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Textile sensors for healthcare

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6.1 Introduction

The term 'smart textiles' is derived from intelligent or smart materials. The concept 'smart material' was defined for the first time in Japan in 1989. The first textile material that, in retroaction, was labelled as a 'smart textile' was silk thread having a shape memory effect (by analogy with the better known 'shape memory alloys'). The discovery of shape memory materials in the 1960s and intelligent polymeric gels in the 1970s were, however, generally accepted as the birth of real smart materials. It was not before the late 1990s that intelligent materials were introduced in textiles. It is a new type of product that offers the same potential and interest as technical textiles.

Smart textiles can be described as textiles that are able *to sense* stimuli from the environment, *to react* to them and *adapt* to them by integration of functionalities in the textile structure. The stimulus as well as the response can have an electrical, thermal, chemical, magnetic or other origin. The extent of intelligence can be divided in three subgroups [Zhang, 2001]:

- passive smart textiles can only sense the environment, they are *sensors*
- active smart textiles can sense the stimuli from the environment and also react to them, besides the sensor function, they also have an *actuator* function
- finally, very smart textiles take a step further, having the gift to adapt their behaviour to the circumstances.

So two components need to be present in the textile structure in order to bear the full mark of smart textiles; a sensor and an actuator, possibly completed with a processing unit which drives the actuator on the basis of the signals from the sensor.

6.2 Smart textiles

6.2.1 Why textiles?

Intelligence is currently embedded in daily objects like watches. However, textiles show several advantages as clothes and are unique in several aspects. They are extremely versatile in products as well as processes. The building stones of the textile material are *fibres* or *filaments*. Innumerable combinations of these source materials result in a whole range of textile materials. Fibres are available in a very broad range of materials, single or combined: natural or synthetic, strong, elastic, biocompatible, biodegradable, solid or porous, optical or electro-conductive. They can have varying lengths, fineness, cross-sectional shape, surface roughness, etc. Fibres of various types can be arranged at random or in a strictly organized way in yarns or fabric structures. From this, even three-dimensional structures can be constructed. After treatments allow the creation of very special properties such as a hydrophilic/hydrophobic nature, antimicrobial, selective permeability etc. Textile materials are able to combine advanced multifunctionality with traditional textile properties.

Clothes are our own personal house. They can be made to measure, with a perfect fit and high level of comfort. Clothes make contact with a considerable part of the body. They are a common material to all of us, in nearly all of our activities. They look nice and attractive, the design and look being adapted to the actual consumer group. We all know how to use them. Maintaining textiles is a daily practice; house as well as industrial laundry are well developed. Last but not least, textiles and clothes can be produced on fast and productive machinery at reasonable cost. These characteristics open up a number of applications that were not possible before, especially in the area of monitoring and treatment, such as:

- long-term or permanent contact without skin irritation
- home applications
- applications for children in a discrete and carefree way
- applications for the elderly; discretion, comfort and aesthetics are important.

It is clear that the intelligent character of the textile material can be introduced at different levels. It can occur at fibre level, a coating can be applied, other threads can be added to the textile material, it is even possible to closely connect completely independent appliances with the textile. Full success however will be achieved only when the sensors and all related components are entirely converted into 100% textile materials. This is a big challenge because, apart from technical considerations, concepts, materials, structures and treatments must focus on the appropriateness for use in or as a textile material. This includes criteria like flexibility, water (laundry) resistance, durability against deformation, radiation, etc.

As for real devices, ultimately most signals are being transformed into electric ones. Electroconductive materials are consequently of utmost importance with respect to intelligent textiles.

6.2.2 Functions of smart textiles

The functionalities of smart textiles can be classified in five groups: sensoring, data processing, actuation, communication and energy. At the moment, most progress has been achieved in the area of sensoring. Many parameters can be measured:

- temperature
- biopotentials: cardiogram, myographs, encephalographs
- acoustic: heart, lungs, digestion, joints
- ultrasound: blood flow
- biological, chemical
- motion: respiration, motion
- pressure: blood
- radiation: IR, spectroscopy
- odour, sweat
- mechanical skin parameters
- electric (skin) parameters.

Some of these parameters are well known, like cardiogram and temperature. Nevertheless, permanent monitoring also opens up new perspectives for these traditional parameters too. Indeed, today evaluation is usually based on standards for global population groups. Permanent monitoring supported by self-learning devices will allow the set up of personal profiles for each individual, so that conditions deviating from normal can be traced an soon as possible. Also diagnosis can be a lot more accurate.

Apart from the actual measuring devices data processing is a key feature in this respect. These types of data are new. They are numerous with multiple complex interrelationships and are time dependent. New self-learning techniques will be required. The introduction of such an approach will be slow, because no evidence of the benefits are available at this moment. 'We don't measure because we don't know the meaning, we don't know the meaning because we don't measure.'

Actuation is another aspect. Identification of problems makes sense only when followed by an adequate reaction. This reaction can consist of reporting or calling for help, but also drug supply and physical treatment. A huge challenge in this respect is the development of high-performance muscle-like materials.

Mechanisms of actuation are:

- chemical: drug supply, skin care
- mechanical: artificial muscles, massage, pressure bandages
- optical: UV irradiation
- thermal: heating/cooling
- electrical: electrotherapy.

Some materials are available today, many need to be developed.

Data processing is a limiting factor as well. The optimal reaction needed strongly depends on the individual. Here again self-learning dynamic steering and control algorithms are required. A smart suit should be a stand-alone unit, not requiring any wired connections for communication and energy supply. These are the topics of other chapters in this book. The textile systems should also resist the normal conditions of use: multiple deformation (extension, bending, compression, etc.) as well as laundry (water, elevated temperatures, detergents, enzymes). This will be discussed in the sections that follow.

6.3 Conductive fibres and fibrous materials

Sensors can be divided into active and passive sensors [Carpi, 2005]. Passive sensors require an external power source, while active sensors are able to convert the input energy (elastic, thermal, etc.) into a measurable difference of potential. Conductive fibres and structures made from them are passive sensors according to this definition. Active sensors are, for instance, based on piezo-electric effects. Electro-conductive fibres are used on a large scale for a variety of functions: antistatic applications, electromagnetic shielding (EMI), electronic applications, infra-red absorption, protective clothing in explosive areas, etc. Their use as a sensor, however, is a rather new field of application.

6.3.1 Fibrous sensors

Heart signals are one of the basic parameters in health care. The heart is basically a muscle that is controlled by the brain though electric impulses. The body being a vessel filled with an electrolyte solution, these signals can be detected in all of its parts. Small metal plates are commonly used to capture these signals while instruments analyse the results, extracting the required parameters such as frequency, phases, etc. Conductive fibres are being used as passive sensors for monitoring biopotential, mainly heart rate. Several research projects have been carried out on this topic (Table 6.1) [Van Langenhove 2003, Smartex, Medes, Georgia Tech]. The feasibility has clearly been demonstrated, although the sensor needs to be optimized and practical problems need to be solved.

Table 6.1 Textile electrodes for measuring heart rate

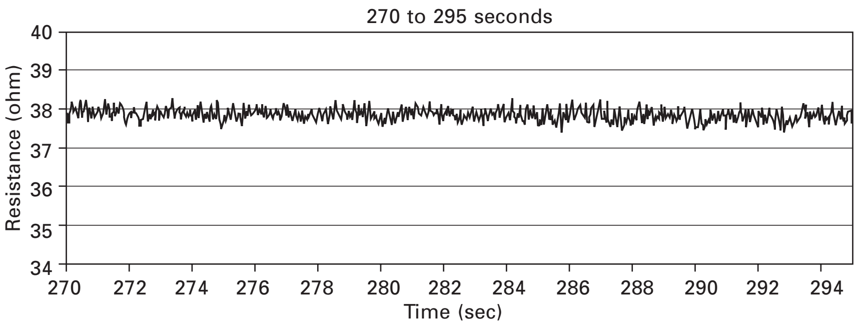
Name	Application	Level of transformation
Smartex	Health care	Woven/knitted textile sensors
Intellitex	Children's health care	Knitted textile structures, textile antenna
VTAM	Health care	Partly textile structures
Wearable motherboard	Health care, military	Partly textile structures

As will be explained in the following sections, several mechanisms cause the resistance to go up or down due to extension of the material. This is called a piezo-resistive effect. The global effect of these combined mechanisms depends on the type of material and its structures. The piezo-resistive effect makes the textile a versatile tool for a broad range of sensor applications where extension is a crucial parameter. This is the case, for instance, for respiration measurements (expansion/contraction of the chest), all kinds of movements (dance, sports, etc.) as well as volumetric changes like volume of inhaled air. For applications as a passive sensor like electrocardiogram electrodes, the conductivity of the textile materials should be as consistent as possible, the piezo-resistive effect being a source of error. This can be achieved by careful selection of fibre type and proper design of the textile structure. The resistance of such a structure is constant when, for instance, a cyclic extension is applied as a simulation of the breathing movement (Fig. 6.1).

6.3.2 Textile strain sensors

Conductive fibres show piezo-resistive effects. By extending the fibres, fibre cross-section is reduced causing the electrical resistance to go up. Secondly the fibre length increases again causing resistance to increase. As a result resistance becomes an indicator of its extension. However, the level of this type of piezo-electric effect is insufficient to allow accurate readings. Additional piezo-electric effects have to be achieved using other principles. Such principles, for instance, exploit mechanisms of conductivity as described by Mattes [2003]. Later, the inclusion of conductive nanoparticles can generate piezo-electric effects, as conductivity will depend on the distance between the nanoparticles [Devaux 2005]. This distance will change due to fibre extension.

Arranging conductive fibres in a structure like textiles generates a material with a complex behaviour in terms of conductivity. Fibre length being limited, the electron flow has to be transferred from one fibre to the other, from one yarn to the other. Contact resistance between fibres plays a determining role here. Contact resistance usually is quite high as compared to the intrinsic



6.1 Textile structure without piezo-resistive effect.

conductivity of the material. Any rearrangement of the fibres in a textile may affect the global conductivity of the structure. It changes the contact resistance, number of contact points, path followed by the current and hence the piezo-resistive effect. Consequently, any process that alters fibre arrangement also has an impact on the sensor properties. It makes the long-term behaviour of such sensors not obvious.

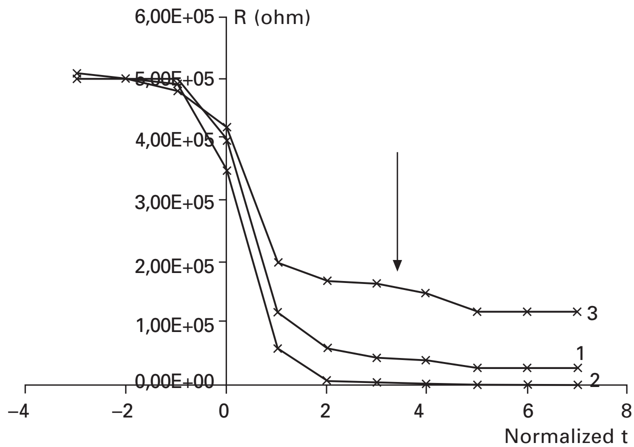
6.3.3 Smart textile structures

The applications mentioned in the previous sections are rather straightforward. Careful design of the textile structure enables more advanced sensing properties. The basic mechanisms are related to conductivity, changes in conductivity, currents or change in currents and so on. Any mechanism that affects such parameters is useful. Electrochemistry is an extremely important discipline in this respect.

A set of fibres, yarns or fabrics separated one way or another can be considered as a double electrode system. Such a system can be used to detect water. The presence of water will be reflected in an increase of conductivity between the two electrodes. This increase will be bigger when the water contains salt. The reaction of such a textile sensor (i.e. resistance as a function of time), consisting of two conductive yarns, on wetting with water with different salt concentrations is given in Fig. 6.2 [Priniotakis 2005].

Impedance spectroscopy has been used to optimize the test set up

A double set of such a two-electrode system of which one is coated with a coating that is impermeable to the salt but permeable to water allows separation of the quantity of water and the quantity of salt. Coatings with selective permeability can be the base for a huge number of specific sensors, for instance, for a qualitative as well as quantitative analysis of sweat. This basic method is suited for a huge range of applications, provided the right



6.2 Decrease of electrical resistance due to wetting of the sensor (1 and 2 high salt content, 3 low salt content).

electrode configuration, measuring conditions and textile configuration are selected. Electrode configuration, for instance, includes diameter of the fibres or yarn electrodes and distance between the electrodes.

Another approach to designing conductive fibre based sensors is based on the piezo-resistive effect, whereby the separation of conductive (nano)particles is not achieved by fibre extension, but by fibre swelling. In this case also one basic technology is capable of generating an enormous range of sensing capabilities. Selection of adequate polymeric materials for the fibres or inclusion of swelling components like gels must be adapted to the triggering agent. In addition coatings with selective permeability can be applied to increase selectivity and specificity of the sensor system. These are just two examples of relatively simple systems with an enormous range of applicability.

6.4 Testing of ECG electrodes

Textile sensors to be used for medical purposes are usually in contact with the skin. This is particularly the case for electrodes used for monitoring heart signals (cardiogram). In order to test the performance of textile structures for this application an actual cardiogram can be recorded. All studies show textile electrodes are basically inferior to classical electrodes and need special treatment for achieving good readings. Skin contact is a first key issue. Electro-conductive gels are commonly used to improve skin contact. Such gels, however, cause skin irritation when used for longer than 24 hours. One of the reasons for choosing textile electrodes is that they can be worn permanently without affecting comfort. One of the main problems here is the extreme variability of the skin properties. Skin conductivity changes between persons and for one person in time and with activity making objective testing very difficult. In addition, any movement changes the textile to skin contact and this is another major source of artifacts. Therefore a phantom test set up has been developed [Westbroek 2006]. In this method an electrolyte is used to simulate body fluids, separated from the textile electrodes by polymeric membranes mimicking the skin. (Fig. 6.3)

Signal transfer is analysed using impedance spectroscopy. This method allows the separation of the impedance of the separate components of the system. By varying different parameters, their influence on resistance can be studied quite easily in an accurate and reproducible way. In this section the overall resistance has been measured. It is composed of the following resistances:

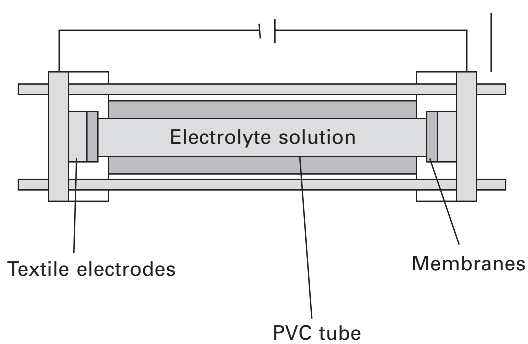
- the textile
- the contact textile/membrane
- the electrolyte solution.

The two first resistances are far bigger that the third. Size and shape of the electrodes has to be optimized as well as distance between the electrodes on the body. The effect of distance between the electrodes can be simulated by varying the length of the PVC tube. The skin properties can be varied by using different membranes (thickness and pore size).

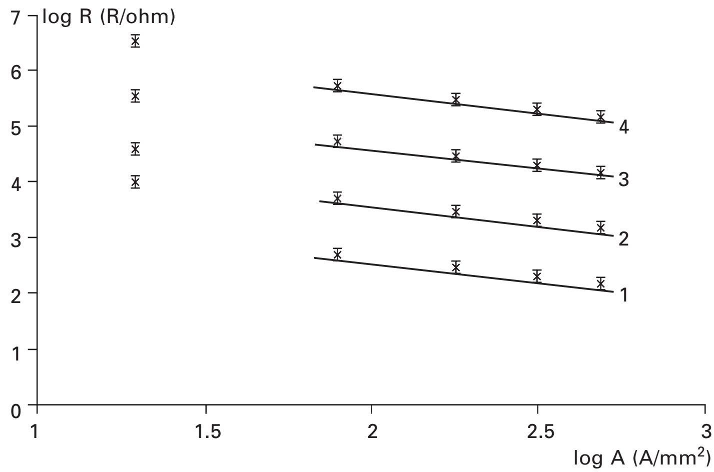
The textile structure itself has a major impact too of course. The following values of the overall resistance have been measured:

- reference material: 310 kΩ
- woven structure: 29 kΩ
- knitted structure: 3.2 kΩ
- non-woven structure: 0.315 kΩ

The textile structures have been made from stainless steel fibres, palladium has been chosen as a reference material. The effect of the size of the electrodes on the resistance of the cell is presented in Fig. 6.4. The four lines represent



6.3 Impedance spectroscopy for characterizing textile electrodes.



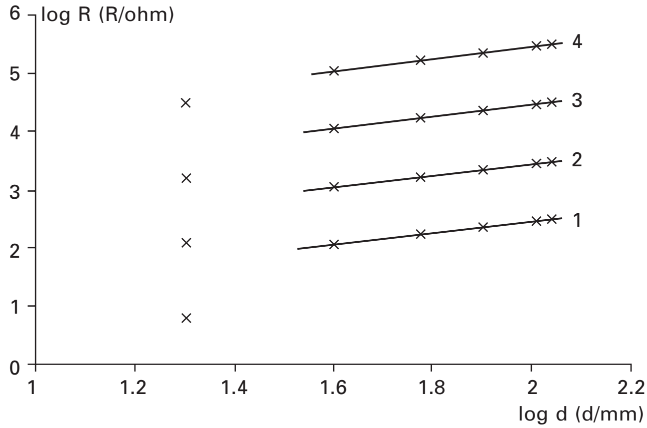
6.4 Effect of electrode size on the resistance of the cell.

different salt concentrations of the electrolyte. As would be expected, the resistance decreases linearly with the logarithm of the electrode surface, except for small areas. This can be explained by edge effects that play a bigger role in smaller electrodes. As resistance should be minimal, electrodes should be large. On the other hand, bigger electrodes are more sensitive to deformation and motion artifacts, so an optimal size should be chosen.

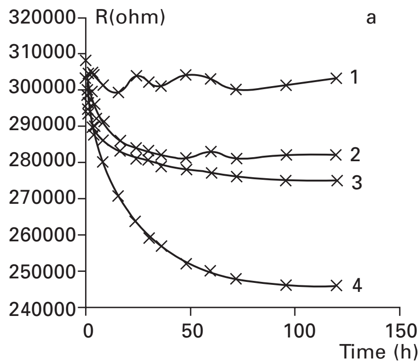
The distance between the positions of the electrodes is another parameter that has to be defined. The effect of this parameter can be seen in Fig. 6.5. The four lines have been measured at different salt concentrations. The resistance increases relative to the logarithm of distance. At short distances the results deviate. This is due to the surface roughness of the textile; the exact distance between the texile is not defined because of this parameter, and this error has an impact when the distance is small.

When permanently worn on the body the textile electrodes will become wet due to sweating. In order to simulate this effect, a porous membrane has been used. The electrolyte migrates through the pores and wets the textile. As can be seen from following graph (Fig. 6.6), sweating considerably reduces the resistance leading to improved measurements (curves 2–4). When wetted with clear water (curve 1), this effect is negligible.

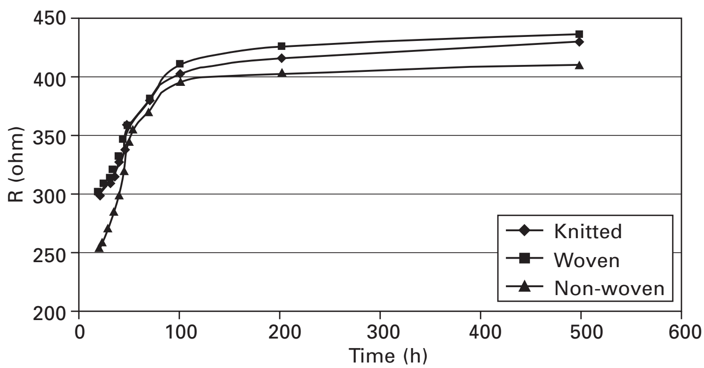
Apart from the positive effect of sweating, corrosion has to be considered as well. Although stainless steel fibres resist corrosion due to, for instance, NaCl, at the skin a voltage also occurs, causing electrochemical attack. As a consequence the electric resistance increases in time when the material is in contact with artificial sweat (measured using the set up described above) [Westbroek 2006] (Fig. 6.7). This graph clearly demonstrates that corrosion has a significant impact on the conductivity of the sensor: the resistance



6.5 Effect of distance between the electrodes on the resistance of the cell.



6.6 Effect of sweating on cell resistance.



6.7 Effect of corrosion of stainless steel fabrics on electrical conductivity.

nearly doubles in a couple of weeks. This means that the accuracy of the sensor will be reduced significantly.

6.5 Testing of strain sensors

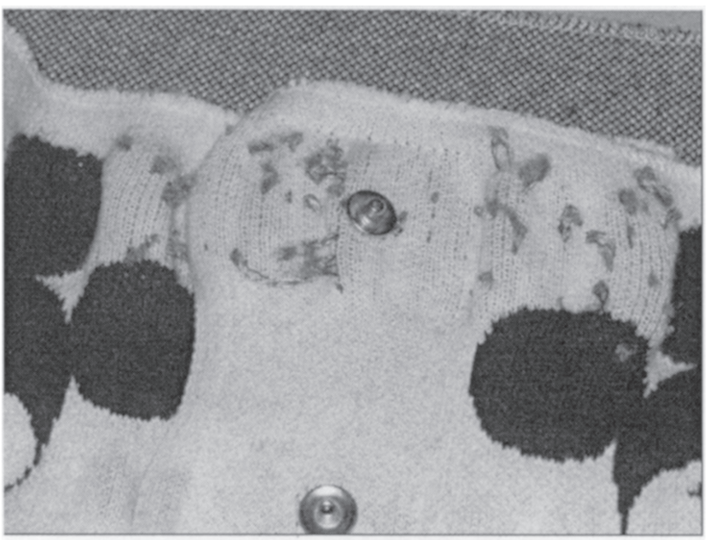
6.5.1 Physical effects

Conductive fibres often have mechanical properties that are quite different from those of 'regular' textile fibres. This causes them to react differently to deformation, bending, extension. As a result a slow but consistent migration of those fibres occurs. This eventually leads to separation of both components and this effect may become clearly visible after long-term use as, for instance, a breathing sensor (Fig. 6.8.) This effect is obviously not welcome for several reasons:

- it negatively affects the aesthetic aspect of the fabric
- it may affect the sensor function
- contacts may occur with the skin or the environment, leading to false signals, increased noise, etc.
- fabric feel may be affected.

6.5.2 Fibre breakage

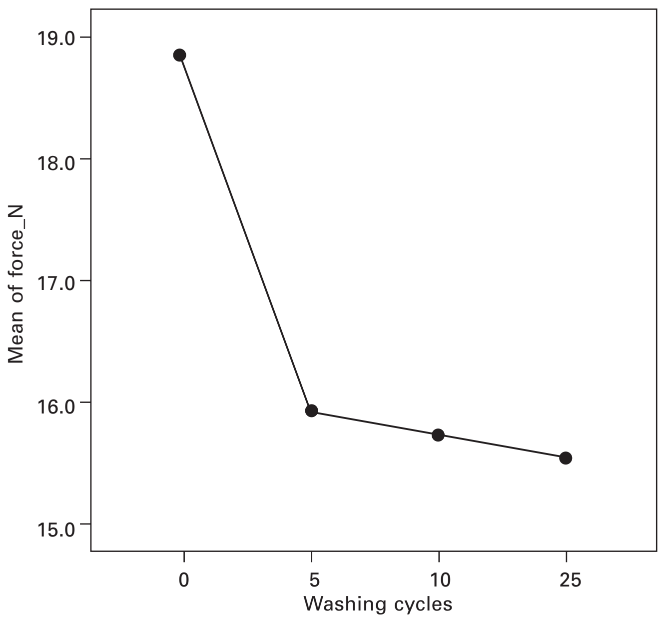
Apart from the quite obvious macroscopic effect described in a previous paragraph more complex phenomena influence the sensor function of textile



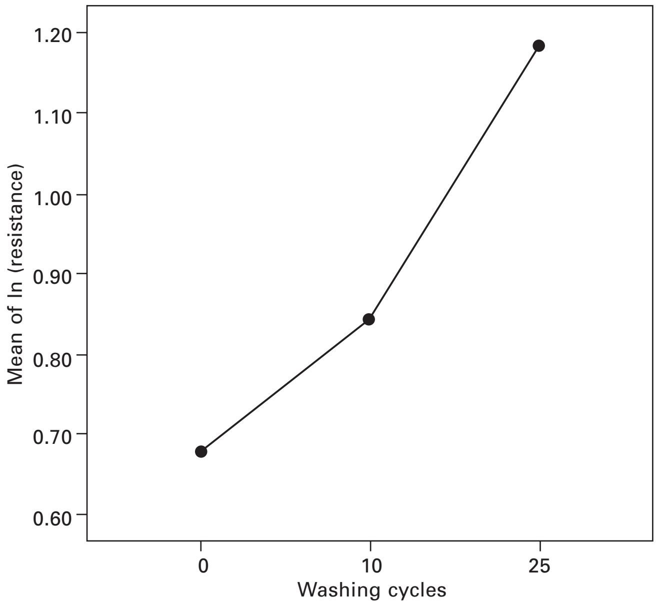
6.8 External loops formed by stainless steel yarns due to repeated extension.

sensors. Stainless steel fibres, for instance, are rather brittle, so repeated extension and bending causes them to break. Consequently, the number of fibre to fibre switches will increase with each fibre breakage and contact resistance being the biggest resistance by far, overall resistance of the textile structure will drastically increase. Particularly during laundry, deformation is quite intensive and laundry is of course a very relevant operation so it is a good way to test the impact of deformation. Measuring changes in length of fibres in an actual textile structure is very difficult because the fibres are embedded in the textile structure and its unravelling may cause more fibres to break. Fibres may also be crimped considerably so the length measurement in itself becomes difficult. An indirect method to evaluate fibre length is yarn strength as this relationship has been demonstrated in numerous studies (Fig. 6.9).

Mechanical damage of fibres has also been reported by Tao [2004]. This work describes the appearance of cracks at the surface of PANi and PPY coated fibres at extensions from 6% onwards. It is quite clear that all factors that affect the conductivity of the material also affect its proper functioning in the intelligent textile (Fig. 6.10). Mechanical damage due to multiple deformation in general is an important problem for all kinds of conductive textile materials. Also interconnections between different components (sensors, actuators, electronics, battery, wires) have been reported in many studies as



6.9 Influence of repeated extension during washing on yarn strength as a measure of fibre breakage.



6.10 Effect of fibre breakage due to multiple deformation on yarn resistance.

weak spots, in particular at places where soft (textile) and hard (electronics) elements are connected.

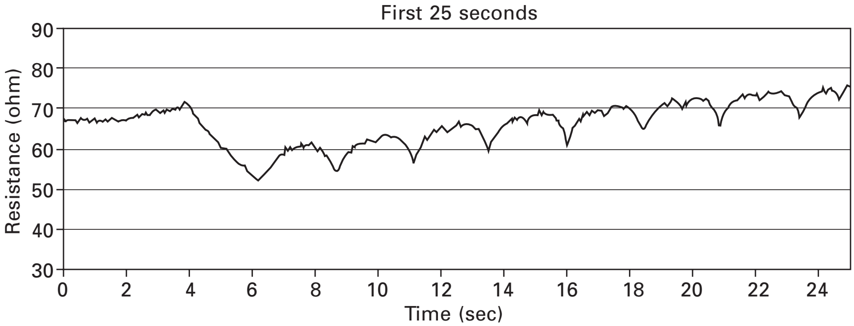
6.5.3 Resulting long-term behaviour of textile strain sensors

As explained earlier, several factors may affect the proper sensor function of textile strain sensors. To test this a cyclic loading was applied whilst measuring the resistance of the textile structure [Lanfer 2005]. This resistance should go up and down with extension and the amplitude should be high enough for an accurate sensor (Fig. 6.11). The strain gauges were used for the characterization of the sensors and for accurate and precise measurement of strain [Heriott Watt 2004]. It is a very simple and handy system applied for sensors with the linear dependence of resistance changes on strain (or elongation) [Puers 1973]. All the developed formulas are true for the homogeneous materials and products. In general, the gauge factor (GF) is given by the following formula:

$$GF = \frac{\Delta R}{R_0} \bigg/ \frac{\Delta L}{L_0}$$

where:

ΔR – an increase of resistance and $\Delta R = R_i - R_0$;



6.11 Variation of resistance due to cyclic loading of the textile strain sensor.

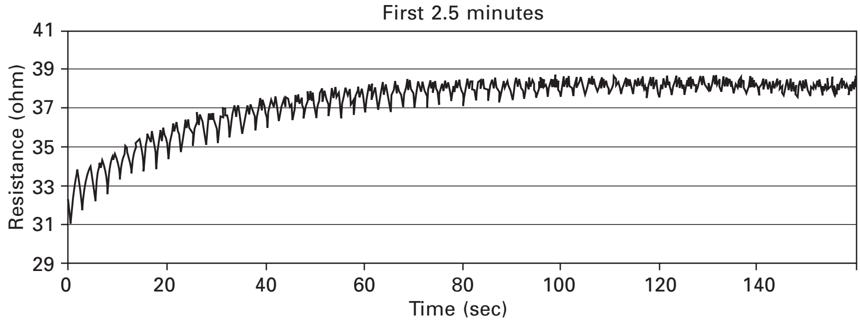
R_0 – initial resistance value;
ΔL – an increase of length and $\Delta L = L_i - L_0$
$\Delta L/L_0$ – the formula describes strain.

Rearrangement of the fibres happens mostly in the initial phase of use. As a result, resistance of a fabric will experience its fastest changes at the beginning of deformation tests; later on it will stabilize more or less (Fig. 6.12). From this figure it can be seen that the gauge factor is maximum at the start of the experiment and stabilizes after about 1.5 minutes. For many textile structures this gauge factor slowly goes down turning the textile material into an unreliable sensor (Fig. 6.13).

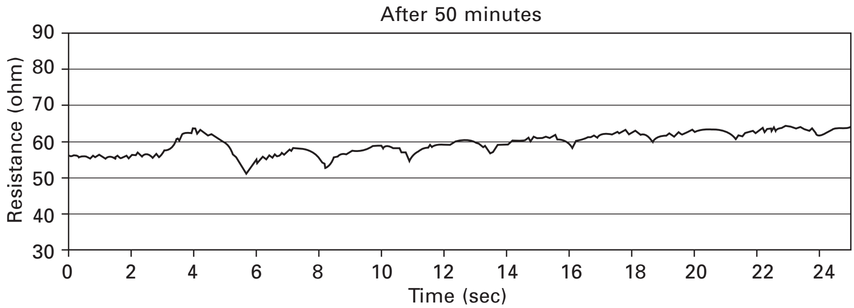
Washing is another important process of use that needs to be considered. Surprisingly the amplitude temporarily increases after washing. This is probably due to a rearrangement of the fibres in the textile structure after washing following the considerable fibre rearrangement during washing (Fig. 6.14). The sensor sensitivity of some textile structures actually improves due to washing. This is reflected in the gauge factor (Fig. 6.15). The gauge factor clearly goes up after washing. The more washing cycles that have been completed, the greater the increase and the better the sensitivity of the sensor. The effect partly disappears again during use, but partly it is permanent. It can be concluded that textile structures behave in a very complex way as sensors. Depending on the actual fibre type and the fabric structure a wide range of responses can be found.

6.6 Future applications of smart textiles

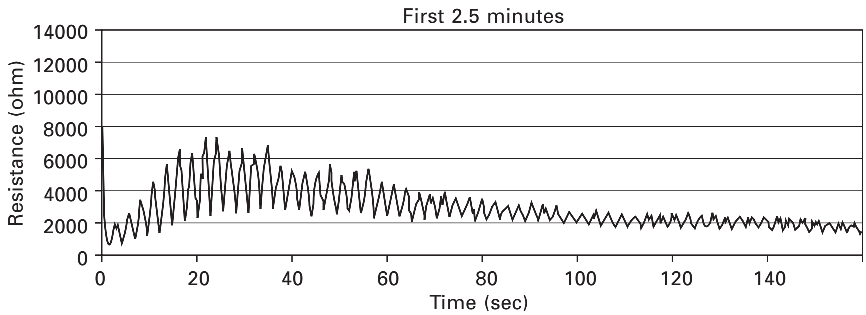
As stated earlier, the potential of smart textiles for health care is still largely unexploited. Apart from individual health, smart textiles can also play a role in public health. Epidemia, and more particularly pandemia, are one of the major threats of the future [Yayaraman 2006]. In the past particular types of flu have caused enormous casualties. With our very mobile society pandemic



6.12 Change of resistance of a conductive yarn during initial phase of use.

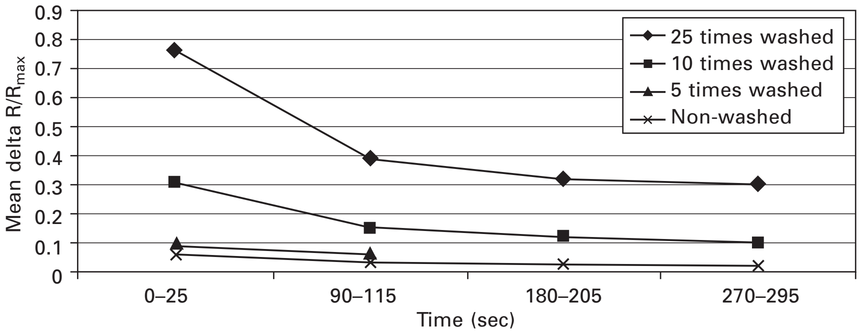


6.13 Loss of sensor capacity due to multiple deformation.



6.14 Effect of washing on sensor capacity of a textile material.

diseases will spread far quicker than ever before. Smart textile suits can play a role in remote monitoring, diagnosis and advanced protection. In an ageing society, falling becomes an increasing risk. Let us look at what smart textiles can offer in this respect. The suit will help to avoid risky situations. It communicates with the house in order to switch on the light when entering a room. It informs about objects lying on the ground. The suit detects when a person has an increased risk of falling, for instance, by detecting a drop in blood pressure or frequent instabilities. It sends out a warning in order to



6.15 Impact of washing on textile strain sensor sensitivity.

inform the person and his relatives. The suit can supply drugs should this be necessary.

Integrated artificial muscles help to maintain equilibrium. When detecting an actual fall, in spite of the integrated muscles, the suit instantaneously turns into an impact-absorbing material. Air bags or mechanical actuators could be used to this end. After a fall, the smart suit assesses whether help is needed. If so, it calls for help and sends out information on the situation. It treats wounds and provides a splint should this be necessary. The suit also provides help in rehabilitation, for instance, by stimulating the healing process or by keeping the body in shape during immobilization. And all this in a discreet way, without any special care or loss of comfort. Of course the components, systems and materials for such a suit are far from being available today but it sets our mind on what could be possible tomorrow.

6.7 Conclusions

Smart textile structures are here to stay. They have demonstrated their feasibility both from the point of view of technical specifications as well as their textile character. The enormous versatility of textiles in terms of (combinations of) fibre types to be used, processing technologies and textile structure is at the same time an opportunity to be exploited but also a confusing space of possibilities. Different textile materials may show different, even opposite behaviour. It is a huge challenge to find the right set of materials for each particular application. Properties that are beneficial for one application may be disruptive for another one. Technical features may be in contrast to textile characteristics so a balance may have to be looked for. Objective testing is another field of research. No evaluation is possible without an accurate and reliable test method but the result will be worthwhile; it will definitely lead to a better quality of life.

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