 7 NK generated good results with Nanotex treatment after washing and after sterilization (see Figure 61). Nano-X treatments are not able to maintain repellence very well after washing, but after sterilization, the property is slightly improved (Figure 62) The cause of this difference might be the mechanical stress caused by the washing of the fabric.

Figure 61. Specimen 7 NK with untreated, Nanotex-treated and unwashed, 20 x washed, and 20 x sterilized surfaces.

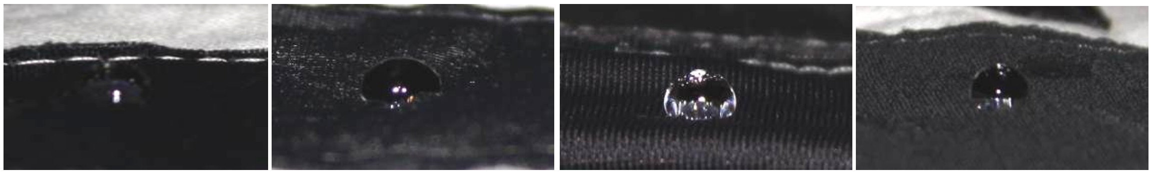

Figure 62. Specimen 7 NK with untreated, Nano-X 1474-treated and 20 x washed, 20 x sterilized, and 1 x disinfected surfaces.

The silver-containing knitted materials had the best results with respect to repellence; even before the repellent treatment, these materials exhibited a similar property. The repellent treatment appears to be even more suitable for smooth knitted surfaces than for woven structures, which have a more 3D surface. The abrasion durability during the cleaning or decontamination process appears to affect the repellence capability; upwards-tilted broken fibres destroy the droplet surface tension.

The cleaning capability of repellent materials in low-temperature washes (30°C) was also studied. All six materials in the repellent study were repellent-treated with Nanotex and with three different Nano–X recipes: 1460, 1463 and 1474. Each repellent-finished specimen was first laundered 20 times at 40°C, and dirt was applied: pork blood, an artificial sweat and a body lotion. The exposure time was 24 hours. The specimens were laundered at 30°C. The evaluation criteria required that the surface must be visually clean. All of the specimens (i.e., 1 C, 3 C, 4 C, 6 NK, and 7 NK) were clean from dirt, except for specimen 2 C, which is a silver-plated weft knit for which some staining was observed. With Nanotex repellent-treated specimen 2 C, some sweat stains remained on the surface. For Nano–X-treated specimen 2 C, blood and sweat stains remained on the material surface with all derivations of the recipe. The body lotion cleaned easily from every repellent-finished material at 30°C. As a result of this test, it can be stated that lower temperatures (30°C rather than 40°C or 60°C) could be used to clean common textile stains in hospitals.

9.3 Statistical analysis of results

Statistical analysis of the results is made by statistical testing. The testing measures the compatibility of the hypothesis given and the results of the observed population. As a result of statistical testing the hypothesis is rejected or not depending on these experimental circumstances.

There are many methods to be used for testing. Most methods like analysis of variance (ANOVA), regression analysis or T-test are suitable only for Gaussian distributed population. This normal distribution of population means that both sides of average values contain equal amount of samples. The analysis of variance is the basic method and is applicable generally in many scientific areas. It tests if the average values of two or multiple groups are statistically significantly different from each other. [184] [185] [188]

The ANOVA –test can be used if:

1. *The samples are independent of each other and they have been chosen randomly.*
2. *The samples have been taken from population which is distributed normally.*
3. *In the population, the variances of the groups are equal.*

One-way analysis of variance, the simplest form of the analysis, has only one variable to be explained. The purpose is to analyze the differences between group means and the means of observations within each group. [184] The aim of the one-way analysis of variance is to identify the variation between the groups, which differs from random variation. The total variance is divided to variance between the groups and the internal variance the group. If the variance between the different groups are equal to the variance within the group an independent variable has not probably caused the variation. The bigger the variance between the groups in comparison to variance within the group is, the more probably is that the independent variable has caused the variation. [186] [189]

In one-way ANOVA (analysis of variance) test method the hypothesis are:

Null Hypothesis (H_0): The average values of the data groups are equal.

Alternative hypothesis (H_1): At least between two groups have a significant difference in values

If there are two independent variables to be explained, two-way analysis of the variance can be applied. The prerequisites of use are the same as with one-way analysis of variance. [186] The analysis of variance is useful in comparing three or more means for statistical significance. The null hypothesis is that the averages are equal. If the null hypothesis is rejected it means that the variance between groups is larger than the variance within the group. [184] [186] [188]

The significance level is the probability that test values determined from observations are located to rejected area, if the null hypothesis (H_0) is valid. [185] Selection of the significance level determines the probability that the researcher rejects the null hypothesis even if it is truth. It is a risk level for the deduction error. By the help of statistical deduction one can never be sure that if the hypothesis is true or not, but the question is, in which probability the researcher is ready the reject the hypothesis. Generally in scientific research the risk levels to be used are 0.05 (5%) or 0.01 (1%). Thus the risk level 5% means that the result of the study is valid with probability of 95% and having the 5% probability for error. In case where the random sample size is 100, in 95 cases the null hypothesis would be rejected as in 5 cases it would stay valid. [187]

The assumption of hypothesis test is that null hypothesis is true. The test is based on p-value: the probability to get at least the same deviation of averages as within the population. In general, if the p-value is below 5%, null hypothesis is rejected, otherwise null hypothesis stays valid. The calculated p-value is presented as the argument of deduction. [186] P-value presents the probability for deduction error as a result for every statistical test. If the p-values is under 0.05 the result is “nearly significant”, if it is under the 0.01 it is said to be statistically “significant” and if it is under 0.001 it is “extremely significant”. [187]

In this study the statistical analysing is made by using one-way ANOVA in every case except where the abrasion resistance and sterilization cycle are compared to surface resistance of the textile, the two-way ANOVA is used (Chapter 9.3.4). The chosen significance level is 0.05 (5%). The testing of hypotheses is presented in next chapters 9.3.1- 9.3.6.

Due to the high variance in certain test results the ANOVA accepted some of the hypothesis claiming that the impact on resistance by a few of the treatments was not significant, although it was clearly demonstrated by the test results. The graphics demonstrate this in earlier chapters. In some cases the functionality of the electrode was not even compromised by slight resistance change, although this development could also be seen by the test results. Therefore, the validity of the tests and the reliability of the test results have been maintained in this research.

9.3.1 Analysis of the surface resistance after sterilization

Null hypothesis (H_0) $_=$ The sterilization cycle treatments (1,3,5,10,20 cycles) have no significant effect on textile surface resistance.

The significance level or risk level is $\alpha = 0.05$.

Table 38. ANOVA: The surface resistance after sterilization cycles. The result is classified: $^{*)}$ = nearly significant, $^{**)}$ = significant, $^{***)}$ = extremely significant

Surface resistance after sterilization cycles (121°C)		**P-Value**		**α=0.05**
Material code	**Material description**	**Row**	**Wale**	**Null hypothesis**
1C	Warp knitting with silver plated Polyamide fiber	9.75961E-07	6.48231E-05	Rejected***
2C	Silver coated weft knitting	0.01302943	0.010472346	Rejected*
3C	Woven band with silver plated polyamide fiber	-	0.243736895	Accepted
4C	Woven band with stainless steel fiber	-	0.005537803	Rejected**
Surface resistance after sterilization cycles (134°C)		**Row**	**Wale**	**Null hypothesis**
3C	Woven band with silver plated polyamide fiber	-	0.062866051	Accepted
4C	Woven band with stainless steel fiber	-	0.99984981	Accepted

The statistical analysis follows the figures (the growing trend as a function of the sterilization cycles) and deductions (see Figure 35 and Figure 36); the variation is clear and even big between the groups except of material 3 C. Null hypotheses are accepted in higher sterilization temperature, where only 5 sterilization cycles were made to the textile, thus the variation between the groups cannot be seen yet.

9.3.2 Analysis of the surface resistance after disinfection

Null hypothesis (H_0) = The disinfection cycle of the textile surface has no significant effect on textile surface resistance.

The significance level or risk level is α = 0.05.

Table 39 ANOVA: The surface resistance after disinfection cycle. The result is classified: $^{*)}$ = nearly significant, $^{**)}$ = significant, $^{***)}$ = extremely significant

Surface resistance after disinfection cycle (95°C)		**P-Value**		**α=0.05**
Material code	**Material description**	**Row**	**Wale / Warp**	**Null hypothesis**
1C	Warp knitting with silver plated Polyamide fiber	0.0090	0.0020	Rejected**
2C	Silver coated weft knitting	4.68206E-05	9.23841E-07	Rejected***
3C	Woven band with silver plated polyamide fiber	-	0.180720562	Accepted
4C	Woven band with stainless steel fiber	-	0.184059599	Accepted

The variances between the groups and within the groups for 4C are very high. Therefore the statistical analyses accept the hypothesis. But actually the test results demonstrate that the surface resistance increases after disinfection cycle. See Table 15 and Table 16. Surface resistance for details. The statistical analysis of the materials 1 C, 2 C and 3 C instead follow the figures and deductions presented in chapter 9.1.2.

9.3.3 Analysis of the surface resistance after cleaning

Null hypothesis H_{0} = The cleaning (20 cycles) of the textile surface has no significant effect on textile surface resistance.

The significance level or risk level is α = 0.05. One-way ANOVA –method is used.

Table 40 ANOVA: The surface resistance after cleaning 20 cycles the result is classified: *) = nearly significant, **) = significant, *) = extremely significant**

Surface resistance after cleaning 20 cycles (40 °C)		**P-Value**	**α=0.05**
Material code	**Material description**	**Row / Warp**	**Null hypothesis**
1C	Warp knitting with silver plated Polyamide fiber	6.64095E-05	Rejected***
2C	Silver coated weft knitting	0.00018	Rejected***
3C	Woven band with silver plated polyamide fiber	0.38572	Accepted
4C	Woven band with stainless steel fiber	0.15810	Accepted

The surface resistance for 4C increases clearly after 20 cleaning cycles as demonstrated in Table 17, despite of ANOVA test as the variance of means between and within the groups are very high. As well as in cases of 1 C and 2 C the variance within the groups is high, whereas 3 C has a small variance within and between the groups.

9.3.4 Analysis of the surface resistance after abrasion

Null hypothesis H_0 for 3 C = The sterilization cycles (1,3,5,10,20) and abrasion cycles (0, 1000, 2000, 4000) of the textile have not the significant effect on textile surface resistance.

Null hypothesis H_0 for 4 C = The sterilization cycles (1,3,5,10,20) and abrasion cycles (0, 1000, 2000, 4000, 6000, 10 000) of the textile have not the significant effect on textile surface resistance.

The significance level or risk level is α = 0.05. Two-way repeated ANOVA –method is used for 4 C and One-way Anova for 3 C.

Table 41. ANOVA: The surface resistance after sterilization cycles and abrasion cycles. The result is classified: *) = nearly significant, **) = significant, *) = extremely significant**

3C	**Woven band with silver plated polyamide fiber**	**Weft**	**Null hypothesis**	**Warp**	**Null hypothesis**
	Surface resistance after abrasion cycles	0.032145	Rejected*	0.001066	Rejected*
4C	**Woven band with stainless steel fiber**	**Weft**	**Null hypothesis**	**Warp**	**Null hypothesis**
	Surface resistance after abrasion cycles	0.047053	Rejected*	0.596275	Accepted
	Surface resistance after sterilization	0.041167	Rejected*	0.073949	Accepted

The variation between the groups is big which can also be seen from Figure 40 and Figure 41. The lowest variation is after sterilization thus it can be stated that sterilization has no effect on abrasion resistance of the material. However the statistical analysis rejects the hypothesis for the surface resistance after sterilization, which is controversial to figures 40 and 41. and accepts the null hypothesis for 4 C after abrasion cycles, even if clear trend of the growth as a function of the abrasion cycles can be seen. The variance within the group is big but between the group small thus it accepts hypothesis, which is not meaning that resistance has not changed after treatment. This is shown in graphs and tables in Chapter 9.1.4.

9.3.5 Analysis of the materials elasticity after sterilization

Null hypothesis, H_0 for 1 C, 2 C: The sterilization cycles (0, 1, 3) have no significant effect on textile unrecovered elongation.

Null hypothesis, H_0 for 5 NK, 7 NK, 9 NB: The sterilization cycles (0, 3, 5, 10, 20) have no significant effect on textile unrecovered elongation

The significance level or risk level is α = 0.05. One-way ANOVA –method is used.

Table 42. ANOVA: The unrecovered elongation after sterilization cycles. The result is classified: *) = nearly significant, **) = significant, *) = extremely significant**

	P-value			
Unrecovered elongation	**Row**	**Null hypothesis**	**Wale**	**Null hypothesis**
1C, 2 C	0.000712011	Rejected***	0.017068848	Rejected*
5NK, 7 NK, 9 NB	4.11292E-08	Rejected***	2.08754E-06	Rejected**

The statistical analysis follows the results of deduction; the unrecovered elongation grows as a function of the sterilization cycles. Null hypothesis is rejected in every case as the variance between groups is bigger than variance inside the group.

9.3.6 Analysis of the surface resistance after repellent treatments

Null hypothesis H_0 = The repellent treatments on the textile surface have no significant effect on textile surface resistance.

The significance level or risk level is α = 0.05. One-way ANOVA –method is used.

Table 43 ANOVA: The surface resistance after the repellent treatments. The result is classified: *) = nearly significant, **) = significant, *) = extremely significant**

Surface resistance after repellent treatments		P-Value			α=0.05
Material code	**Material description**	**Row**	**Null hypothesis**	**Wale / Warp**	**Null hypothesis**
1C	Warp knitting with silver plated Polyamide fiber	0.042006668	Rejected*	1.76248E-07	Rejected***
2C	Silver coated weft knitting	2.31416E-06	Rejected***	2.55933E-06	Rejected***
3C	Woven band with silver plated polyamide fiber	-	-	0.001596378	Rejected**
4C	Woven band with stainless steel fiber	-	-	0.001717641	Rejected**

In every case the statistical testing results that the null hypothesis is rejected. However, as the values of each are under the observation (see Table 34 and Table 35), the difference between the groups are not significant as the material suitability for body monitoring is discussed, except of material 4 C where the growth of the resistance after repellent treatment is significant. In some cases the surface resistance seems to even decrease after the treatment.

10 Findings

The findings concerning the research questions are presented in this chapter. The study is divided into three main sections: the sterilization, disinfection and stain repellence of textile electrode materials. Primarily, the focus is on the surface electrical resistance of conductive materials after the above-mentioned treatments, with a secondary focus on abrasion resistance and dimensional change evaluations.

10.1 Textile electrode decontamination

The textile electrodes used in this study were produced by using conductive metal fibres or metal coating on textiles. Metal fibres have a higher conductivity than conductive polymers or carbon fibres and better durability against the high temperatures used in sterilization, disinfection and repellent treatments. Based on literature studies and interviews with professionals, the autoclave hot steam sterilization method was selected for this study. This method is commonly used, non-chemical, cost-effective and a fairly rapid sterilization process for textiles. Standard testing methods were used when relevant. The aim of testing was to simulate the real end-use of materials in the medical and health care environment. The answers to the research questions are presented below.

Q1: What is the effect of the autoclave textile sterilization process on the surface resistance of conductive textile materials?

Autoclave sterilization treatment was performed for all four (4) conductive textiles. The surface resistance was measured after 1, 3, 5, 10 and 20 treatment cycles. Comparisons with a reference sample were also made.

The fabrication technology of a textile electrode affects its endurance after sterilization. This study indicates that the best way to fabricate textile electrodes to be sterilized is to use highly conductive and durable silver-plated conventional fibres in the structure. The most commonly studied and commercialized fibres have a similar construction as the fibres used in this study: silver-plated PA fibres. These fibres are widely used in sportswear applications. [173] In addition, 100% steel fibres endure the sterilization process but cannot tolerate the mechanical stress caused by washing or disinfection without losing conductivity. Thus, the application areas of these fibres in medical and health care are very limited because the material must be visibly clean before sterilization; therefore, the material must be washed before sterilization. The silver-coated weft knit 2 C lost its conductivity after five cycles. The coating was made using the chemical vapour deposition method. The hot steam process caused the delamination of the coating. No mechanical abrasion is caused by the process; thus, the bonding force between the polymer and the conductive coating under high temperature and pressure is the most important factor.

Q2: What is the effect of the autoclave textile sterilization process on the abrasion resistance of conductivity?

The effect of abrasion was studied only for woven band structures because the silver-coated weft failed to exhibit conductive durability during the sterilization process. The secondary reason for studying only woven structures was that the standard Martindale tester (EN ISO 12927-2) [188] that is used for woven materials is a rougher method than a standard pilling test for knitted materials. This research question was approached with samples 3 C and 4 C. The surface resistance of the materials was measured after 1,000, 2,000, 4,000, 6,000, and 10,000 abrasion cycles. The woven bands contained silver-plated PA in specimen 3 C and 100% stainless steel fibres in specimen 4 C. The sterilization cycles had no effect on the abrasion resistance of the fabric. As the base fibres and woven structures of these materials were practically the same, the textile electrode with stainless steel has a much lower abrasion resistance. The stainless steel fibre–based woven structure 4 C had an abrasion resistance of only 4,000 cycles, meaning that after that point, the electrode is no longer conductive. In contrast, the silver-plated PA fibre–based structure 3 C still had a resistance as low as 1.14-4.70 Ω/30 mm after 10,000 cycles.

Q3: Does the autoclave textile sterilization process have an effect on the elastic properties of knitted textiles?

The elasticity of the material is an important property in wearable solutions, as comfort in use is desirable. In most body-monitoring measurements, the electrodes must have good contact with the skin. The best way to achieve this contact is to use elastic materials in electrodes and in electrode platforms, such as garments. Low elongation negatively affects usability and comfort in body-worn, vital function-monitoring applications, and high values for the unrecovered elongation imply that the materials are unfit for use in garments, particularly for electrodes, as such values indicate that the contact size has changed, which might negatively affect the measurement quality.

The results indicate that all elastane-containing elastic materials have high elongation in the range of 150-250% in both directions. Except for material 2 C, the sterilization treatment does not affect this parameter, indicating that these materials can maintain their maximum elongation despite sterilization cycles. However, the unrecovered elongation exhibited a clear increase as a function of sterilization cycles for all elastane-containing materials. The unrecovered elongation of elastane-containing materials was in the range of 2-32% before sterilization. After sterilization, this value was 4-64% in the wale direction and 8-30% in the row direction. However, the growth of the unrecovered elongation after 20 cycles was in the range of 25%-300%, except for material 2 C, which was not sterilized for 20 cycles like the other samples because it lost its conductivity after three cycles. Overall, the non-conductive specimens 7 NK and 9 NB succeeded better than the conductive specimens 1 C and 2 C in elasticity testing, which is obviously due to the different elongation properties of the silver-plated PA fibre and the silver coating in comparison to non-conductive structures, which contain only elastane and PA in their structures. In contrast, sample 5 NK had an original unrecovered elongation as high as 29% in the row direction. However, after 20 cycles, this value had grown only 3.4% to 30%. In the wale direction, this value grew from 2 to 4%. Specimen 5 NK had no elastane fibres in its structure, which explains its good resistance to sterilization. The results indicate that in accordance with theory, elastane cannot tolerate the sterilization process and that elastane-containing materials lose their elasticity as a function of sterilization treatments, as indicated by the unrecovered elongation.

In addition to the amount of elastane in the structure, the quality and number of elastane fibres and the textile construction impact the sterilization durability of elasticity, especially for unrecovered elongation. Roughly, the smaller the original unrecovered elongation, the higher the acceptable growth percentage. Samples 7 NK and 9 NB had the lowest original unrecovered elongation, meaning that although the growth of the unrecovered elongation as a function of sterilization cycles is high, the absolute growth is not necessarily significant. The use of elastane in the structure to improve bi-elasticity is highly beneficial. This study demonstrates that the elasticity of each material must be verified after treatment and that by choosing the correct material and structure, elastic “fast-dry sport” materials can be used for wearable technology in the medical and health care sector.

Q4: Is there a dimensional change in autoclave-sterilized textiles?

The dimensional change of material leads to a transformation of the product's visual appearance and a change in the textile electrode's dimensions. The dimensional change might even shift the location of the electrodes. The dimensional changes must be known because the electrode shape, size and placement are essential for obtaining reliable measurements from the body. In addition, the dimensional change of all of the other materials in the product must be equal in order to manage the dimensional change and maintain the quality of the body measurement and the visual appearance of the product.

A negative dimensional change (i.e., shrinkage) of all knitted materials can be observed. However, the shrinkage does not appear to be cumulative, and the greatest change occurred after one treatment cycle, whether the treatment was sterilization, disinfection or repellent finish. The common factor for all of these treatments is the exposure of the material to heat during the treatment process.

Weft knits appear to have a more equal shrinkage percentage in both directions than warp knits. However, the warp knits appear to be much more stable in the wale direction, as the shrinkage is only 0.5-1.5%; in the row direction, this value is in the range of 5.0-9.5%. It can be concluded that the conductive element itself has no impact on the dimensional change of the textile material.

The dimensional change of a material depends on the fibre materials, the textile structures and the production technology of the fibres and textiles, as well as the finishing treatments. The exact dimensional change of the textile material in each case is difficult to predict. Thus, material stability during the sterilization process and the disinfection process can be achieved with heat treatment at the sterilization temperature before product assembly.

Two commercial heart-monitoring products were sterilized during the study. The Polar Wearlink+ consists of textile electrodes (3C), and another monitoring strap has the moulded TPU electrodes attached by lamination onto an elastic textile belt. This structure is used commercially by many heart rate-monitoring brands. Wearlink+ showed rare symmetrical dimensional changes in all of the included materials; thus, these materials together are suited for sterilization. However, the overall shrinkage is in the range of 3.7-6.5% and is so significant that it must be considered in research and development, as it may impact the body measurement quality. The TPU electrode belt structure is not suitable for sterilization because the treatment destroys the appearance of the product by changing the shape and dimensions of the electrode.

Q5: Does the autoclave textile sterilization process have visual or hand-feel impacts on the textile?

Sterilization does not appear to change the hand-feel of the material, but a yellowing and browning effect were observed in some specimens. Yellowing was observed for non-conductive materials, and browning was observed for conductive knits.

Q6: What is the impact of the laundering and sterilization process on the water/stain-repellent property?

Every laundering cycle wears out the textile by decreasing its properties. Thus, finishing treatments, such as water/stain-repellent treatments, are also removed from the textile during washing. However, 20 cycles of machine washing or sterilization do not significantly worsen the repellent properties of the textile. Knitted conductive materials succeeded especially well in comparison to non-conductive knits or woven band varieties. The textile structure of a woven band is more three-dimensional. In addition, the abrasion caused by washing and disinfection breaks the fibres, which weakens the surface tension of the droplets on the substrate.

Q7: What is the effect of the textile disinfection process on the surface resistance of the textile?

Disinfection is the process by which textile washing and decontamination are accomplished simultaneously. The decontamination level is lower than that achieved with sterilization, but depending on the application’s end use, disinfection might be a sufficient decontamination method in the medical and health care environment.

The conductive materials were disinfected, and the surface resistance was measured. The steel fibre-based woven band lost its conductivity completely after one disinfection cycle, whereas the silver-based woven band managed well. As the steel fibre can tolerate the sterilization process, the mechanical stress caused by the disinfection process likely breaks the fibres. Washing chemicals might also increase the resistance level. The steel fibre-based textile had the same negative reaction after 20 cycles of ordinary laundry washing at 40°C.

Q8: Is a dimensional change of the textile electrode caused by the disinfection process?

Textile body-monitoring systems consist of many materials. Disinfection and sterilization are always applied to the whole product; thus, the dimensional changes of various materials must be known. The overall dimensional stability appears to be much better after the disinfection process than after sterilization. The results indicate that larger dimensional changes occur when the temperature increases from the disinfection temperature of 95°C to the sterilization temperature of 121°C. After one cycle of sterilization, the conductive weft knit 2 C had a 4% shrinkage in the row direction and a 3.5% shrinkage in the wale direction. After disinfection, the row direction shrinkage was 0%, and the wale shrinkage was 0.5%. The non-conductive warp knit 7 NK had a 5.0% shrinkage in the row direction and a 0.5% shrinkage in the wale direction after sterilization. In contrast, after disinfection, the corresponding values were 0% in the row direction and 0.5% in the wale direction.

10.2 Stain repellence of textile electrodes

The stain-repellent finish improves the cleaning effectiveness of the substrate, resulting in a so-called self-cleaning surface; the need for laundry washing is consequently decreased. This finish is a chemical treatment that is cured on the textile substrate by heat. The textile must be clean before the sterilization process. Thus, it is a real advantage if the textile can be cleaned easily and well to remove hard stains by means of a water/stain-repellent treatment.

Q9: What is the effect of a nanoscale water/stain-repellent treatment on the surface resistance of conductive textile materials?

Fluorocarbons, which are based on C6 technology, are suitable finishes for textile electrodes, as they have no negative effect on the surface resistance. The Nano-X repellent finish even positively impacts the material by decreasing the surface resistance of all silver-based conductive materials. Some minor differences in resistance were observed between different repellent finish recipes; thus, the suitability of a finish for each substrate must be ensured. However, stainless steel is unable to maintain its conductivity after the finishing process.

Q10: How well is the repellent treatment adapted to uncoated/non-laminated knitted textiles?

The water/stain-repellent treatment makes the material surface hydrophobic, which forces water droplets into a near-spherical shape that minimizes contact with the surface. The drop rolls off easily and carries away dirt, leaving the surface dry and clean. A water/stain-repellent treatment is typically used for outdoor textiles, for which the woven textile structure is often laminated or coated on the reverse side. For this reason, the water/stain-repellent treatment of uncoated/non-laminated knit structures has not been examined widely.

When the textile is used in contact with skin in hospitals, the health care environment or wellness and sports applications, specific stains, such as blood, sweat and body lotion, are encountered. The liquid stains pork blood and artificial sweat were used to identify the repellent effect of the treated fabric. The hydrophobic properties were examined by visual observation of the liquid drop shape and the rolling effect when tilting/angling the material. The repellent treatment also works well for ordinary knitted textiles, which do not have any reverse-side waterproof coating. Variations in the chemical content of the repellent finish were found to impact the repellent properties. In addition, the applied agent and technology and the substrate affect the results.

Q11: Does the water repellent treatment improve the cleaning effectiveness of textiles against blood, sweat, and body lotion?

A possible improvement in the stain release property after laundry washing could not be clearly identified because after a 24 h exposure, both repellent-treated and untreated reference materials were visibly clean after laundry washing at 40°C. Only the silver-coated conductive knit exhibited a better cleaning effect after the repellent finish treatment. The test results showed that on the repellent-treated surface, dried blood forms a layer that delaminates easily without leaving any stain on the substrate.

Hydrophobic water-repellent treatment presumably improves the removal of stains from textiles. PA and PES textiles are commonly recommended to be cleaned by washing at 40°C. Washing at 30°C saves energy, which makes the use of this method more ecologically sound. Conventional hospital textiles and cloths should withstand 250 cycles of laundry washing. [28] The specimens were machine-washed at 40°C for 20 cycles, and pork blood, artificial sweat and body lotion were then applied to the substrate. After 24 h of exposure, the specimens were washed at 30°C. No dirt particles could be seen by visual observation.

11 Conclusions

In this chapter, a summary of the research is presented first. The second part of this chapter evaluates the validity and reliability of the study. This section provides evidence based on the results of the study and previous research in this area and proposes ideas for future research.

11.1 Summary

This section summarizes the whole study, from the background and motivation to the testing and the findings of the study.

11.1.1 Background

In 2014, the wearable electronics business was estimated to be worth over $14 billion, and this figure is predicted to increase to over $70 billion by the end of 2024. The dominant application area will remain the healthcare sector, meaning medical care, fitness and wellness. The aim of wearable textile electronic applications is to add, expand and improve the properties of the original textile applications. At the same time, these applications should not worsen the primary and already available properties of textiles or clothing. It is also estimated that approximately 25 billion wearable devices will be in operation by 2020. The development of this area is now moving in a direction to make wearable technology a part of everyone’s daily life. Textile electronics-based body monitoring systems have already been a feature of everyday life in sports, fitness and wellness for over a decade.

In body monitoring, textile electrodes, in other words conductive textiles, can be used to measure bio-signals, such as ECG, pulse, heart rate, stress level, sleep quality, physical pain, EMG of muscle rate and balance, body motion, EEG of brain function and vitality level, respiration rate and frequency, body composition, including fat content and fluid balance, which are obtained via bioimpedance measurement, temperature and conductivity of the skin and blood oxygen saturation. In addition to electrodes, conductive fibres and textiles can be applied to signal and power transfer, to heating elements, antennas, detectors and actuators, and to EMI-shielding and static dissipation control. One rapidly increasing field in healthcare applications is wearable home care monitoring solutions, which are combined with mobile health applications (mHealth). The most reasonable solution for positioning the body-measuring unit for vital functions is naturally the shirt or the sleeve. The garment must fit perfectly for technical reasons. The electrodes must find their correct places without any adjustment or special knowledge of measurement on the part of the user. In addition to the hospital environment, this feature enables the use of such products in home monitoring systems (e.g., for chronic or at-risk patients or for rehabilitation after surgery or injury). To prevent and follow the progress of chronic diseases, long-term monitoring of the patients' vital functions is necessary, and the use of textile electrodes embedded within clothing is an obvious and relevant solution. However, health is in many ways a personal and sensitive issue. Therefore, especially for long-term body monitoring, clothing is a natural, comfortable and invisible platform for electronics. Common plastic electrodes are not meant for continuous monitoring due to the risk of skin irritation and the required expertise for placing the electrode. Long-term monitoring can be used for pre-emptive actions or to detect changes or follow patient health after surgery or injury. The possibility of home monitoring would lead to shorter hospital stays for patients, which naturally appeals to both hospital personnel and the patient.

Textile body-monitoring systems are more expensive than plastic systems; thus, textile systems must be reusable. In the hospital environment, intelligent clothing must endure all of the same treatments and procedures as standard hospital textiles, especially disinfection and sterilization. The lack of information concerning how the textile electrode should be sterilized and how the electrode will react electrically and mechanically to this treatment is at least one barrier to the commercialisation of products for the medical sector. Before sterilization, the textile must be cleaned properly, primarily to remove blood and sweat. Improved easy-clean properties would consequently be desirable, and antibacterial materials are also desirable. Second, hospital textiles are made primarily from cotton and other natural fibres, but the use of man-made fibres in a body-monitoring garment is more reasonable. The aim is long-term body monitoring, which affects the garment system. The garment must be like any other technical underwear; the garment must fit well, be comfortable, be elastic, be breathable, have easy-care properties and endure several cycles of laundry washing. Researchers and hospitals need and desire to make commercial applications available as soon as possible. This research will be one necessary step in that direction, as the sterilization, disinfection and easy-care properties of textile electronics used for body-monitoring applications in hospitals and medical research will be more fully understood.

As the disadvantages or weaknesses of textile electronics are being discussed, the mechanical durability, cleaning effectiveness and manufacturing cost of these systems in comparison to plastic systems must also be considered. Laundry washing is conceived as the best method for cleaning textiles. However, every washing cycle wears out the textile to some extent and affects the mechanical features and appearance of the textile, thus shortening its useful lifetime. By improving the stain-repellent and cleaning properties of the textile, the need for washing can be reduced, and a less damaging, lower temperature program can be used for laundering. These factors not only save energy but also lengthen the lifetime of textile electronics. A longer lifetime reduces the cost per instance of use. On the other hand, the cost per piece for disposable plastic sensors might be low in comparison to textile electrodes, but disposable sensors produce much more waste, thus increasing the cost per piece. The longer the lifetime of a textile electrode, the less waste is produced in comparison to disposables. As these systems are complex, they must be reusable and recyclable from user to user. A vital function shirt would also be especially useful for medical research in which large user groups wear the shirt for a long period of time. Invisibility and comfort are key factors in such cases. Exchange between users requires the disinfection or sterilization of the product. In addition, sterilized exchangeable measuring systems would reduce the need for the storage space and ensure the availability of the correct size.

Research results can be extrapolated to many other textile electronics components, such as conductors, antennas, heat elements, switchers and detectors, in addition to electrodes, because all of these components can be achieved with the same elements: conventional textile fibres combined with conductive fibres or coatings. In the end, the whole system, which is a combination of these elements, must be sterilized. The obvious application areas for body monitoring using textile electrodes are hospitals, health care centres and medical research centres. In those environments, it is essential that products can be sterilized before and after use and that products are easy to clean to remove secretions of the human body. Easy-clean properties are necessary features in every application in which textile sensors are not covered or integrated invisibly.

The research objectives of this study were:

- *To determine the most efficient sterilization method for elastic knit electrodes and woven fabric electrodes*
- *To investigate how textile electrodes endure the disinfection process*
- *To identify a safe fluid-repellent treatment for elastic and inelastic conductive textiles in order to make them easy-to-clean*

11.1.2 Performing the study

The aim of the material selection process was to choose materials that are approved as suitable for body-measuring purposes, meaning that the products are commercially available via mass production or the electrical suitability of the products has been proved using laboratory testing. The textile electrode materials that are applicable to sports and well-being applications have properties and requirements similar to healthcare applications for long-term body monitoring and represent an obvious starting point for the selection of textile electrodes. During the selection of water- and stain-repellent finishing treatments, the emphasis was on commercially available products that do not contain PFOA or PFOS in their composition and on the sensitivity of applying the technology to textile fibres. The selection of the autoclave as the sterilization method was based on the frequency with which this process is used in the health care sector, as well as on the reliability, simplicity, durability and safety of the process. Based on the literature related to material properties and user experiences with commercial electrodes, as well as a study of sterilization methods, silver and steel were chosen for making the textiles conductive. Silver is even more suitable for health care environments because this material provides a wide range of applications due to its durability, high electrical conductivity, and antibacterial properties. Steel was chosen as a reference, as this material is the second-best option for a conductive element in the structure. Thus, other metals, conductive polymers and carbon fibres were excluded. Softness, elasticity and moisture management are desired features for textile materials to be used in body-monitoring sensors in contact with skin. These features add comfort during long-term use. Two of the conductive materials were knits; the warp knit (1 C) contains the same silver-plated PA fibre as woven band 3 C, and the other knit is a silver-coated weft knit (2 C). The woven bands (3 C, 4 C) that were made for this study have the same woven structure; one of these materials contains silver-plated PA fibres, and the other material contains steel fibres. In addition, three non-conductive knits (5 NK, 6 NK, 7 NK) and two woven elastic bands (8 NB, 9 NB) were included in the study. Decontamination treatments are applied to a product rather than to a single fabric; thus, two heart-monitoring straps were also used for testing: the Suunto Comfort Belt and the Wearlink+. Materials 1 C and 3 C are used commercially for heart rate-monitoring in sports. Some researchers have also managed to use these devices to measure the bioimpedance of the body.

The material properties to be tested were chosen according to the end use of the electrode. As the user environment is the medical and health care sector and the application is wearable, the properties to be measured provide essential information for researchers, designers and producers of wearable textile technology. The principle of testing was that the method correlates with the actual use of the material or product. Thus, in cases for which the standard test is not the most appropriate test, an alternative testing method was used. The electrical properties were studied using a point-to-point-method, by measuring the material electric surface resistance after 1, 3, 5, 10, and 20 sterilization cycles, after one cycle of disinfection, after 20 cycles of laundry washing, and after two different repellent treatments. The surface resistance was also measured for some repellent-treated materials after sterilization, disinfection and washing. In addition, conductivity was observed as a function of abrasion cycles. The surface resistance of the materials was measured after 1,000, 2,000, 4,000, 6,000 and 10,000 abrasion cycles with standard wool fabric. Hand-feel and appearance observations after the treatments were made using subjective visual evaluation. The impacts of the treatment processes on the materials' mechanical properties were studied by measuring dimensional changes after sterilization, disinfection and repellent treatment. The elastic properties were studied only after sterilization. The function of the repellent finish on the substrate was observed visually; a water droplet was applied onto the substrate, and the form and the rolling effect of the droplet were evaluated. The cleaning effectiveness of repellent fabric was studied by staining the substrate with pork blood, artificial sweat and body lotion. After an exposure time of 24 hours, the specimens were washed by ordinary 40°C laundry washing.

11.1.3 Outcomes

As a summary of the findings, all of the silver-based textile electrodes were durable during normal laundry washing at 40°C. However, if silver is coated onto textile 2 C, the material loses its conductivity during the sterilization process after only a few treatments, indicating that the bond is not strong enough in this material and begins to delaminate. The visual evaluation revealed yellowing and stains on the fabric (2 C) surface. Sterilization and disinfection are suitable for woven and knitted structures when silver-plated PA fibre is used. Stainless steel fibres do not survive either ordinary laundry washing or the disinfection process, indicating that the durability of these materials for sterilization is not sufficient for medical applications in which washing is needed as a pre-treatment for sterilization. The abrasion resistance is much lower than for silver fibre-based materials; the material completely loses its conductivity after 4,000 cycles of abrasion. The hand-feel is hard after 1,000 abrasion cycles and is too hard to be used in skin contact. The largest negative dimensional change was observed after a single sterilization cycle; after additional cycles, the material becomes much more stable, indicating that dimensional stability can be gained by pre-treatment of the material before its use in an application. The different dimensional changes in each material that are caused by the treatments must be considered when designing textile electronics for the medical environment. Some elastane knits exhibited positive dimensional changes only after disinfection. Depending on the material, in some cases, disinfection might even be more stressful than sterilization due to the combination of heat, mechanical stress, abrasion and stretching. The elastane content provides elasticity (recovered elongation) to a textile in all directions. The cumulative and significant growth post-sterilization can be seen as unrecovered elongation in elasticity testing. The maximum elongation was maintained as a function of sterilization cycles, except for one material: the silver-coated PA weft knit 2 C. Overall, the most stable materials with respect to dimensional changes and elasticity were the woven material 9 NB and the warp knit 7 NK, which are both non-conductive samples. Different elongation behaviour of metal and polymer fibres might have an effect on mechanical stability after treatments. The repellent finishes do not have a negative impact on the surface resistance of silver-based materials. The Nano-X finish even appears to improve the conductivity of all silver-based materials. The stain-repellent finish can also be applied to knitted structures to improve the cleaning process. All materials except for 2 C were cleaned well to remove dirt, pork blood, artificial sweat and body lotion after 20 cycles of laundering.

In conclusion, silver-plated PA fibres in a knitted or woven structure with an additional repellent treatment generate a highly conductive and durable solution for wearable electronics in medical and health care. Based on the results of this study, the use of woven bands as electrodes is recommended rather than knitted material due to their superior dimensional stability. However, knitted electrodes have superior softness and flexibility; thus, compromises must be reached when using textile electrodes in wearable technology. The use of a conductive coating on knitted materials is not the best choice for wearables because the cracking of coatings during use is a relatively obvious problem. All of the materials used in this study (i.e., woven and knitted, elastic and inelastic, coated and non–coated) showed clear shrinkage during the sterilization process; however, a single heat treatment makes the materials much more stable. To avoid negative material dimensional changes after whole-product decontamination, pre-treatment of the material with heat before use is highly recommended. For this reason, man-made fibres are more useful for medical products that need to be sterilized or disinfected than natural fibres, which tend to continue shrinking after every temperature-driven treatment. Elastane fibre can be used to improve the material recovery of elongation in both directions for knitted textiles, but when designing the material, the unrecovered elongation as a function of sterilization must be verified. The variation in the unrecovered elongation might be extremely high, and success depends on the raw materials and textile structures. Steel fibres and textiles cannot tolerate mechanical stress caused by disinfection, washing, or repellent treatment. Textiles with silver coating cannot tolerate sterilization electrically or mechanically.

11.2 Validity and reliability

The decontamination of textiles is a necessary process in hospitals. Depending on the end use, decontamination is performed by washing, disinfection or sterilization. The endurance of textile electrodes was tested in all of those processes using standard decontamination devices and procedures that are common in the hospital environment. The electrode provides the best signal quality if there is a low and consistent surface resistance. Thus, the surface resistance of the electrode was measured after the treatments using a conventional standardized point-to-point method. In addition, strength in use and a constant size and shape are essential for a good textile electrode, which is why the abrasion resistance, the dimensional changes and the elastic properties after decontamination processes were studied using standard methods. The textile electrodes used in this study have been studied previously and are in use in commercial sports applications for heart rate-monitoring. The textile materials used for sports have desirable properties similar to those of materials to be used in the medical sector: elasticity, comfort, vapour permeability, fast-drying, etc. It is predicted that wearable technology is an emergent technology, especially in medical and health care applications. Knowledge about textile electrodes in the context of decontamination processes is a relevant question. Textile repellent finishes are widely used in outdoor garments. Improved cleaning during the decontamination process would be an absolute benefit. The repellent chemicals used in this study are commercially available and were applied to the substrate by the chemical producer on their premises. The textile electrode consists of a base yarn and a conductive component in the fibre or on textile as a coating. Thus, the results can be utilized widely in many kinds of applications that use silver or steel as conductive components in the textile structure. In addition to body monitoring, the conductive textiles can be applied as heating panels, as electrical conductors, for data transfer, as switchers, as antennas and in EDS and EMI-shielding.

The textile has an anisotropic character and might exhibit variations in electrical and mechanical properties in the same material. The textile manufacturing process is complicated, with many variables. In textile-testing procedures, the use of a number of replicate samples is essential. In this study, every measurement included three to five replicate measurements or samples. The manufacturer of the finishing agent applied the repellent treatment to the substrate on their premises, meaning that the reference pieces are not exactly the same specimen before treatment. All measurements used for the analysis were measured on the same date and in the same place; thus, the measurement conditions were constant. However, the study was performed *in vitro*; *in vivo* measurement would ensure the function of a sterilized heart rate-monitoring system that contains multiple materials in its structure.

The repeatability of the study is fairly simple because the testing methods were based on standards; when an alternative test method was used, it has been described clearly. The main aim during testing was to imitate the use of an electrode use in practice, in a real hospital environment; thus, some test methods differed from the standard method.

11.3 Ideas for future research

The results and findings of this study are based on experimental investigation. In the future, the fundamental mechanisms of the identified textile material effects should also be studied and determined. As an example, the reason that the steel fibre-based electrode (4C) could not withstand the disinfection or repellent treatments should be demonstrated. Are the steel fibres really broken? In addition, the Nanotex (fluorocarbon-based) repellent treatment caused colour changes in silver-plated PA by making the material brownish. However, no colour changes were observed with another fluorocarbon treatment (Nano–X). What is the reason for this behaviour?

In this study, the decontamination of textiles by sterilization was limited to 20 cycles, and the silver-plated PA fibre-based textile electrode performed well. However, in hospitals, some textiles are washed up to 250 times during their lifetime. What would be the lifetime of a textile electrode that includes other conductive materials, such as CNTs and ICPs, which were excluded from this study? Sterilization is naturally performed for the whole product or device, not for a single material, such as an electrode. What if the smart wearable system contains other embedded electronic components? Are those components able to be sterilized? Which method should be used? Only the electrode and electrode systems of heart rate-monitoring straps were measured in the laboratory. The function of the whole product after sterilization should be evaluated.

The stain and water repellence of a material would be a beneficial property in medical and health care applications. The treatment forms a layer around a single fibre in the textile. The aim of the study was to investigate how the water-repellent treatment affects the electrical properties of textile electrodes, and results indicate that this treatment does not have a negative impact on the surface resistance of the fabric; in contrast, such treatment might even improve the resistance. An interesting question is whether the surface conductivity and durability against mechanical stress, such as washing, disinfection and sterilization, can really be improved by repellence treatment.

Previous research indicates that skin-contact body-monitoring sensors need a moisturising layer between the skin and the electrode. Thus, the next aspect to be studied is how well the repellent electrode works in real body monitoring by measuring R-R intervals via ECG, as an example. In theory, sweat from the body could even form a better contact between the skin and the repellent electrode than ordinary absorbed water, which might lead to improved signal quality.

Hospitals are currently using primarily disposable electrodes, meaning more waste in comparison to textile electrodes. However, it would be interesting to perform a Life Cycle Assessment (LCA) study by determining the carbon footprint for both electrode types in terms of manufacturing, use and recycling. The textile must be washed, disinfected or sterilized depending on the end use in the hospital, which uses energy and water. Is there significant variation between the different conductive fibres, such as ICPs, CNTs and silver? In theory, the repellent finish should reduce the need for washing, and the same cleaning effect should be possible at lower temperatures. Thus, is there a positive effect of repellent treatment on environmental impact during use? The repellent textile has less water in its structure after washing, which should lead to faster drying of the material; how much faster would drying be? Would this property be beneficial in the hospital environment? Antibacterial materials are an emergent research area. If these materials are applied to textile electrodes, how will they affect the electrical properties of the electrode and how will they maintain their properties during medical and health care textile processes? Would it be possible to avoid or reduce the need for the textile disinfection process? The safety of finishing chemicals that are in contact with skin should also be studied and verified.

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Tampereen teknillinen yliopisto
PL 527
33101 Tampere

Tampere University of Technology
P.O.B. 527
FI-33101 Tampere, Finland

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